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Historical Fire In Longleaf Pine (*Pinus palustris*) Forests of South Mississippi and Its Relation to Land Use and Climate

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Historical fire in longleaf pine (*Pinus palustris*) forests of south Mississippi and its relation to land use and climate

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Abstract. We characterized historical fire regimes in *Pinus palustris* (longleaf pine) forests of southern Mississippi with regard to global and regional coupled climate systems (e.g., El Niño–Southern Oscillation) and past human activity. The composite fire chronology spanned 1756–2013 with 132 individual scars representing 89 separate fire events. The mean fire interval was 2.9 yr, and mean intervals were significantly different between identified time periods (e.g., settlement period vs. management period). Evidence of biannual fire activity (up to three fires occurring within a 12- to 15-month period) was found coeval with a peak in livestock grazing and logging from the 1850s through the 1880s. Connections were also found between historical fire and Pacific climate variability (e.g., El Niño–Southern Oscillation and Pacific Decadal Oscillation; $P < 0.05$), yet the fire–climate linkage was likely at least partially masked by substantial human land use activities over the past several centuries. Coupled climate and human land use activity controlled the historical fire regime over the past ca. 240 yr. Although the many fire adaptions of *P. palustris* yield limitations in tree-ring-based fire history studies (e.g., thick bark), we highlight the efficacy of considering the height at which fire scars are analyzed along the bole as a way to glean a more accurate depiction of historical fire occurrence, especially in ecosystems characterized by a frequent, low-severity fire regime. This study suggests growing-season fire prescribed at a 2- to 3-yr interval would be the first step toward simulating historical landscape conditions and fire activity, should that be the goal by land managers.

Key words: dendrochronology; disturbance ecology; El Niño–Southern Oscillation; fire history; Gulf Coast; Pacific Decadal Oscillation; Piney Woods; wildfire.

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Introduction

The historical range of *Pinus palustris* Mill. in the southeast United States covered approximately 37 million ha (Frost 2006), but only approximately 1.3 million ha remain (Oswalt et al. 2012). Frequent fire, either forced by climate or ignited by humans, was an important disturbance for the maintenance of historical *P. palustris* forests across the southeast United States. The relationship between wildfire regimes and climatic factors on global and regional scales has been documented through many studies (e.g., Swetnam and Betancourt 1990, 1998, Kitzberger et al. 2001, 2007, Heyerdahl et al. 2002, Schoennagel et al. 2005, Taylor and Beaty 2005). Cycles of sea surface temperature (SST) anomalies that influence global precipitation patterns such as El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) can cause changes in fire regime frequency, season, and spatial extent (Kitzberger et al. 2007). The relationship between global ocean–atmosphere oscillations is more apparent in the western United States (e.g., Swetnam 1990, Heyerdahl and Alvarado 2003, Swetnam and Baisan 2003, Hessl et al. 2004, Brown and Wu 2005, Fulé et al. 2005, Schoennagel et al. 2007, Skinner et al. 2008) than in the southeast. Yet, fire–climate relationships were reported for Virginia (Lafon et al. 2005, Aldrich et al. 2010, 2014, Flatley et al. 2011), West Virginia (Lynch and Hessl 2010), Tennessee (Flatley et al. 2011, 2013), Florida (e.g., Brenner 1991, Jones et al. 1999, Harrison and Meindl 2001, Prestemon et al. 2002, Beckage and Platt 2003, Beckage et al. 2003, Goodrick and Hanley 2009, Slocum et al. 2010), Arkansas (Guyette et al. 2006), and Louisiana (Stambaugh et al. 2011).

Although many previous fire history studies in the southeast found climate to be an important driver of fire (e.g., Stambaugh et al. 2011), anthropogenic activities also had a strong influence on fire activity over the past several centuries (e.g., Huffman et al. 2004, Maxwell and Hicks 2010, Flatley et al. 2011, Stambaugh et al. 2011). Before European settlement, the southeast landscape contained vast areas of old-growth *P. palustris* forests, but the strong heartwood of the species made it particularly desirable for lumber during the 19th century after marked human population increase and influx of settlers to the region (Earley 2004, Hickman 1962). Despite abundant fire-related research in the southeast, little is known about the historical fire and its relation to climate and human activities in the Gulf Coast region of the United States.

Frequent fire in *P. palustris* ecosystems facilitates ecological biodiversity and restricts succession from open-canopy pine woodland to a closed-canopy forest dominated by fire-intolerant species (i.e., *Quercus* spp.). *P. palustris* forests in south Mississippi contain some of the last natural habitats for fire-climax species such as *Picoides borealis* (red-cockaded woodpecker) and *Gopherus polyphemus* (gopher tortoise) within the Gulf Coast region, but these communities are threatened because of continued fire suppression and habitat fragmentation that started during the 20th century (Tesky 1994, Innes 2009, USDA 2012). Despite frequent use of prescribed fire in state and national forests in the region over the past several decades, the historical fire regime (i.e., frequency, season, spatial extent) and its relation to climate and settlement history is unknown. In this study, we describe the historical fire regimes across two study sites in De Soto National Forest, south Mississippi, to better understand how previous fire activity related to human land use and climate. We address the following research questions:

1. What was the historical fire regime (i.e., frequency, seasonality, spatial extent) in the *P. palustris* ecosystems of southern Mississippi?
2. Are there differences between the pre- and postsettlement period fire regimes?
3. Does a connection exist between historical fire and Pacific climate variability (e.g., ENSO, PDO)?
4. What is the relationship between climate, human activity, and historical wildfire in southern Mississippi?

Methods

Study area

De Soto National Forest (Fig. 1) comprises 210,000 ha in southern Mississippi across two ranger districts: De Soto and Chickasawhay. The De Soto Ranger District covers approximately 2000 km^2 and represents one of the most suitable habitats remaining for the *P. palustris* ecosystem in the Gulf Coast region. Approximately 60% of De Soto was treated with fire during the period 2010–2013 (USDA 2013). Southern Mississippi has a humid subtropical climate with hot summers (mean August temperature 27°C), mild winters (mean January temperature 8.5°C), and adequate precipitation throughout the year (mean annual precipitation 1480 mm). The wettest month is March (mean precipitation 158 mm) and the driest month is October (mean precipitation 74 mm) (1895–2015; NCDC 2014).

Two sites were chosen for this study based on the availability of remnant woody material with recorded fire scars. Because of widespread historical logging and turpentine activity, forest managers helped identify these sites as the only known locations within DSNF containing an abundance of remnant *P. palustris* stumps and logs that might include the fire scars needed for this study. The Fern Gulley Ridge site (FGR; 31.17° N, 89.04° W) and the Death Scar Valley site (DSV; 30.95° N, 89.03° W) (Fig. 1) were located in upland xeric *P. palustris* forest habitat. Elevation ranged at FGR and DSV between 55 and 80 m above sea level, and terrain was rolling with small

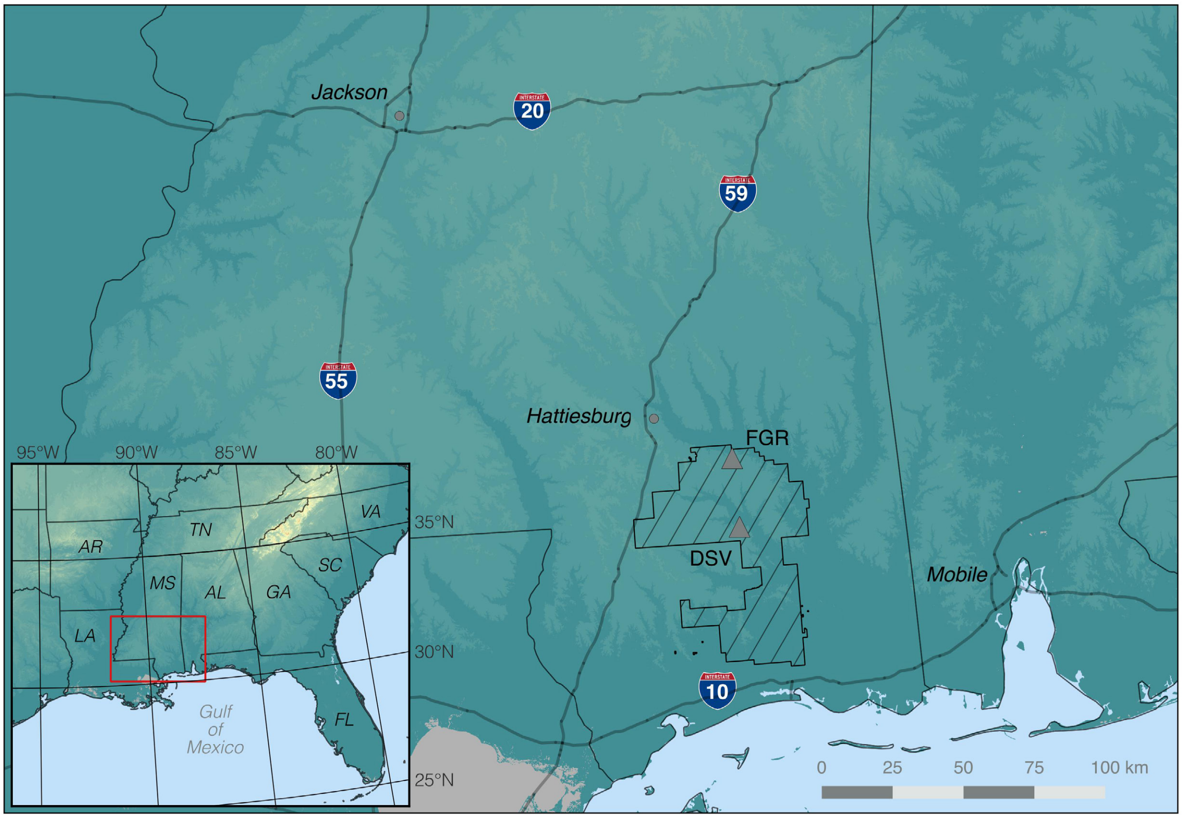

Fig. 1. Location of De Soto National Forest, Mississippi, USA. Map showing locations of the Fern Gulley Ridge (FGR) and Death Scar Valley (DSV) fire history sites (gray triangles) in De Soto National Forest (hatched area).

ridges and drainage swales. Vegetation structure was characterized by an overstory dominated by *P. palustris*; *Quercus marilandica* (blackjack oak) in the midstory; *Myrica heterophylla* (southern bayberry), *Ilex vomitoria* (yaupon shrub), and *Ilex glabra* (inkberry) in the shrub layer; and *Lophiola aurea* (golden crest), *Rhexia alifanus* (deer grass), and *Lobelia brevifolia* (shortleaf lobelia) in the herbaceous layer (Peet 2006). Also scattered in the shrub layer on north-facing slopes was *Kalmia latifolia* (mountain laurel), which is at its western range limit for the species in DSNF. Fire was recently prescribed at FGR (spring 2014), whereas DSV last burned during the year 1996.

Field methods

Partial cross sections from living trees and full cross sections from remnant material containing fire scars were obtained from FGR (n = 15) and DSV (n = 15) using a chain saw (Arno and Sneck 1977). A targeted sampling method was used at each site to identify samples for collection based on the amount of preserved fire scars and proximity to other samples. Our sampling strategy was to collect a well-distributed set of samples to represent fire across the broadest area possible at each study site. The location of each sample was recorded with a GPS.

Sample preparation and laboratory methods

We used standard dendrochronological methods to sand the fire-scarred samples to a high polish (Orvis and Grissino-Mayer 2002). The samples were scanned on an Epson Expression 10000XL Scanner at a resolution of 1200 dpi, and then, ring widths were measured to the nearest 0.01 mm using WinDendro software (Regent Instruments, v. 2012 Ch Sainte-Foy, Quebec, Canada). A reference *P. palustris* chronology was developed previously for DSNF (G. L. Harley, *unpublished data*) and was used to visually and statistically cross-date fire-scarred samples (Stokes and Smiley 1968). Using the computer program COFECHA, the accuracy of visual cross-dating was statistically verified by checking for cross-dating errors that might be caused by locally absent rings or false rings (Holmes 1983, Grissino-Mayer 2001*a*). Fire scars within each sample were identified as areas showing callus tissue and dated using the calendar year in which each fire scar occurred. The season of each fire was identified by assessing the intra-annual position of each scar within the annual growth ring. Seasons were classified as earlywood (E), transition zone between earlywood and latewood (T), latewood (L), or dormant (D) season (Huffman et al. 2004, Harley et al. 2014). Earlywood was defined as the first half of the earlywood zone, transition wood is the last half of earlywood and the first half of latewood, and latewood is the last half of the latewood zone. Dormant-season scars were located on the annual ring boundary.

All fire years were recorded, and the percentage of samples scarred was calculated for each event and used to determine the relative spatial extent of each fire event. The categories used for relative extent were as follows: at least one sample, ≥25%, and ≥50%. We used FHX2 software to calculate mean fire interval (MFI) statistics (Grissino-Mayer 2001*b*) for the following time periods of analysis: settlement (prior to 1880), logging (1880–1935), fire suppression (1936–1979), and prescribed fire period (1980–present). We used Student's *t* tests to compare MFIs between time periods.

Fire–climate analyses

We compared regional and broadscale climatic conditions to fires that scarred any percentage of samples (e.g., all fire events) recorded in the composite DSNF fire record (e.g., combined FGR and DSV fire chronologies). Reconstructed Palmer Drought Severity Index (PDSI) from North American Drought Atlas (NADA) grid point 212 (90° N, 32.5° W; Cook et al. 1999, Cook and Krusic 2004) was compared to the composite fire chronology. The NADA consists of grid-point drought reconstructions across the United States located at 2.5° intervals. Each grid point is associated with a tree-ring-based reconstruction of PDSI. We also tested relationships between all fire event years and climate indices of ENSO and PDO to represent potential climate forcing of wildfire at a broader spatial scale. SST anomalies from the Niño3.4 region (1856–2013; 5° N–5° S, 120° W–170° W) were used to represent ENSO variations. The annual SST anomalies in the North Pacific Ocean (1900–2013; poleward of 20° N; Mantua et al. 1997, Mantua and Hare 2002) were used to represent cycles of PDO. We used superposed epoch analysis (SEA) in the FHX2 program to compare climate conditions before, during, and after each fire event in a 3:1-yr window (3 yr before, 1 yr after; Baisan and Swetnam 1990, Grissino-Mayer 2001*b*). Monte Carlo simulations (n = 1000) were used to calculate confidence limits and examine the difference in climate before, during, and after a fire event (Swetnam and Baisan 2003).

We used bivariate event analysis (BEA) to further investigate the relationships between long-term climate oscillations and fire activity. The K1D software package (Gavin et al. 2006) was used to detect whether two or more event patterns were synchronous, asynchronous, or independent from each other across multidecadal timescales (Gavin et al. 2006). For the BEA, we used the composite of all fire years at FGR and DSV, and 25th percentile events were used to represent extreme negative and positive ENSO and PDO phase conditions. We assumed that fire events follow climate events; thus, bivariate-forward K- and L-functions were calculated along with confidence limits at a 95% envelope using 1000 Monte Carlo simulations. We considered individual negative and positive phases of ENSO and PDO, as well as all phase combinations (e.g., −ENSO/+PDO, −ENSO/−PDO) in the analysis. We used the same ENSO and PDO time series for BEA as for SEA.

Results

Fern Gulley Ridge fire history

Sample overlap varied through time at FGR (Fig. 2), and replication of fire scars across samples was low (Fig. 2); thus, interpreting fire regime statistics (i.e., MFI, seasonality, spatial extent) should be performed with caution. The FGR fire chronology extended from 1756 to 2013 and comprised 15 fire-scarred samples. Only two samples at FGR had open catfaces (recorder year fire

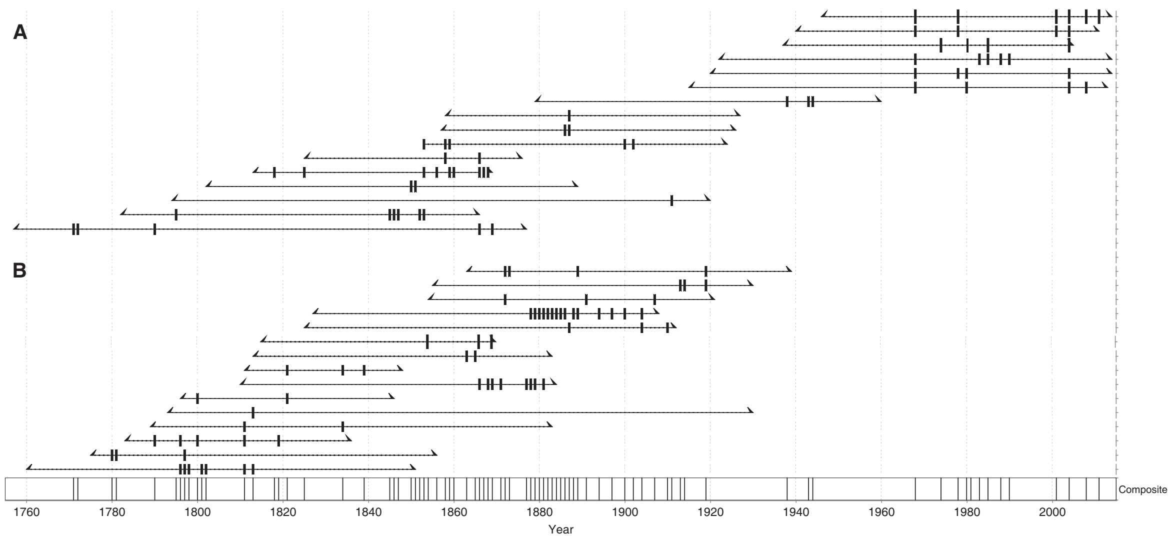

Fig. 2. Fire history chart for De Soto National Forest, Mississippi. Master fire chronologies for (A) the Fern Gulley Ridge (FGR) and (B) Death Scar Valley (DSV) fire history sites in De Soto National Forest during the period 1760–2014. Horizontal lines represent fire-scarred samples, and vertical tick marks denote a fire event.

scars); thus, most scars were classified as internal or buried scars. A total of 63 (53 of which were internal) recorded scars representing 42 separate fire events were included in the chronology. Fire activity at FGR was low from the 1770s to the 1850s. Starting in the 1850s, fires burned regularly until the fire suppression period, during which existed several fire-free periods centered in the 1920s and 1960s. Fire activity increased starting in the year 1968 and continued to current. Biannual fire events—evidence of two fire scars within a 12-month period, or three fire scars within a period of 12–15 months—were discovered on one sample at FGR (Appendix S1: Fig. S1; Table 1).

The MFI was 5.9 yr at FGR during the entire study period (1756–2013) (Table 2). The fire interval distribution was positively skewed, with approximately 40% of fire intervals less than 3 yr. The positive skewness was greatest during the settlement period, at which time the MFI was 4.9 yr. The MFI increased during the logging and fire suppression periods. The MFI decreased to its shortest interval during the prescribed fire period. The most frequent fire interval in FGR existed during the settlement period from 1840 to 1880, during which the MFI was significantly different (*t* test; $P < 0.05$) than during the prescribed fire period (Table 2).

The spatial extent of fires (percentage of samples scarred) varied between the early and late periods of the chronology (Table 2). Prior to the year 1880, scarring percentage ranged between 10% and 20% of samples. From the logging period and extending to current, fires scarred a higher percentage of trees. Other than the 100% scarring during the years 1771 and 1772 (an artifact of low sample depth), the most widespread fires occurred during the years 1968 and 2004 during which 83% of samples collected were scarred. The season of fire occurrence was identified on 63 of the 65 fire scars (97%). Most recorded fires occurred during the growing season (E, T, and L = 57%). This pattern was demonstrated during the settlement (66%), logging (83%), and fire suppression periods (75%). Since 1980, dormant-season fires became more prevalent than growing-season fires.

Death Scar Valley fire history

Compared to FGR, sample overlap and fire scar replication were improved at DSV, yet no living fire-scarred samples were collected. Thus, the DSV fire chronology extended from 1760 to 1939 and contained 15 samples with a total of 69 (53 of which were internal) recorded scars representing 47 separate events (Fig. 2). Similar to

Table 1. Dendrochronological samples with biannual fire scars (either two scars during a 12-month period or three scars during a 12- to 15-month period) collected at Fern Gulley Ridge (FGR) and Death Scar Valley (DSV) in De Soto National Forest, Mississippi.

Sample ID	Inner date	Outer date	Fire scars	
			Year	Season
DSV029	1770	1845	1780	D
DSV029	—	—	1781	L
FGR100x	1812	1869	1859	T
FGR100x	—	—	1859	D
FGR100x	—	—	1860	T
FGR100x	—	—	1866	D
FGR100x	—	—	1867	T
FGR100x	—	—	1867	D
FGR100x	—	—	1868	T
FGR100x	—	—	1868	D
DSV026	1863	1918	1872	D
DSV026	—	—	1873	D
DSV026	—	—	1874	L
DSV108A	1827	1907	1881	T
DSV108A	—	—	1881	D
DSV108A	—	—	1882	L
DSV108A	—	—	1883	T
DSV108A	—	—	1883	D
DSV108A	—	—	1884	T
DSV108A	—	—	1884	D
DSV108A	—	—	1885	T
DSV108A	—	—	1885	D
DSV108A	—	—	1886	T
DSV108A	—	—	1886	D

Note: Abbreviations are as follows: D, dormant; L, latewood; T, transition.

FGR, only three samples had open scar faces, and a large number of internal scars were recorded. The first recorded fire occurred in the year 1780, and fire activity was steady from the 1780s to the 1820s. A marked decrease in recorded fires occurred during the period 1820–1850 CE. Beginning in the 1860s, fire activity increased until the end of the chronology in the year 1939 CE. We identified evidence of biannual fire occurrence on three samples at DSV (Table 1). On one sample (DSV108), we noted 11 separate fire events recorded over a 6-yr period (1881–1886), as well as a distinct difference in fire scars visible along the height of the catface (Fig. 3).

Like FGR, the distribution of fire intervals at DSV demonstrated positive skew as approximately 60% of the intervals were less than 3 yr. During the entire study period (1760–1939), the MFI was 3.0 yr. During the settlement period, the MFI was higher than the composite at 3.8 yr, but then decreased significantly during the logging period to 2.0 (t test; $P < 0.05$; Table 2). Fire occurred more frequent from 1863 to 1919 (a period of time spanning the settlement and logging periods) than it did during any other time period at either study site.

Settlement period fires were more spatially extensive at DSV compared to FGR, and a different pattern of extent was gleaned from the fire chart (Fig. 2). Fires prior to 1880 were more widespread, commonly scarring over 20% of samples. Scarring percentage at DSV ranged from 9% to 50%. The 50% values were tallied for the years 1780, 1781, and 1919, during which sample depth was low. The season of fire occurrence was identified on all 69 recorded fire events (100%) (Table 2). Similar to FGR, most fires occurred during the growing season (E, T, and L = 59%), and seasonality of fire events was consistent throughout the chronology.

Southern Mississippi fire history

A combination of fire samples ($n = 30$) from the two study sites produced a composite fire history with adequate sample depth, overlap, and scar replication that spanned the period 1756–2013 and contained 132 individual scars representing 89 separate fire events (Fig. 2). The composite chronology revealed a MFI of 4.0 yr during the entire study period (Table 2). However, given that living fire-scarred samples were only collected from the FGR site, the common period of overlap between sites was 1760–1939 CE. Fires during the settlement period burned on average every 4.3 yr, and fire activity continued at a similar frequency to the end of the logging period ca. 1935 CE.

Fire–climate relationships.—SEA revealed significant relationships ($P < 0.05$) between the DSNF composite fire chronology and oscillations of SSTs in the Pacific Ocean (Fig. 4). Three years prior to historical fire events in DSNF, SSTs in the Niño3.4 region were above average ($P < 0.05$; $n = 52$ fire events tested during the period 1856–2012). During fire event years (0-yr lag), SSTs were below average but not statistically significant ($\alpha = 0.05$). Along with ENSO, the PDO exhibited warm phases 3 and 2 yr prior to fire events ($P < 0.05$). BEA revealed a trend of synchrony between PDSI and fire at short timescales (ca. 1–5 yr; $P < 0.05$) (Appendix S1: Fig. S2), but the association was not

Table 2. Fire intervals and seasonality during the settlement (1760–1879), logging (1880–1935), fire suppression (1936–1979), and management (1980–2013) periods for the Fern Gully Ridge site (FGR), Death Scar Valley site (DSV), and composite fire history in De Soto National Forest, Mississippi.

Characteristic	All years	1760–1879 Settlement	1880–1935 Logging	1936–1979 Fire suppression	1980–2013 Management
Fern Gulley Ridge fire interval					
MFI	5.9**	4.9*,**	6.3*,**	8.0*	3.4*
Seasonality (%)					
Growing season	57	66	83	75	31
Dormant season	43	35	17	25	69
Death Scar Valley fire interval					
MFI	2.0**	3.8*,**	2.0*,**	—	—
Seasonality (%)					
Growing season	59	64	52	—	—
Dormant season	41	38	45	—	—
Composite DSNF fire interval					
MFI	4.0	4.3	4.2	8.0	3.4
Seasonality (%)					
Growing season	58	65	68	75	31
Dormant season	42	37	31	25	69

Notes: DSNF, De Soto National Forest. Significant difference in period mean fire interval tested via Student's *t* test ($P < 0.05$) within (*) and between (**) sites.

supported by SEA. A discernable but insignificant ($P > 0.05$) pattern was found between fire and reconstructed PDSI during the period 1768–2002 ($n = 79$ fire events tested) (Figs. 4 and 5). PDSI was positive (wet) 3 yr prior, but the departure was not significant. More convincing were negative (dry) departures in PDSI 1 yr prior to and the year of fire events.

Negative phases of ENSO and PDO demonstrated asynchronous relationships with fire events over the past several centuries. However, the BEA confirmed SEA results that positive phases of ENSO and PDO were important drivers of fire in the region (Fig. 6). Positive phases of ENSO and PDO, as well as phase combinations of −ENSO/+PDO and +ENSO/+PDO, were synchronous with fire events ($P < 0.05$). All other relationships between extreme ENSO and PDO conditions and wildfire demonstrated independence or asynchronous temporal association.

Discussion

We present the first (1) known dendrochronology-based historical fire record in Mississippi and (2) suggested linkages between Pacific Ocean–atmosphere teleconnections and historical wildfire in the Gulf Coast region of the United States. Further, this study provides only the second known evidence of biannual fire activity and confirms previous assertions by Stambaugh et al. (2011) that a frequent fire regime was present in the region prior to establishment of national forests and management efforts by the U.S. Forest Service. Our results indicate that both human land use practices and settlement of the region, along with broadscale climate oscillations, were important influences on historical fires, at least since the 1750s CE.

Southern Mississippi fire regime

Fire frequency covering ca. 240 yr in DSNF showed that *P. palustris* can be used to assess the fire regime over an extended period, as was shown by previous research (e.g., Stambaugh et al. 2011). The large number of internal scars (nonrecorder year) suggests the historical fire regime was characterized by low-intensity, low-severity, fast-moving surface fires not able to open or maintain catfaces (e.g., basal bole wounds) on trees, and this is common in open-canopy *P. palustris* forests (Platt et al. 1988, Frost 1993, Platt and Rathbun 1993). The 4-yr MFI during the entire study period is comparable to other fire histories in *P. palustris* forests. Stambaugh et al. (2011) recorded a fire interval of 2 yr (1650–1905) in Kisatchie National Forest, Louisiana. Other similarities between the DSNF and Kisatchie fire

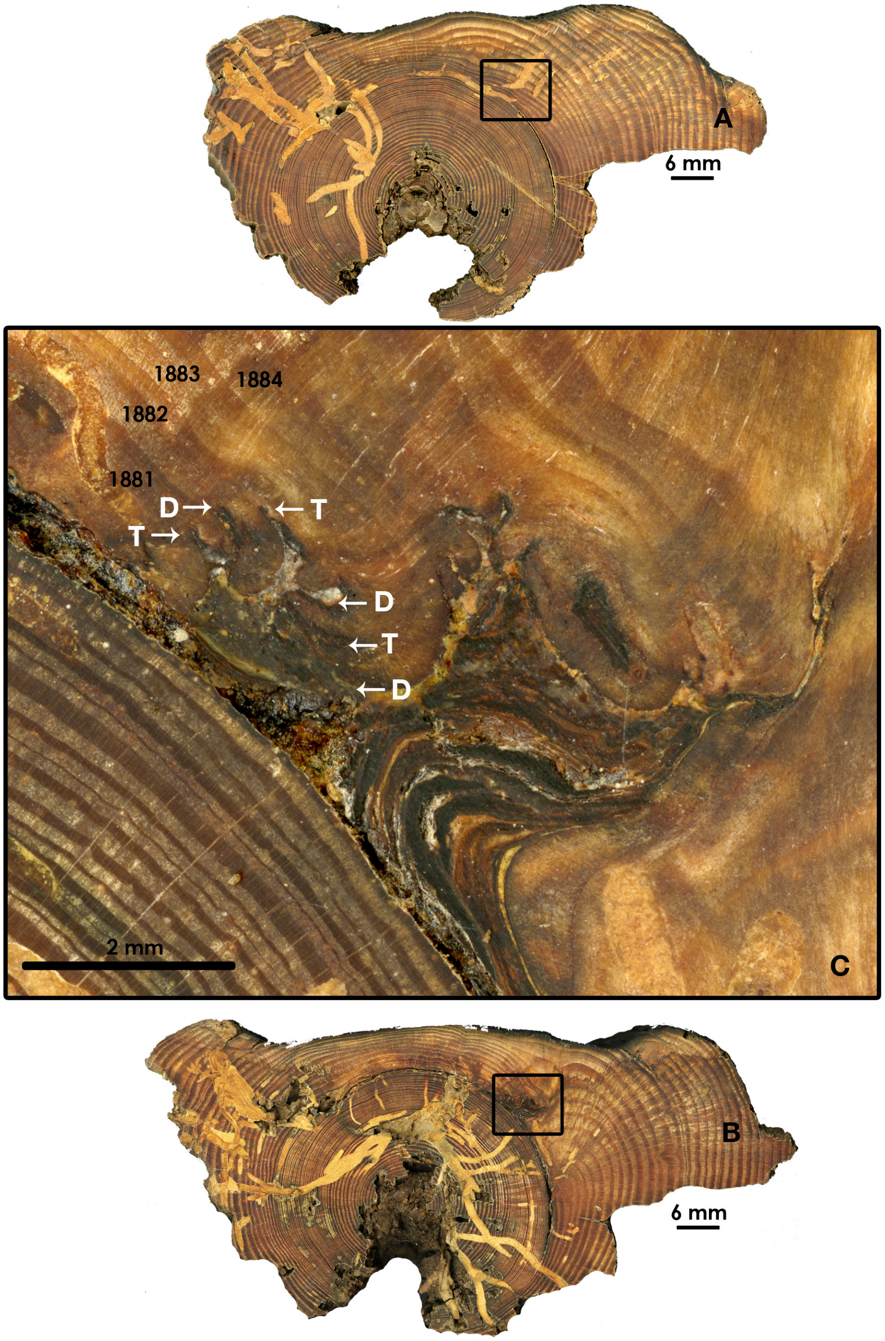

Fig. 3. Microscopic photographs of biannual fire scar evidence from the Death Scar Valley site (sample DSV108), De Soto National Forest, Mississippi. Reference insets (A) and (B) demonstrate the importance of height at which fire scar analysis is conducted on a catface. Inset (C) shows further examples of scars exhibiting biannual fire frequency during the following years/seasons: 1881 transition (T) and dormant (D), 1882 latewood (L), and transition and dormant scars each year during the period 1883–1886. Sample DSV108A recorded 11 fires over a 6-yr period (1881–1886). Inset (D) shows the fire-scarred stump (DSV108) with location references to inset views (A) and (B) and demonstrates the marked difference in fire scar occurrence over approximately 4 cm height along the catface.

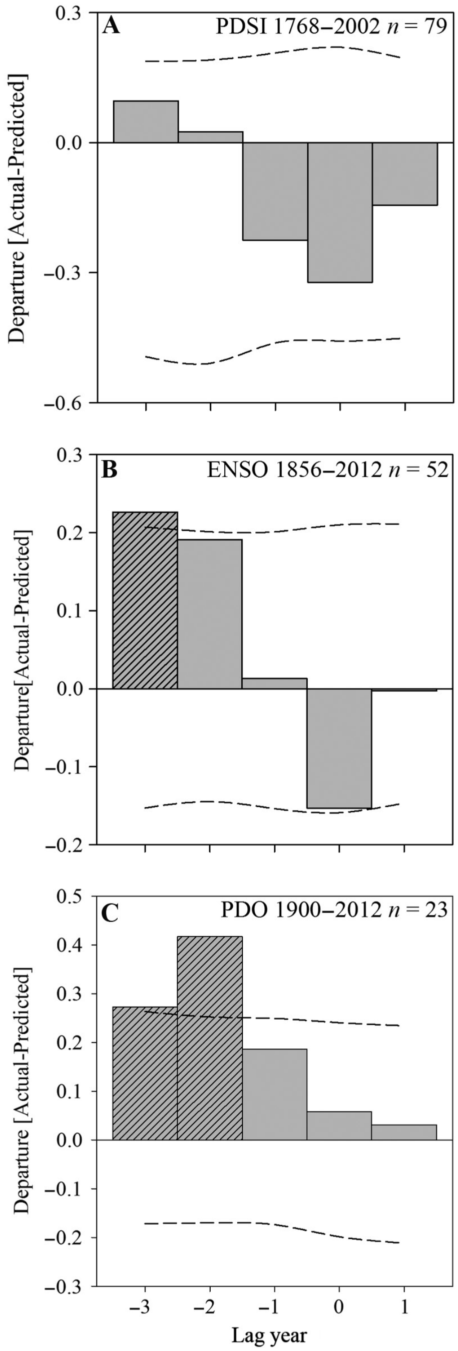

Fig. 4. Fire–climate relationships revealed from superposed epoch analysis in De Soto National Forest, Mississippi. Results show departures from mean annual (A) PDSI, (B) ENSO, and (C) PDO during years in which a fire occurred in De Soto National Forest. Dashed lines are 95% confidence intervals derived from 1000 Monte Carlo simulations performed on the entire climate data sets. Hatched bars represent lag years with departures exceeding confidence limits. Abbreviations are as follows: PDSI, Palmer Drought Severity Index; ENSO, El Niño–Southern Oscillation; PDO, Pacific Decadal Oscillation.

records are a similar MFI pattern through defined time periods (e.g., settlement, logging), and increased fire activity during the middle to late 1800s. In northwest Florida, Huffman et al. (2004) recorded an interval of 3.2 yr for a barrier island *Pinus elliottii* Engelm. forest. Also in northern Florida, Henderson (2006) reported settlement period fires occurred within a *P. palustris* savanna at a mean interval of 6 yr. The fire history from DSNF was not long enough to provide a comparison of pre- and post-European settlement due to the lack of well-preserved remnant material. However, the periods of settlement provide an indication of how fire intervals changed over the past several hundred years.

Although we found synchronous fire years between study sites, the majority of scars were recorded during different seasons. We found seven synchronous fire years between FGR and DSV (approximately 20 km distance), yet only two scars were recorded during the same season (1790—dormant; 1900—earlywood). Historical fires in a *P. palustris* forest were known to be fast-moving, possibly covering a large amount of territory quickly (Earley 2004), and thus could have spread over large areas of the landscape before roads and other infrastructure were installed. However, the inconsistency between seasons makes it difficult for this study to determine concretely whether large tracts of contiguous land burned as a characteristic of the historical fire regime.

Historical land use and fire

Land use and fire have long been linked in the Gulf Coast and southern Mississippi regions. Following the American Revolutionary War, possession of southern Mississippi land began a slow transition from the Choctaw Indians to U.S. Territory. The Treaty of Mount Dexter in 1805 ceded the southern portion of Choctaw territory to the U.S. government and enabled rapid European settlement (Barnett 2012). The first census taken near the study area was in the year 1820 for Perry County, Mississippi, and revealed

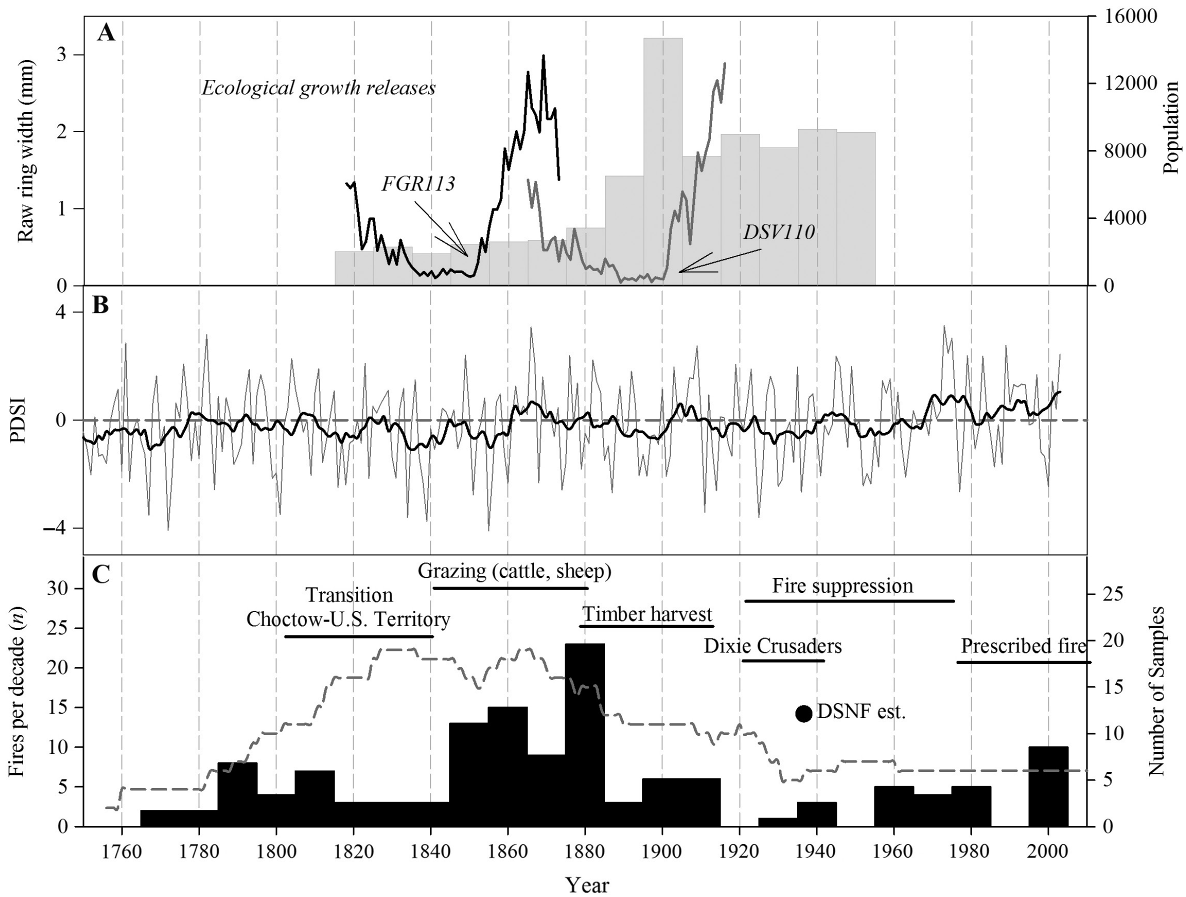

Fig. 5. Fire activity in De Soto National Forest, Mississippi, during the period 1760–2010 CE related to cultural activities and drought. (A) Examples of ecological growth releases in raw ring width (lines) demonstrated by two example tree-ring samples (FGR113 and DSV110) shown with population of Perry County, Mississippi (Forstall 1996), during the period 1820–1950 (gray bars). (B) Annual reconstructed Palmer Drought Severity Index (Cook et al. 1999) from grid point 213 (30° N, 90° W) for the coastal Mississippi region (gray) shown with a decadal smoothing spline (black). (C) Cultural activities and events plotted over the number of fires per decade (bars) and number of fire-scarred samples (dashed line).

2037 inhabitants in the area. Slow and steady population growth persisted through the end of the 19th century (Forstall 1996; Fig. 5). The first European inhabitants were of Scottish–Irish descent, and brought to the region open-range cattle herding practices, as the open savanna of the *P. palustris* ecosystem was conducive for grazing livestock (Hickman 1962). In addition to controlling pests (i.e., Trombiculidae, Ixodoidea), hunters and herdsmen frequently burned the forest to maintain an open landscape (Earley 2004). The following excerpt from Hickman (1962) attests to the use of fire by herders and hunters before the Civil War:

> *Cattle kept fat all the year around from the canebrakes before forest fires destroyed them. The bear, deer, and turkey roamed the forest; wild game was so plentiful up to the Civil War, that the deer had trails in the woods like cattle. All the hunter needed to do was to take a stand behind a tree near the trail and wait for his game.*

Following the American Civil War, timber harvesting and turpentine extraction became important economic activities (Hickman 1962). Turpentine operations were a potential cause of wildfires, as the extraction of resin from tapped trees left flammable residue, which provided a fire accelerant. The fear of severe fires destroying lumber crops caused logging operations to

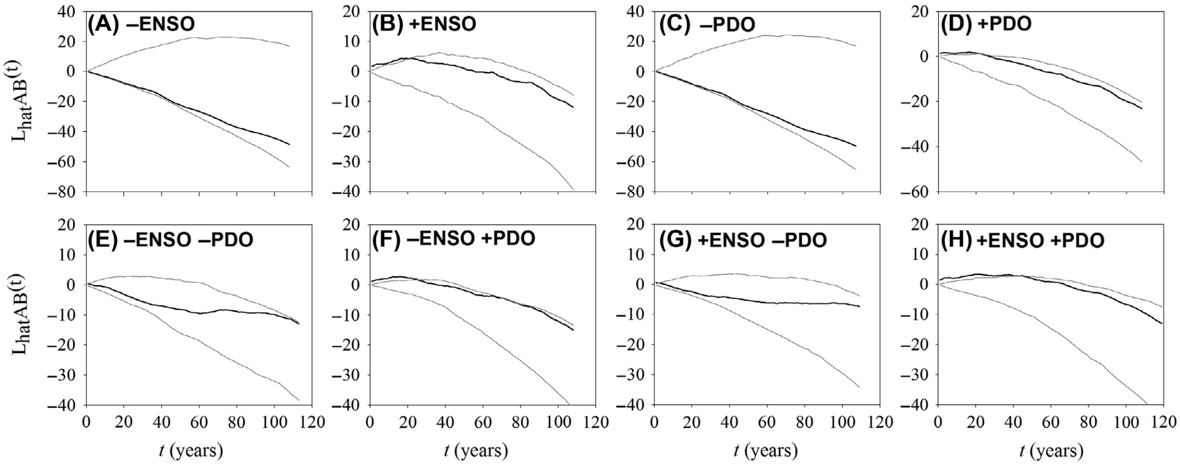

Fig. 6. Temporal associations between Pacific climate variability and historical fire in De Soto National Forest, Mississippi. Bivariate event analysis results showing tests of temporal association between two-way phase combinations of extreme (A, B) ENSO, (C, D) PDO, and (E–H) combined ENSO and PDO and wildfire years in De Soto National Forest, Mississippi. Gray lines denote 95% confidence limits, and L_{hat} values are represented by the black line.

quickly harvest as much timber as possible (Earley 2004). As logging progressed into the early 1900s, the virgin timber desired by both the naval store and logging industries was scarce. Some companies in the region, such as Hercules in Hattiesburg, Mississippi, removed *P. palustris* stumps from the ground that were cut during timber harvesting and used them to produce turpentine (Grant 2005). As a result, remnant stumps are scarce in the region and explain the difficulty we had in locating suitable sites for this study.

Coeval with the period of most frequent fire at both FGR and DSV from ca. 1850s through the early 1900s was a peak in cattle herding and logging activities in the region (Israel 1970, Frost 2006). The broad introduction of commercial logging beginning ca. 1880 represented a transition from cattle herding to logging activity, but the transition occurred gradually across the landscape. The purchase of land was limited to 32 ha by the Southern Homestead Act of 1866, making the process of land speculation for logging difficult. This act was repealed in 1876 and enabled speculators to purchase large tracts of land soon thereafter (Earley 2004). The subsequent increase in logging took several decades to reach all areas of DSNF. Open-range cattle herding was still broadly present in the area even during the period of logging, although logging certainly decreased the impact of cattle herding. Open-herding practices were not banned in Mississippi until the year 1968 (Pitts and Sponenberg 2010).

After the logging period subsided, the fire suppression and prescribed fire periods represent a concerted human influence on the fire regime. During the early 20th century, fire suppression efforts by antifire groups like the Dixie Crusaders, who traveled around Louisiana, Mississippi, Alabama, and Florida during the 1920s–1930s giving antifire demonstrations, altered the frequent fire regime from earlier decades (Rooney 1993, Van Lear et al. 2005). The infrequency of fire beginning in the 1920s as seen in the FGR and DSV fire chronologies suggests antifire groups like the Dixie Crusaders had a profound impact on the landscape through their fire suppression demonstrations. The following period of fire management indicated an emphasis from land managers on introducing prescribed fire back into the landscape, and thus resulted in fire intervals that mirrored historical conditions.

Biannual fire in south Mississippi

The phenomenon of two or more fire scars recorded within an annual growth ring has only been shown by one previous study by Stambaugh et al. (2011). To ensure that we were accurately classifying biannual fire scars, we required that any identified biannual scar be corroborated with the identification of a fire scar on another sample at the same site during the same year. The first evidence of potential biannual burning occurred during the period 1780–1781, although it should be noted that this early evidence of biannual scarring was not corroborated by another sample. A 1780 dormant-season fire, which could have occurred from November 1780 to February 1781, was recorded at DSV followed by a late-season fire in the year 1781. Subsequent evidence of corroborated biannual fire occurred during the 1850s through the 1880s. Although drought conditions were prevalent in the region from the 1830s to the 1860s, the pattern of highly frequent and biannual fire activity (dormant/winter-season fire and transition/summer-season fire) suggests that humans were the primary influence on the fire regime during this time period.

Livestock herders who wanted to enhance the diet of their livestock could have caused the frequent fire activity that started in the 1850s–1870s, as this was a time period of rapid settlement in the region; timber harvesting was not prevalent until the 1880s. Cattle herders of Scottish–Irish descent began moving into southeastern Mississippi from areas such as South Carolina and Georgia starting in the late 1700s. Cattle in the area fed on a number of indigenous plants such as *Avena fatua* (wild oats), *Lathyrus aphaca* and *Lathyrus hirsutus* (peavine spp.), *Lolium perenne* (rye grass), and *Aristida beyrichiana* (wire grass) (Israel 1970). Wildfires increased the amount of nutritional protein, phosphorus, and calcium in the forage used for grazing (Komarek 1974). When most of the forage reached mortality or dormancy during the winter, the evergreen *Arundinaria* spp. (canebrake) became the most important plant for herders. Unlike today, *Arundinaria tecta* (small cane) and *Arundinaria gigantea* (giant cane) were ubiquitous on the Gulf Coast landscape during the period of biannual fire activity in DSNF. *Arundinaria* grew near the streams around southeastern Mississippi. The new growth of *Arundinaria* following a wildfire was tender and nutritious for livestock (Israel 1970). However, the increased value of nutrition only lasted a few months following a fire (Komarek 1974), which likely prompted herders to set subsequent fires. The seasonal pattern of biannual fire activity occurred during the transition season (summer; May–July) and the following dormant season (winter; November–February). Livestock herders likely burned the landscape to increase the nutritional value of forage in areas that were repeatedly grazed.

Fire scar seasonality data suggest that growing-season fires were historically more prevalent than today. All fires recorded during the prescribed fire period occurred during the dormant season. The record of growing-season fires in the early 1800s and subsequent pattern of summer/winter biannual fire during the period 1850s–1880s could be explained with the following scenario. Herders grazed cattle on *Arundinaria* during the winter and burned the area after the cattle migrated to another location of the open range. The next spring, the herders returned to area to graze on an array of flora including *Arundinaria*. As livestock migrated throughout the summer, herders burned the area again to ensure nutrient-rich *Arundinaria* would be present in the upcoming winter. This scenario would explain the high frequency of fire activity and the occurrence of biannual fires revealed in the record.

All of the biannual fire activity was recorded coeval with an ecological release in radial tree growth (Fig. 5A). This release, which was present in nearly all samples collected at FGR and DSV, occurred primarily during the 1850s and the 1900s. The releases were evident on most samples suggesting that they were caused by a widespread disturbance event such as a high-severity fire or logging. Timber workers would often burn the forest prior to logging to create a more open landscape conducive for logging equipment and safety (Earley 2004). Further, harvesting timber increased availability of fuel in the form of debris waste (e.g., branches, needles, logs) left by logging operations. Logging activity would have created open-canopy conditions and increased biomass, and hence likely increased fire intensity.

We highlight the importance of the height at which fire scars are analyzed on a catfaced stump or log in dendropyrochronological studies. The 11 fire scars recorded from 1881 to 1886 by sample DSV108 were only visible on a cross section analyzed close to the root–shoot interface. Future tree-ring-based fire history studies that incorporate the thick-barked, fire-tolerant *P. palustris* in the southeast United States should consider analyzing fire scars at multiple height locations along a catface, as this could potentially provide a more comprehensive fire record in landscapes controlled by a low-intensity, low-severity fire regime.

Fire–climate relationships

In addition to finding strong evidence of human impacts on historical fire, our fire–climate analyses revealed connections between Pacific climate variability and fire in southern Mississippi over the past several centuries. Although we found significant linkages between Pacific climate variability and wildfire, the fire–climate relationship was likely at least partially masked by anthropogenic influences. Nonetheless, climate has been shown to influence fire regimes in the southeast (e.g., Beckage and Platt 2003, Beckage et al. 2003, Stambaugh et al. 2011). Harley et al. (2014) found a similar temporal pattern with Pacific climate forcing (ENSO–PDO) of wildfire in a *P. elliottii* var. *densa* savanna in the Florida Keys. Despite the significant relationships suggested between Pacific climate variability and fire activity in DSNF, the effect of climate on fire occurrence cannot be fully discerned because humans were likely igniting incendiary fires for a variety of aforementioned reasons (i.e., clearing brush, insect reduction, boosting gramminoid reproduction for livestock).

Dry periods were present during the most frequent fire intervals. A visual inspection of the drought time series for the closest NADA grid point to the study sites revealed drier conditions were prevalent from the 1830s through the 1870s, which could have aided the spread of incendiary or natural wildfires that were frequent beginning in the 1840s. Wet conditions during the 1870s and prior to the 1880s biannual fire activity could have contributed to above-average biomass, preconditioning a fire-prone landscape with growth of fine fuels (e.g., gramminoids). The correspondence of fire juxtaposed with wet and dry periods suggests a potential linkage between drought and fire during the 17th century, but this assertion was not supported statistically.

Wet conditions brought on by El Niño and warm PDO phases and subsequent increase of growth of fine fuels (e.g., *Aristida beyrichiana*; *Arundinaria* spp.) 2–3 yr prior to fire could have produced the biomass needed to carry fire over the landscape at short-term frequency. Although the relationship between historical fire and negative departures of ENSO (La Niña events) is not significant ($P > 0.05$), the pattern of drier-than-average conditions during fire years is convincing and similar to previous fire–climate research in the southeast (Beckage et al. 2003, Harley et al. 2014) and southwest US (e.g., Rother and Grissino-Mayer 2014). BEA provided further evidence of Pacific climate forcing of historical fire with the temporal association tests between ± phase combinations of ENSO and PDO. Both −ENSO/+PDO and +ENSO/+PDO combinations were temporally synchronous over decadal to multidecadal timescales.

Conclusions

The Gulf Coast region is understudied in terms of dendrochronology relative to other subregions of the southeast United States, and this research represents a first step in understanding the interactions between climate, land use, and fire that have shaped the *P. palustris* landscape in southern Mississippi. Further, the *P. palustris* ecosystem has developed under a frequent fire regime; thus, this species is characterized by a number of fire adaptations, including rapid height growth, long needles that shield the apical meristem during grass stage, and thick bark. As such, fire history research with *P. palustris* is limited to a few studies. The FGR site-specific fire chronology is limited with low sample depth and overlap during the period ca. 1890–1920, and an individual interpretation of the fire statistics at this site should be performed with caution. Nonetheless, we stress the importance of interpreting fire regime characteristics (e.g., MFI, seasonality) and fire–climate relationship implications with the composite DSNF fire chronology. This study provides baseline fire regime knowledge that can be used by forest managers in landscape restoration plans. Yet simulating the historical fire regime as a restoration goal, marked with decades of frequent fire some with biannual events and growing-season fires, would be difficult to recreate given the recent increase in population and limited resources.

During each identified time period (e.g., settlement, logging), humans were motivated to burn the landscape for (1) clearing the landscape and hunting (Native Americans and early European settlers), (2) increasing plant nutrients for cattle and sheep (Scottish–Irish herders, livestock farmers), and (3) making the land more conducive for logging practices and turpentine operations (timber harvesters). Despite the likely historical prevalence of incendiary fires, we also suggest linkages between Pacific climate variability and wildfire in the region, as wetter (drier) weather associated with El Niño (La Niña) and warm (cold) phases of the PDO likely preconditioned the landscape making it favorable for fire spread. Further research is needed in the region to better understand the interactions between climate, land use, and fire in the *P. palustris* ecosystem of the Gulf Coast region. Although the many fire adaptions of *P. palustris* yield limitations in tree-ring-based fire history studies (e.g., thick bark), we highlight the importance of considering the height at which fire scars are analyzed along a fire-scarred surface as a way to glean a more accurate depiction of historical fire frequency.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.1458/full