Final Report

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Developing and Using Fire Scar Histories in the Southern and Eastern United States

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Abstract

Land managers developing fire management plans in the eastern and southern United States lack quantitative information on historic fire regimes. Twelve new fire histories were developed from dated fire scars on trees from regions where no fire scar history data had existed before in the states of Alabama, Louisiana, Kentucky, Iowa, Wisconsin, and Michigan. Sites represent highly variable climates from extreme cold (with long snow cover duration) to subtropical. All sites utilized oak or pine recorder species that were collected from closed forest to open savanna structures. Pre-industrial mean fire intervals ranged from 3 to more than 35 years at sites that typically encompassed less than 2 km^2 in area. The most frequent fire regime was found in Louisiana's Kisatchie National Forest (MFI = 3 yrs) while the longest fire intervals were at inland sites near the shore of Lake Superior (MFI > 35 yrs) some 1900 kilometers to the north. The subtropical site in Louisiana is perhaps the only site in the U.S. where fires are documented to have occurred more than once a year. The history of fire at sites in Wisconsin, Louisiana, and Michigan showed distinct temporal progressions in changes in fire frequency that we attributed to changing human population. Sites in Wisconsin showed potential for very large fires associated with drought years. Fire history data analyses and summaries were presented at multiple venues (workshops, conferences) and have been published in scientific journals and reports to regional land managers. Fire history data has also been made publicly available through the International Multiproxy Paleofire Databank (IMPD).

New fire history data from this project combined with previously collected fire history data from the Missouri Tree-Ring Laboratory and published fire histories in North America were used to parameterize and calibrate a continental fire frequency model based on climate. The most important contribution of this model is towards understanding climate forcing of fire regimes across the continental U.S. We have developed a suite of climate-based fire frequency models for the continental U.S. that show to be highly robust. Models and calibrations were validated with empirical fire history data during pre-industrial periods so to minimize non-climate influences associated with U.S. settlement (land conversion, changing cultures). Fire frequency models follow theoretical concepts from physical chemistry, utilize spatially-explicit fire and climate data, and were parameterized and validated using statistical methods. Data from fire history studies were accumulated from 37 states and include data based on fire scars (n = 168), expert estimates (n = 7) and charcoal (n = 3). Historic mean fire interval (MFI) models were parameterized using mean maximum temperature, precipitation, their interaction, and estimated population density (anthropogenic ignitions). Models are being used to: assess the role of climate in forcing fire frequency, map coarse-scale historic fire frequency for the continental U.S., and assess departures in fire regimes and smoke emissions.

I. Background and purpose

A common obstacle for public land managers developing fire management plans in the eastern and southern United States is the lack of scientifically-derived data on historic fire regimes. Forest managers often struggle to implement fire reintroduction plans partially due to a lack of scientific documentation describing historic fire regimes. Fire regimes and fire frequencies are sometimes based solely on anecdotal accounts of past fire occurrence, and could potentially have the opposite effect on ecosystem integrity than what is intended.

Previous studies conducted in the western U.S. have indicated the potential value and applicability of fire history studies in understanding coarse-scale ecosystem processes and the relationships between fire, climate, and ignitions. Compared to the western U.S. such studies are lacking for the eastern and southern portions of the country. We proposed this project to both meet the needs of forest / fire managers in these areas and analyze coarse-scale variability in continental fire regimes and their major influences (e.g., climate and humans).

Fire scars on trees provide unique temporal, spatial, and ecological information about historic fires. Fire scars, typically located at the base of a tree, are the result of partial cambial death of the tree bole from sub-lethal heating (Gutsell and Johnson 1996; Smith and Sutherland 1999). Tree-ring dating of fire scars provides not only high precision dating of fire events, but also temporal information about the effect of an injury on a single tree's subsequent growth or the forest-wide growth response following fire disturbance. Collating tree-ring data from many trees from the same site can increase the length of the fire history record (because some trees will be longer lived than others) and increase the probability that both very low and high severity fires are identified. Spatial arrangement and temporal distribution of fire scars in a particular year provides information about the location of historic fires, fire size, and fire severity (e.g. percent of trees scarred).

Fire scar history information is scale-dependent, where at large extents (e.g., 1000 km^2, landscapes) the locations of fire scarred trees can be used to understand fire size, and at small scales (e.g., 1 km^2, a fire history site) the locations of fire scarred trees can be used to understand fire severity or intensity. At present, combining the spatial and temporal information of fire scars is one of the best techniques for understanding the ecological significance fire at a particular site over multiple centuries. The primary objective of this research was to collect fire scar history data (3/4 project effort) in eastern and southern deciduous and subtropical forests that have no fire scar record. Specific objectives were to 1) develop 10 new fire scar chronologies in forested areas of the southern and eastern U.S., and 2) model and map the coarse-scale variability in pre-European settlement period fire intervals.

Our major hypotheses were:

1. Oak and pine remnant wood will yield fire scar data suitable for constructing multi-century and pre-European period fire scar histories.
2. Variability in continental-scale fire intervals is a function of mean maximum temperature and ignition frequency.

II. Study description and location

We contacted eastern region fire and forest managers and scientists as a first attempt to locate potential fire history sites in states with little or no existing fire history studies. With the help of many of these peoples we located and surveyed sites in across 13 eastern U.S. states for fire scarred trees and stump remnants that had the potential to extend to the time period prior to EuroAmerican settlement. Sites were chosen to fill geographic and ecological voids in the knowledge of historic fire regimes of eastern deciduous and subtropical forests. Based on information needs, initial literature review, and field surveys, we developed fire scar

Table 1. Characteristics of fire scar history sites developed during this project.

Site	LabCode	State	Species[a]	Location	Time period[b]	Years
Land Between the Lakes	LBL	KY	PO	36°46'N, 88°03'W	1688-2005	318
Pine Camp	PCP	KY	SP	36°38'N, 88°01'W	1790-2005	216
Hatton Ridge	HTN	KY	Pinus	37°54'N, 83°41'W	1742-2004	263
Kisatchie Hills	KIS	LA	LP	31°31'N, 93°05'W	1595-1906	312
Choccolocco Mountain	CHO	AL	LP	33°49'N, 85°42'W	1547-2006	460
Brymer Mountain	BRY	AL	LP	33°42'N, 85°34'W	1634-1928	295
Nye Homestead	NYE	IA	WO	41°27'N, 90°59'W	1700-1858	159
Grindle Lake	GRL	WS	RP	45°13'N, 88°21'W	1651-2005	355
Waubee Lake	WBE	WS	RP	45°21'N, 88°26'W	1638-1871	234
Burnt Mountain	BRT	MI	RP	46°50'N, 87°55'W	1536-1900	365
Pine Lake and River	PLK	MI	RP	46°52'N, 87°52'W	1480-2005	526
Rush Lake	RSH	MI	RP	46°53'N, 87°54'W	1439-1976	538

[a]PO = Post Oak (Quercus stellata), SP = Shortleaf Pine (Pinus echinata), Pinus = unkown Pinus spp., alba), RP = Red Pine (Pinus resinosa) LP = Longleaf Pine (Pinus palustris), WO = White Oak (Quercus alba); [b]Period of tree-ring record

chronologies in eastern and western Kentucky, southern Appalachia, the Louisiana Coastal Plain, eastern Iowa, northern Wisconsin, and the upper peninsula of Michigan (Table 1). For modeling, data from these locations were combined with fire scar history data from throughout the U.S. (n=150) to comprehensively assess regional to continental patterns of fire frequency, climate, and ignitions, providing a broader perspective on fire intervals in the east and south.

During the study site selection process we utilized both suggestions solicited from local managers and physical reconnaissance in the targeted regions to prioritize suitable study sites. Potential study sites were ultimately chosen based on availability and quality of fire history material (e.g., suitable tree species, non-prescribed burned regions, old trees, remnant wood).

III. Key findings (sites, fire scar data, fire frequency modeling)

The key findings of this research pertain to: 1) new fire scar history reconstructions and descriptions of historic fire regimes from throughout the eastern U.S. and 2) development of a continental model and maps of historic fire frequency.

A. Fire scar history methods

Fire scar history studies were completed at twelve sites (Table 1). Below are site descriptions that include location data and key findings. Cross sections of trees were collected from natural remnant and live trees using a chainsaw or crosscut saw. Locations of samples were recorded using a GPS unit and notes were made about each sample's orientation with respect to cardinal direction, aspect, and slope. In the laboratory cross sections were surfaced with an electric hand planer and the cellular detail of annual rings and fire scar injuries were revealed by sanding with progressively finer sandpaper (80 to 1200 grit). A radius (pith-to-bark tree-ring series) of the cross-section with the least amount of ring-width variability due to fire injuries was chosen for tree-ring measurement. Ring-width series from each sample were plotted and the resulting plots were used for visual crossdating (Stokes and Smiley 1968). Visual matching of ring-width patterns allows for the weighting of important "signature years" over years with low common variability among trees. Plots also aid in identifying errors in measurement and missing and/or false rings that can be associated with injury or drought. Samples were crossdated with master dating chronologies. The COFECHA software (Holmes 1983) was used to aid in absolute tree-ring dating and measurement quality control.

Once the pieces of wood were tree-ring dated we were able to assign calendar years, and at times seasonalities, to fire scar injuries. Fire scars were identified by the presence of callus tissue, charcoal, traumatic resin canals, liquefaction of resin and cambial injury. Fire scar dates were assigned to the first year of response to cambial injury. We used FHX2 software (Grissino-Mayer 2001) to construct fire chronologies and generate summary statistics. Analysis began with the first year of tree-ring record. Mean fire return intervals, Weibull median fire intervals, and sub-period fire frequencies were derived from the composite fire scar chronology. When possible, fire scars were assigned to the season of year.

B. New fire scar history reconstructions

Site 1) Name: Land Between the Lakes (LBL); Location: Land Between the Lakes National Recreation Area, KY (USFS); Fire history tree species: Post Oak (*Quercus stellata*)
The Land Between the Lakes (LBL) site consists of 36 post oak trees. The 318-year period of tree-ring record spanned from AD 1688 to 2005 and fire scar dates ranged from 1709 to 1944. One hundred and nine fire scars were identified from thirty six trees yielding forty five fire intervals (46 fires). The mean fire interval for the entire period was 5.22 yrs and fire intervals ranged from 1 to 16 years in length. The Weibull distribution better fit the distribution of the fire intervals and the Weibull median fire interval was 4.56 years for the entire period. All fire scars occurred during the dormant season. Fire occurrences at the sites at the Land Between the Lakes (LBL, PCP) showed considerable variability through time. Fire interval length has increased by more than 10 times since about 1950. The LBL site shows an increase in fire frequency beginning about 1773 that is coincident with the western migration of eastern Native Americans.

Site 2) Name: Pine Camp (PCP); Location: Land Between the Lakes, TN (USFS); Fire history species: Shortleaf Pine (*Pinus echinata*). The Pine Camp (PCP) site clearly shows fire interval length increased from the late EuroAmerican settlement period (1860 -1954) to the last 50 or more years. The 216-year period of tree-ring record spanned from AD 1790 to 2005 and the fire scar dates ranged from 1797 to 1953. Ninety eight fire scars were identified from twenty eight

trees yielding thirty one fire intervals (32 fires). The mean fire interval for the entire period was 5.03 and fire intervals ranged from 1 to 23 years in length. K-S tests showed that the Weibull median distribution did not better describe the fire interval data. Ninety –four percent of the fires had a determinable seasonality. Ninety-six percent of those fires occurred during the dormant season, and four percent during the growing season (one latewood, three late earlywood). This site is about 5 km from historic Fort Henry which was built in late 1861 into early 1862. Interestingly, there is a pulse of regeneration at PCP during the 1860's. Possibly due to increase need of timber for fort construction, or to feed charcoal furnaces for the production of iron for the fort.

Site 3) Name: Hatton Ridge (HTN); Location: Daniel Boone National Forest, KY (USFS); Fire history species: Dead remnant wood from stumps, unknown pine, probably shortleaf pine (*Pinus echinata*). The study site is located on Hatton Ridge within the Morehead Ranger District, on the Daniel Boone National Forest, in Menifee County, Kentucky (37°53'N, 83°41'W). The study site included the upper portions of southwest facing slopes of Hatton Ridge, above the Camp Branch of Spaas Creek in the Red River Gorge drainage. Forest composition is currently dominated by oak (Quercus spp.), hickory (Carya spp.), and pine (Pinus spp.). We exhaustively searched and sampled the entire Hatton Ridge area for pine stumps and natural remnant wood exhibiting external evidence of fire scarring. The samples are most likely shortleaf pine based on physical and anatomical properties of the stumps and wood. Shortleaf pine is considered a fire adapted species as it has moderately thick bark, is able to survive multiple fires (e.g., >30), and saplings can resprout following top-kill. The majority of the samples collected were taken from landscape positions that are highly sensitive with respect to fire scarring because of upper slope positions, xeric aspects and large fetch (valley bottom to ridge top) distances. Wood preservation at the site was relatively poor compared to other shortleaf pine fire history sites we have conducted. This resulted in relatively small pieces of wood available and hence short time periods represented from the remnant trees (stumps). Fire scars were prevalent throughout the area. Thirty-one trees were used in the fire history analysis. The period of record was AD 1742 to 2005, a 264 year period. A total of 75 fire scars were dated resulting in 38 (14.4%) years with fire. No fires were recorded from 1928 to 2005, however few samples are represented in the fire chronology during this period. One stump had 14 fire scars, most which occurred in the 19th century. The majority of fires occurred in the dormant season (e.g., September to April), particularly prior to 1820. The year with the highest percentage of trees scarred was 1839. Over 20% of the sample trees were scarred in the fire years 1774, 1839, 1879, 1904, 1910, 1917, 1925, and 1928. The mean and Weibull median fire intervals for 1748 to 2005 were 4.7 and 3.0 years, respectively. The mean and median fire intervals for 1748 to 1800 were 6.0 and 4.0 years, respectively, however only 7 fire intervals were analyzed.

Site 4) Name: Kisatchie Hills (KIS); Location: Kisatchie National Forest, LA (USFS) (Coastal Plain); Fire history species: Dead remnant wood from stumps and snags, remnant dead pine trees likely longleaf pine (*Pinus palustris*). The study site is located in the northwest portion of the 8,700 acre federally designated Kisatchie Hills Wilderness Area, Natchitoches Parish, Louisiana (31°28.7" N, 92°59.6" W). The study site is located between two upper forks of the Bayou Cypre. The terrain of the Kisatchie Hills Wilderness is particularly rugged. Rocky outcrops, steep hills, and mesas contrast to the highly productive surrounding forests. Forest composition is dominated by longleaf pine (*Pinus palustris*), loblolly pine (*Pinus taeda*), and sweet gum

(*Liriodendron tulipifera*). Much of the forested area is characterized as having a closed forest to woodland structure (i.e., 50-80% canopy cover). Areas of grass are common in upland areas, especially adjacent to the Longleaf Vista overlook. Cross sections were collected from the base of 19 stumps and natural remnants that were located both inside and outside of the wilderness area. Samples inside the wilderness were cut with a two-man crosscut saw and samples outside of the wilderness were cut with a chainsaw.

A total of 190 fire scars were dated and compiled into a composite (site) fire event chronology. Scars represented 120 different fire events between the calendar years 1650 and 1902. Fire intervals ranged in length from 0.5 to 12 years. The mean fire return interval (MFI) for the pre-European settlement period (1650-1713) was 3.3 yrs. Significant new findings include: evidence for years of biannual burning, temporal variability in fire seasonality, an increase in fire frequency and percent trees 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. A manuscript describing this study is in review with the Journal of Vegetation Science.

Site 5) Name: Choccolocco Mountain (CHO); Location: Talladega National Forest, AL (USFS); (Southern Appalachians), Fire history species: longleaf pine (*Pinus palustris*). Located on the southwest portion of the Appalachian Mountains within the Blue Ridge region, Choccolocco Mountain is home to one of the last remaining old growth remnant longleaf stands in the montane ecoregion. This site and the Brymer Mountain site (following) are located approximately 15 kilometers to the east of Choccolocco Mountain where few remnant longleaf have managed to survive. Fire scarred stumps were located throughout the slopes within this area, but the majority of stumps that recorded a high number of scarring events were found near the tops and shoulders of the slopes and confluences of the ridges. The area is known to have been previously used by a cluster of red-cockaded woodpeckers (RCW), a species known to inhabit old growth stands. The area had been actively managed for RCW use. Management within the area included periodic burning and thinning of hardwoods and non-desirable pine species to create a longleaf pine savanna with an abundant herbaceous layer to better facilitate the RCW needs. Intermediate and advanced regeneration within the stand was minimal, indicating the need for shorter fire intervals to remove competing vegetation.

A composite fire chronology for Choccolocco Mountain site was developed from 179 individual fire scars that were seasonally distinguishable (e.g., dormant, early, and late growing season). The 179 fire scars represented a total of 113 years with fire. The period of record ranged from 1547 to 2006 C.E. (460 yrs.), but is insignificant for fire frequency testing before 1653. Fire scar dates ranged from 1550 to 2001, and the percentage of trees scarred during fire years ranged from 5 to 100. Fire frequency for the pre-EuroAmerican settlement period from 1653 to 1831 had a mean fire interval (MFI) of 3.2 years. Following EuroAmerican settlement, fire frequency increased to 2.5 years from about 1832-1940. The majority of scars occurred at the beginning of a growth ring, indicating that fires occurred most often during the dormant season. Dormant season fire scars constituted 97.2 percent of all fire events throughout the length of the fire chronology. Only 2.8 percent of fire scars were located in the middle earlywood to latewood portion, and only 0.6 percent of all fire scars were not seasonally distinguishable. A thesis (Bale 2009) describing more details on this study is located at http://edt.missouri.edu/Spring2009/Thesis/BaleA-051109-T950/. A manuscript describing these results is in preparation.

Site 6) Name: Brymer Mountain (BRY); Location: Talladega National Forest, AL (USFS); (Southern Appalachians), Fire history species: Longleaf Pine (*Pinus palustris*). Located almost entirely on two ridges facing south to southeast, the majority of fire recorders were found in protected midslope positions. The encroaching hardwood line coming from the valley bottom played a major factor in locating stumps that were at higher elevations. Where stumps on the lower slope could be obtained, very few scarring events were evident and the stumps had decayed very rapidly, possibly decreasing the ability of fires to damage the cambial tissue.

A composite fire chronology for the Brymer Mountain site was developed from 193 individual fire scars that were seasonally distinguishable (e.g., dormant, early, and late growing season). The 193 fire scars represented a total of 106 years with fire. The period of record ranged from 1550 to 1940 (391 yrs.), but is insignificant for fire frequency testing before 1660. Fire scar dates ranged from 1660 to 1934, and the percentage of trees scarred during fire years ranged from 4 to 100. Fire frequency for the pre-EuroAmerican settlement period from 1660 to 1831 had a mean fire interval (MFI) of 2.7 years. Following EuroAmerican settlement, fire frequency increased to 2.6 years from about 1832-1940. Some fire years during this period had a high percentage of trees scarred, perhaps indicating more severe fire. Information for pre-1660 and post-1940 is incomplete due to lack of samples covering this time period. Much like the Choccolocco Mountain site, the majority of scarring events occurred before the beginning of a growth ring, indicating that fires occurred most often during the dormant season. Dormant season scars constituted 92.4 percent of all fire events throughout the length of the fire chronology. Only 7.1 percent of scarring events were located in the middle earlywood to latewood portion, and only 0.5 percent of all fire scars were not seasonally distinguishable. A thesis (Bale 2009) describing more details on this study is located at http://edt.missouri.edu/Spring2009/Thesis/BaleA-051109-T950/. A manuscript describing these results is in preparation.

Site 7) Name: Nye Cabin (NYE); Location: Mississippi River Loess Hills, Muscatine, IA Fire history species: White Oak (*Quercus alba*). This site represented a unique opportunity to recover a fire history from base of trees that were used to build a log cabin during the mid-19th century. The cabin was erected from trees located approximately 3 km from the Mississippi River. Current forest composition represents oak-dominated savannas in an agricultural landscape. The southern extent of white pine in Iowa is within this region and near Wildcat Den State Park. Twenty trees (cabin logs) with obvious butt ends and fire scars were used to construct the fire scar chronology. Samples spanned the period 1699 to 1860 (162 yrs). A total of 49 fire scars represented 20 different fire event years. The mean fire interval for this period was 5.0 years and ranged from 1 to 10 years. Eight-five percent of the fire events occurred during the dormant season.

Site 8) Name: Waubee Lake (WBE); Location: Chequamegon-Nicolet National Forest, WS (USFS), Fire history species: Red Pine (*Pinus resinosa*). Two sites were conducted in northern Wisconsin and are compared here, in the description of site 9, and in Table 2. The Waubee Lake site is relatively rough terrain and is presently dominated by northern hardwoods with only a few individual live red pines. Historic red pine regeneration at Waubee Lake Site is unknown, but may have been more uneven aged than at Grindel Lake. As expected based on topography, the percentage of trees scarred during fire events was generally less at the Waubee Lake site than at the Grindel Lake site. Less severe fires are expected in more topographically complex landscapes

Table 2. Wisconsin site and fire history data

	Grindel Lake	**Waubee Lake**
Major present day tree species	Red pine	Northern hardwoods
Community structure	Pine Savanna	Northern hardwood forest
Approximate site area	1 km^2	0.3 km^2
Topography	Gentle, large wetlands	Rough, steep slopes
Mean fire interval (~1705 to 1864)	10.8 years	6.3 years
Mean fire interval (~1705 to 1805)	8.6 years	6.5 years
Mean fire interval (~1805 - 1864)	19.7 years	6.0 years
Range of fire intervals	2 to 35 years	3 to 21years
Major fire years	1756, 1743, 1780	1756, 1730, 1804
Fire years in common	1864,1840, 1780, 1756, 1721,1718	
Red pine regeneration type	Even aged	Uneven aged

because fire spread rates are decreased due to variable and slowed winds and increased variability in fuel moisture contents.

Site 9) Name: Grindel Lake (GRL); Location: Chequamegon-Nicolet National Forest, WS (USFS), Fire history species: Red Pine (*Pinus resinosa*). The Grindel Lake Site has relatively gentle slopes, is interspersed with wetlands, and is presently more densely occupied by red pine than the Waubee Lake site. Early red pine regeneration (~ 1680) was even aged at the Grindel Lake Site indicating stand replacement perhaps associated with the 1664 fire. The 1664 fire is also documented in the Huron Mountains of Michigan. No evidence of fires occurred after 1923 at the Grindel Lake site. The longer historic mean fire intervals at the Grindel Lake site compared to the Waubee Lake site suggests that factors other than topography (possibly humans) were important in the past fire regime. In 1669, as many as 600 Native Americans lived in the village of Oak-a-toe south of the study sites. Wild rice along the rivers and lakes of the study region was a staple of the Menominee whom now live to the south of the study area. Canoe travel for rice and hunting may have been an accidental or purposeful source of ignitions. Severe fire years indicate that very large fires occurred in the past, particularly during known drought periods. Of the fire years in common between the two sites the 1756 and 1780 fires were probably the largest. Both the within site data (the percent trees scarred) and between site data indicate these were large high severity fires. Fires in 1780 are also documented to in the Upper Peninsula of Michigan and across much of the eastern United States (McMurry et al. 2007, Guyette et al. 2006). Based on both local and continental information about the severity of these fire years we surmise that they likely burned over an area larger than about 175 km2 in our study a region (estimated from the area of a circle between Grindel and Waubee Lakes).

Reconstructions of the Palmer Drought Severity Index show moderate to severe drought (-2.5 to -3) in the region during the severe fire years of 1840, 1780, 1743, 1721, and 1664 (Cook et al. 2004). The fire years 1718, 1735 and 1736 corresponded to extreme droughts (PDSI = < -4.0). At Grindel Lake there were eight relatively high severity fires (during drought years) between

1718 and 1840; a high severity fire every 15 years. The severe fires at Grindel Lake may have burned through the wetlands located in the middle of the site. This is suggested based on common dates of scarring of the samples in and around the wetlands. Other wetland sites have shown a similar pattern of burning during years of severe drought.

Site 10) Name: Burnt Mountain (BRT); Location: Huron Mountains, MI (Huron Mountain Club), Fire history species: Red Pine (*Pinus resinosa*). The study site is located in the south facing slope of Burnt Mountain within the Huron Mountain Club, a private property located in Marquette County, in the Upper Peninsula of Michigan (Table 1). The Huron Mountain Club, formed circa 1890, consists of 30,000 acres, including much of the Huron Mountains area. Much of the Club property has been protected from development and encompasses many lakes and 10,000 acres of old-growth forest. Forest composition of the site is dominated by eastern white pine (*Pinus strobus*) and eastern hemlock (*Tsuga canadensis*), with glades near the top of Burnt Mountain surrounded by northern red oak (*Quercus rubra*) and Red Pine. The 412-year period of tree-ring record spanned the period 1494 to 1905 and fire scar dates ranged from 1580 to 1894. Forty-four fire scars from thirty trees were dated yielding twenty six fire intervals (27 fire years). The mean fire interval for the entire period was 12.8 yrs and fire intervals ranged from 1 to 90 yrs in length. The Weibull distribution better fit the distribution of the fire intervals and the Weibull median fire interval was 7.3 years for the entire period. The composite fire chronology was characterized as having quasi-periodic fires in the latter half of the 17th and 18th centuries, followed by an increase in fire frequency and annual burning in the early 19th century. A long period of dramatically decreased fire frequency has characterized the last 180+ years at Burnt Mountain. Despite this decreased frequency a very severe fire occurred in the dormant season (approximately August to April) between 1894 and 1895 which has resulted in a high abundance of dead standing trees, particularly on the mid- to upper-slope positions on the south aspects of the mountain. This was a severe stand-replacing event that caused growth suppressions in the samples trees that survived (i.e., BRT024 and BRT030). A similar event occurred in 1674 that is recorded as a fire scar, caused increased red pine tree recruitment (e.g., many sample trees initiated circa 1674), and an abrupt growth release. Based on the percentage of trees scarred in fire years the three most severe fires occurred in 1763, 1822, and 1894.

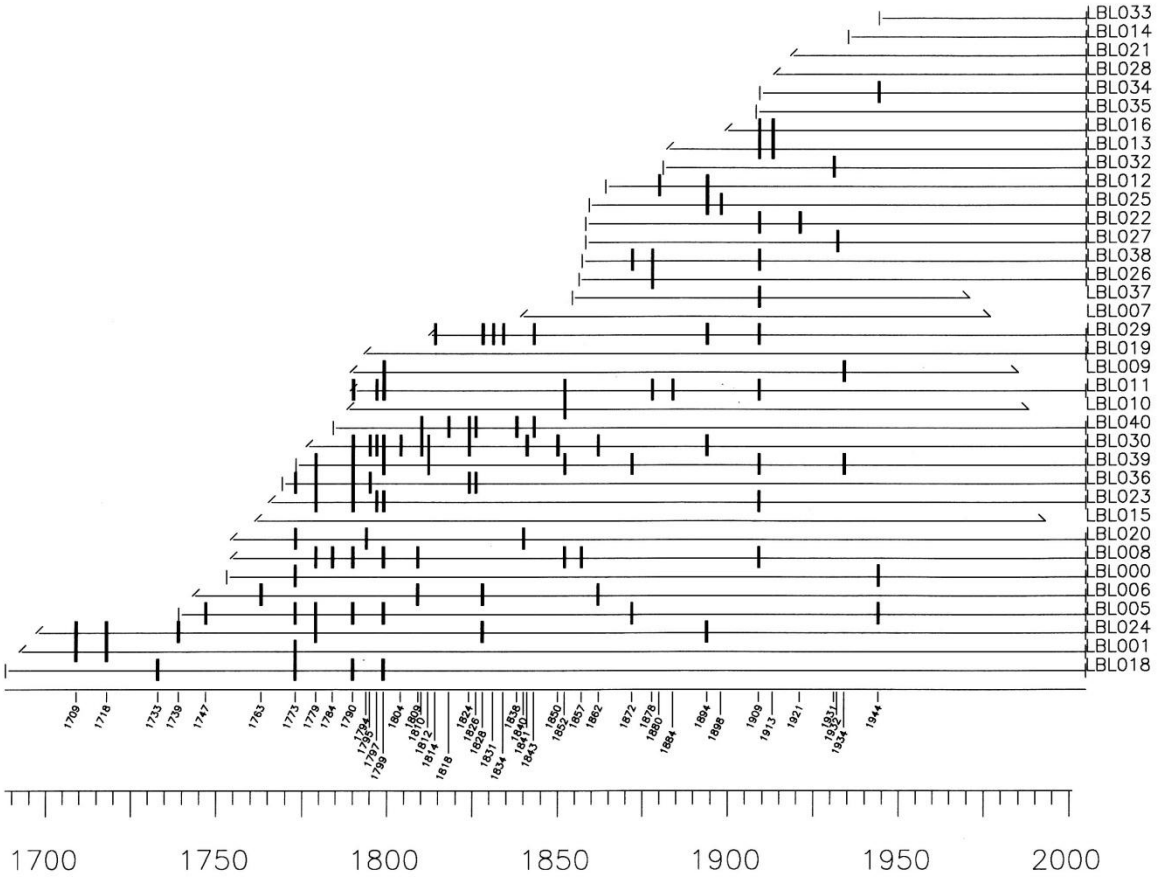
Nearly all fire scars were positioned in the latewood portion of the rings (i.e., mid- to late summer seasonality) or between rings (i.e., dormant season during fall/ winter). There appeared to be a transition from scars occurring in the latewood season to scars occurring in the dormant season coincident with the increased fire frequency at the beginning of the 19th century. This transition may be an indication of fire ignitions transitioning from being primarily natural (e.g., lightning) to anthropogenic. A manuscript describing these results is in preparation.

Site 11) Name: Pine Lake and River (PLK); Location: Huron Mountains, MI (Huron Mountain Club), Fire history species: Red Pine (*Pinus resinosa*). The study site is located on an approximately one half mile wide strip of coastal flats between Lake Superior and Pine Lake within the Southern Superior Uplands Section (Bailey 1998). The site is within the Huron Mountains complex located in Marquette County, in the Upper Peninsula of Michigan (Table 1). Pine Creek flows from Pine Lake into Lake Superior through the study site. Elevation of the study site ranges from 599 to 868 feet above sea level. The Huron Mountain Club, formed circa 1890, consists of 30,000 acres, including much of the Huron Mountains area. Much of the Club

property has been protected from development and encompasses many lakes and about 10,000 acres of old-growth forest. A manuscript describing these results is in preparation.

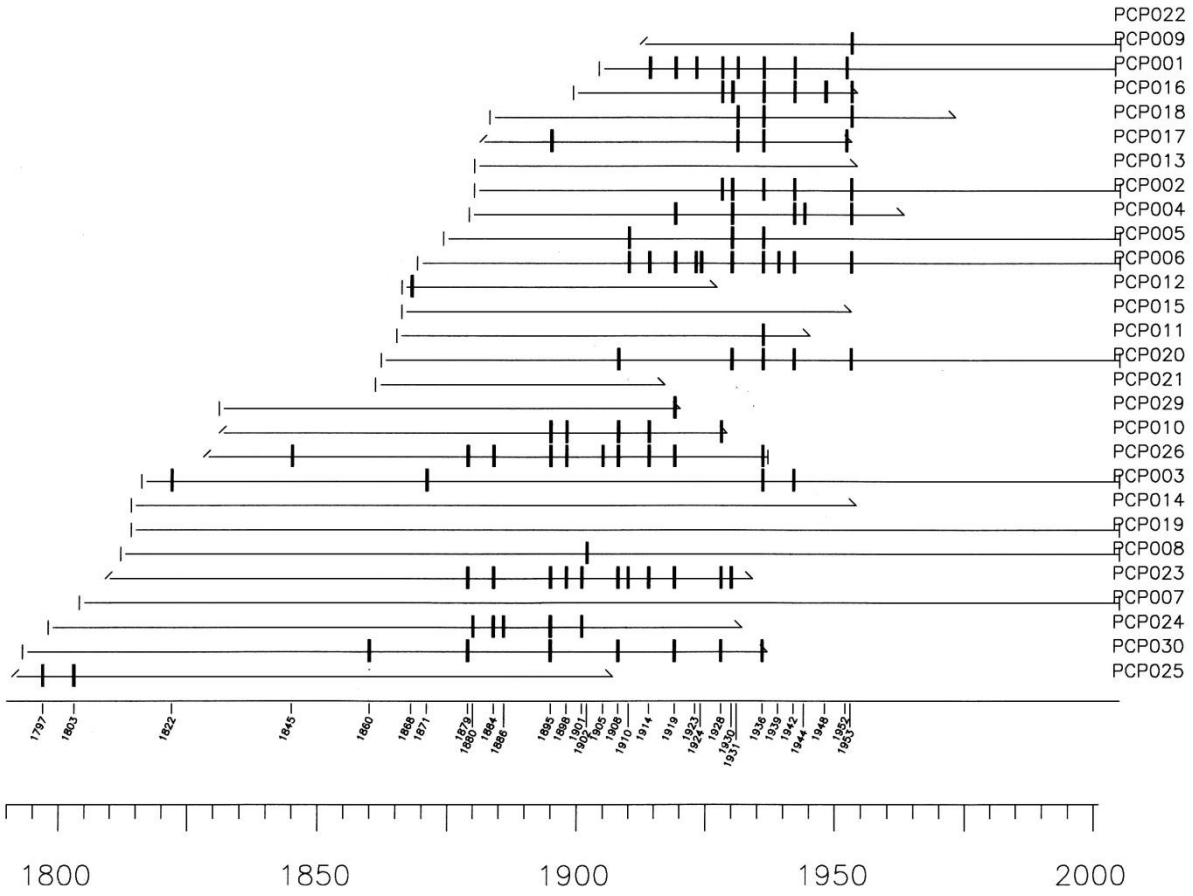
Site 12) Name: Rush Lake (RSH); Location: Huron Mountains, MI (Huron Mountain Club), Fire history species: Red Pine (*Pinus resinosa*). The Rush Lake site, consisting of a low elevation lake side red pine forest, had longer fire intervals than nearby mountain top sites, e.g. Burnt Mt. Similar to the Pine Lake site, Rush Lake showed fire events that scarred many trees during fire events. The area was logged in the early 1900's, perhaps a salvage of trees burned after the last fire at the site in 1897. One sample extended to 1440 CE, but the first fire evident on that sample occurred in 1598. Rush Lake is an example of an area with relatively long intervals between fires. Fires showed the potential to be high severity evidenced by the fire in 1781 that occurred on 95% of the trees sampled. The fire in 1871 also appeared on most of the samples present. Interestingly few trees were scarred during fire events between these two major fires (90 year period). A fire at Rush Lake in 1665 appears to be a high severity, stand-replacement event, based on putative recruitment in the years following. From samples collected in 2008 at Pine Lake, we also found a high percentage (70%) of trees scarred in 1664. It is likely that the fire season 1664 / 1665 represented a severe and spatially extensive fire event that played an important role in maintaining and initiating pine dominated areas of the Huron Mts., particularly those at lower elevations. Evidence of a 1664 stand replacing fire was found at Grindel Lake (northeastern Wisconsin) and this fire year also occurs at many other places in North America, likely associated with extreme drought conditions (Cook et al. 2004). The second most severe fire year (1871) at Rush Lake occurred in the same year as the Peshtigo, WI fire and the Great Chicago Fire. Interestingly fire scars from 1871 did not show up at any other site sampled at the Huron Mts. except for one individual at the Pine Lake and River site. A manuscript describing these results is in preparation.

Land Between the Lakes (LBL), KY



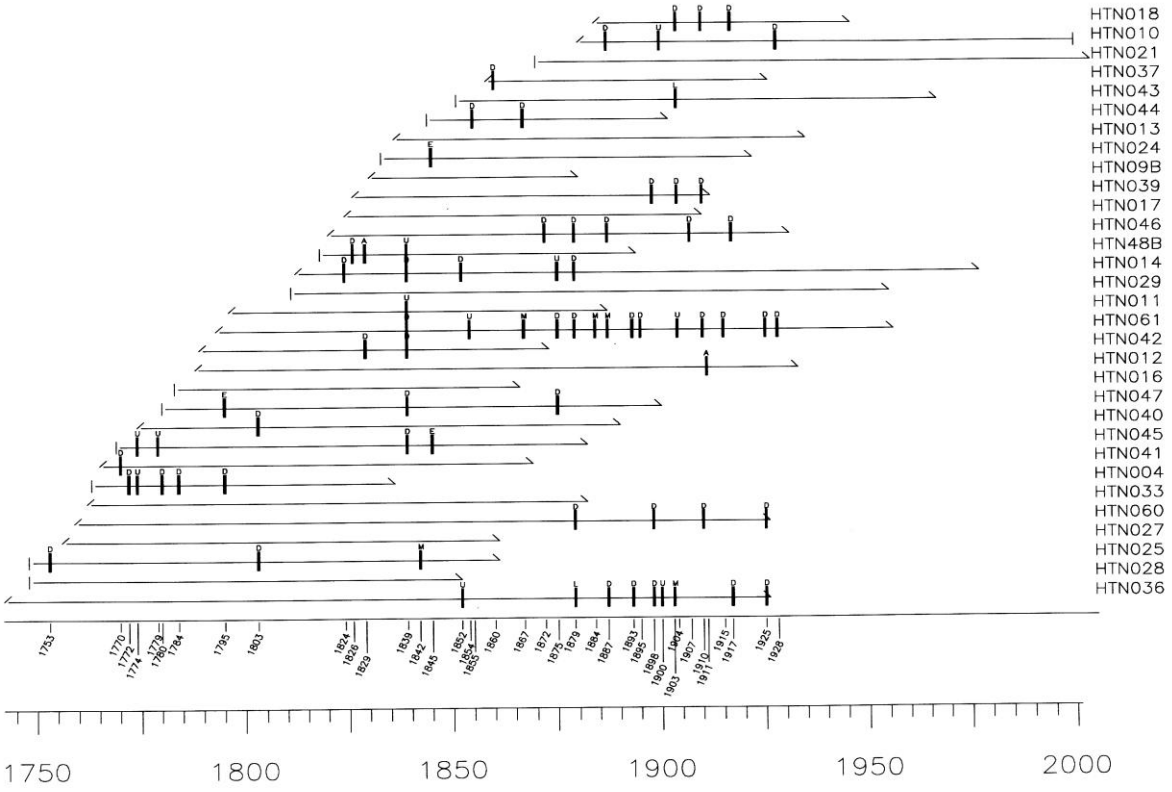
Fire scar history chart for Land Between The Lakes, eastern Kentucky. Each horizontal line represents the length of the tree-ring record of a post oak (*Quercus stellata*) sample tree. Bold vertical bars represent the year of a fire scar. The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Pine Camp (PCP), Land Between the Lakes, KY



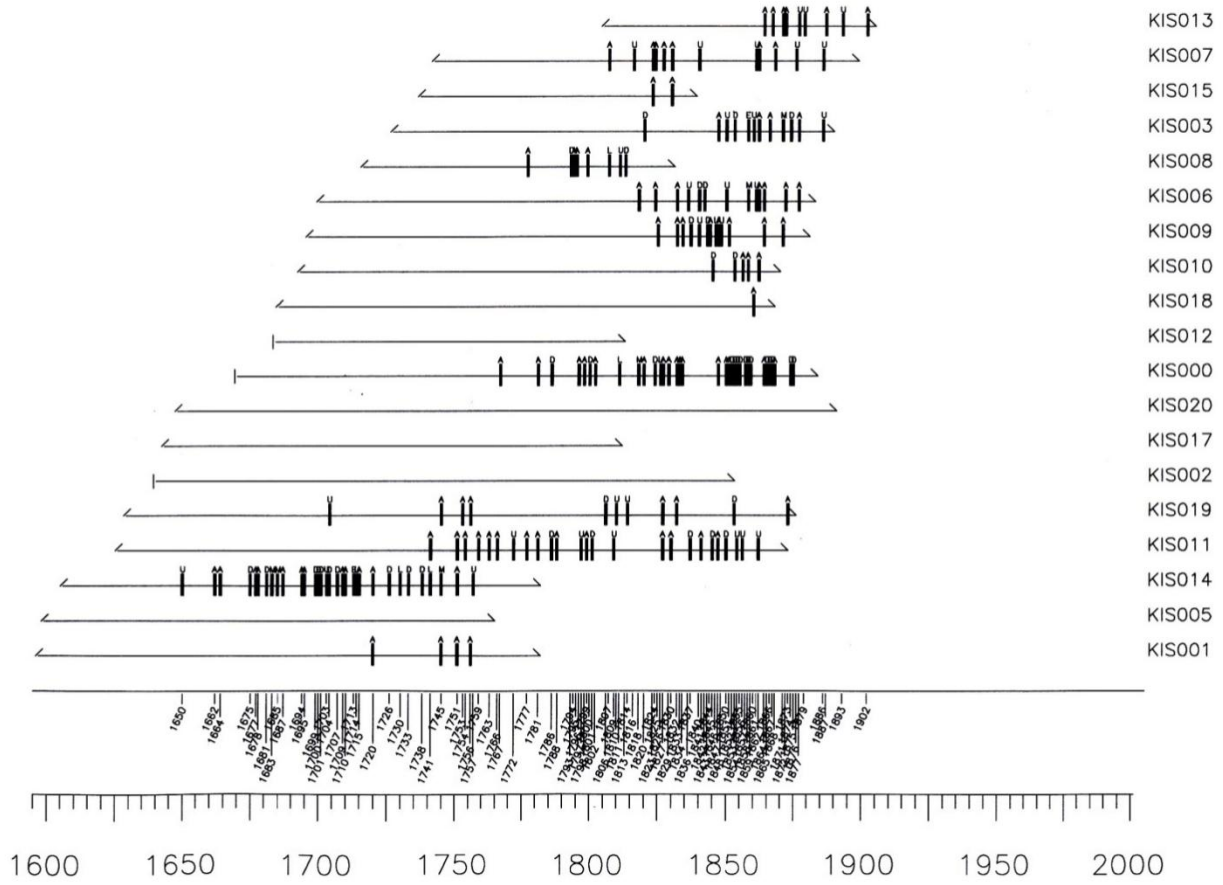
Fire scar history chart for Land Between The Lakes, eastern Kentucky. Each horizontal line represents the length of the tree-ring record of a shortleaf pine (*Pinus echinata*) sample tree. Bold vertical bars represent the year of a fire scar. The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Hatton Ridge (HTN), Daniel Boone National Forest, KY



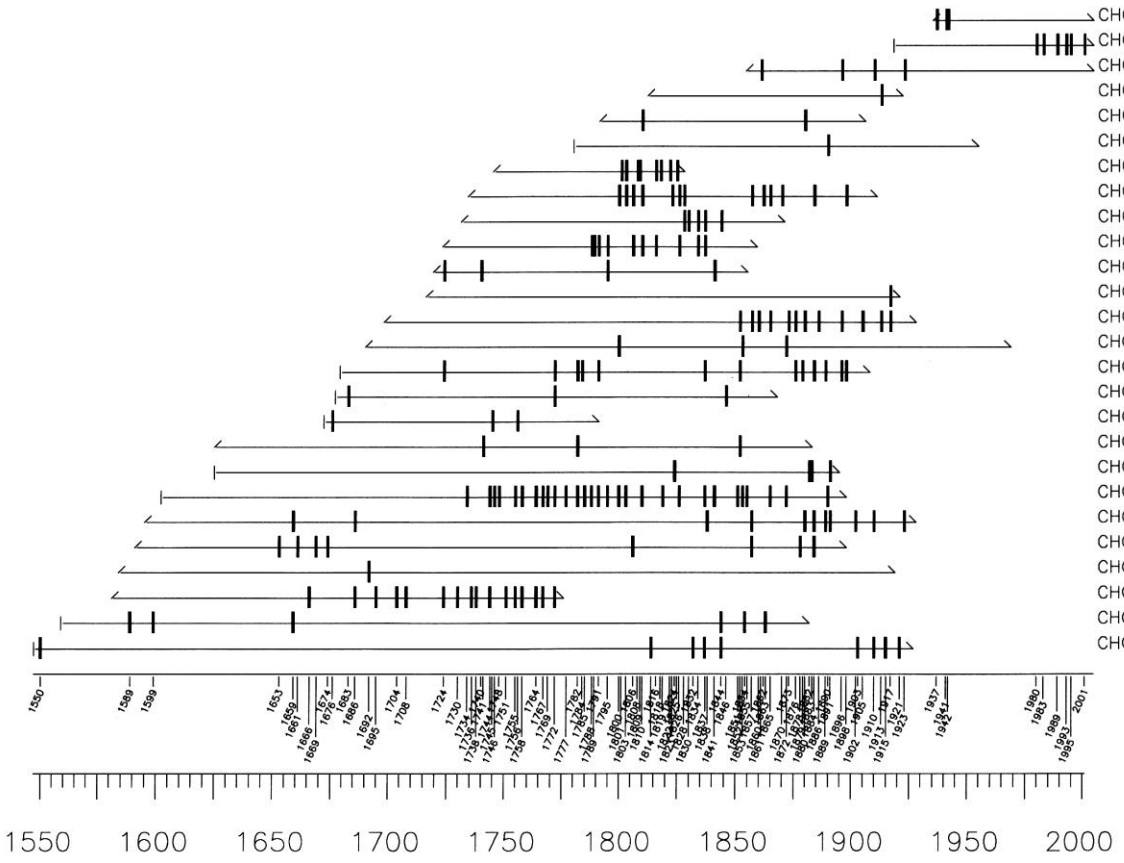
Fire scar history chart for Hatton Ridge, Daniel Boone National Forest, western Kentucky. Each horizontal line represents the length of the tree-ring record of a pine tree, likely shortleaf pine (*Pinus echinata*). Bold vertical bars represent the year of a fire scar with the season of the injury coded above each bar (D = dormant season scar, U = undetermined season scar, E = earlywood scar, M = middle earlywood scar, L = late earlywood scar, A = latewood scar). The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Kisatchie Hills (KIS), Kisatchie National Forest, LA



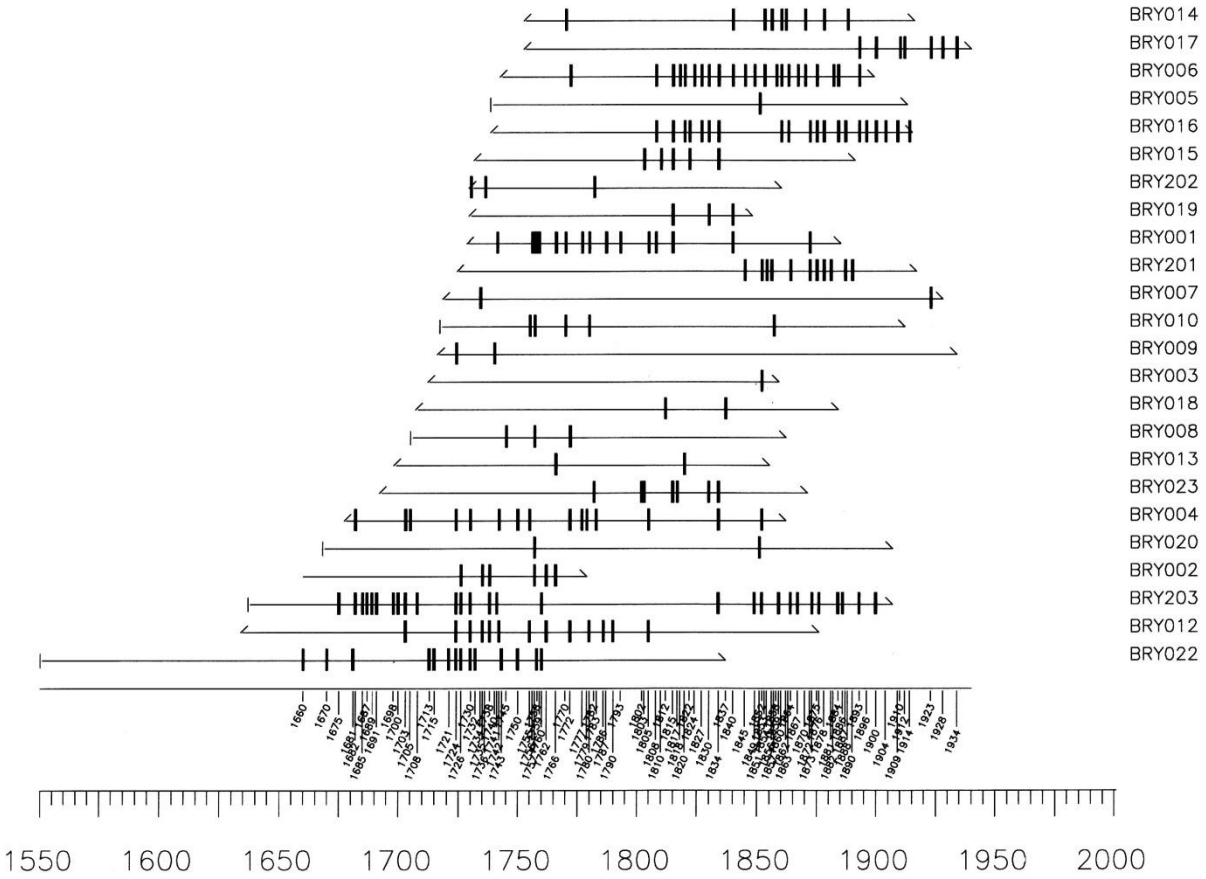
Fire scar history chart for the Kisatchie Hills, Kisatchie National Forest, central Louisiana. Each horizontal line represents the length of the tree-ring record of a pine tree, likely longleaf pine (*Pinus palustris*). Bold vertical bars represent the year of a fire scar with the season of the injury coded above each bar (D = dormant season scar, U = undetermined season scar, E = earlywood scar, M = middle earlywood scar, L = late earlywood scar, A = latewood scar). The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Choccolocco Mountain (CHO), Talladega National Forest, AL



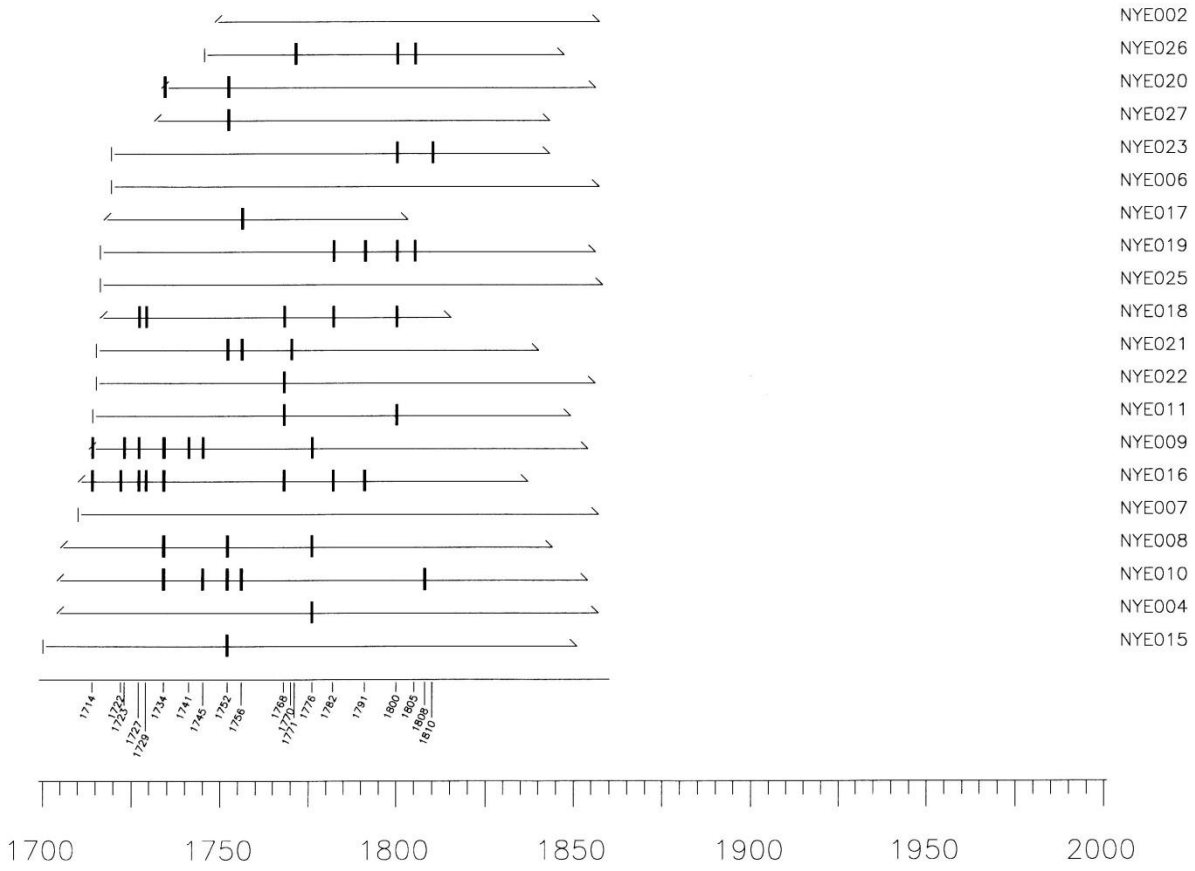
Fire scar history chart from near Choccolocco Mountain, Talladega National Forest, northern Alabama (Bale 2009). Each horizontal line represents the length of the tree-ring record of a longleaf pine (*Pinus palustris*). Bold vertical bars represent the year of a fire scar. The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Brymer Mountain (BRY), Talladega National Forest, AL



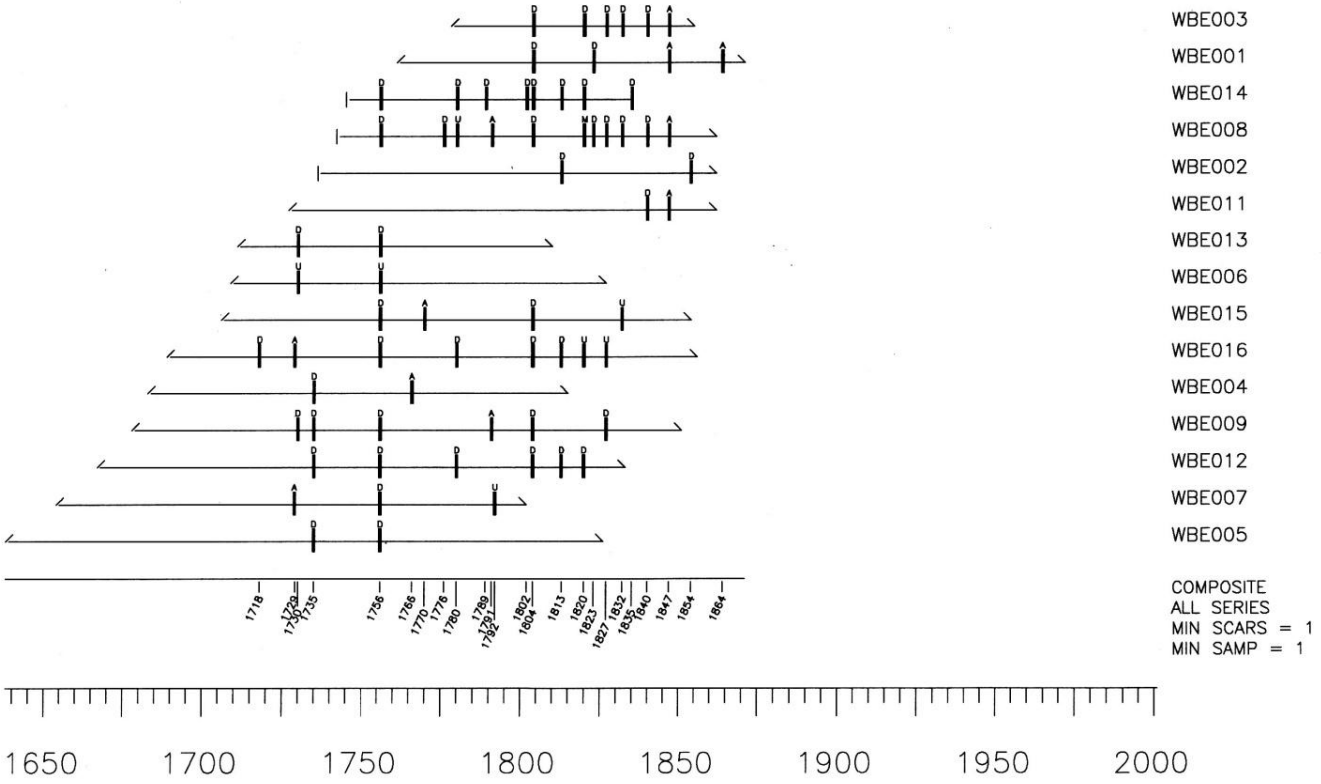
Fire scar history chart from Brymer Mountain, Talladega National Forest, northern Alabama (Bale 2009). Each horizontal line represents the length of the tree-ring record of a longleaf pine (*Pinus palustris*). Bold vertical bars represent the year of a fire scar. The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Nye Cabin (NYE), Mississippi River Loess Hills, IA



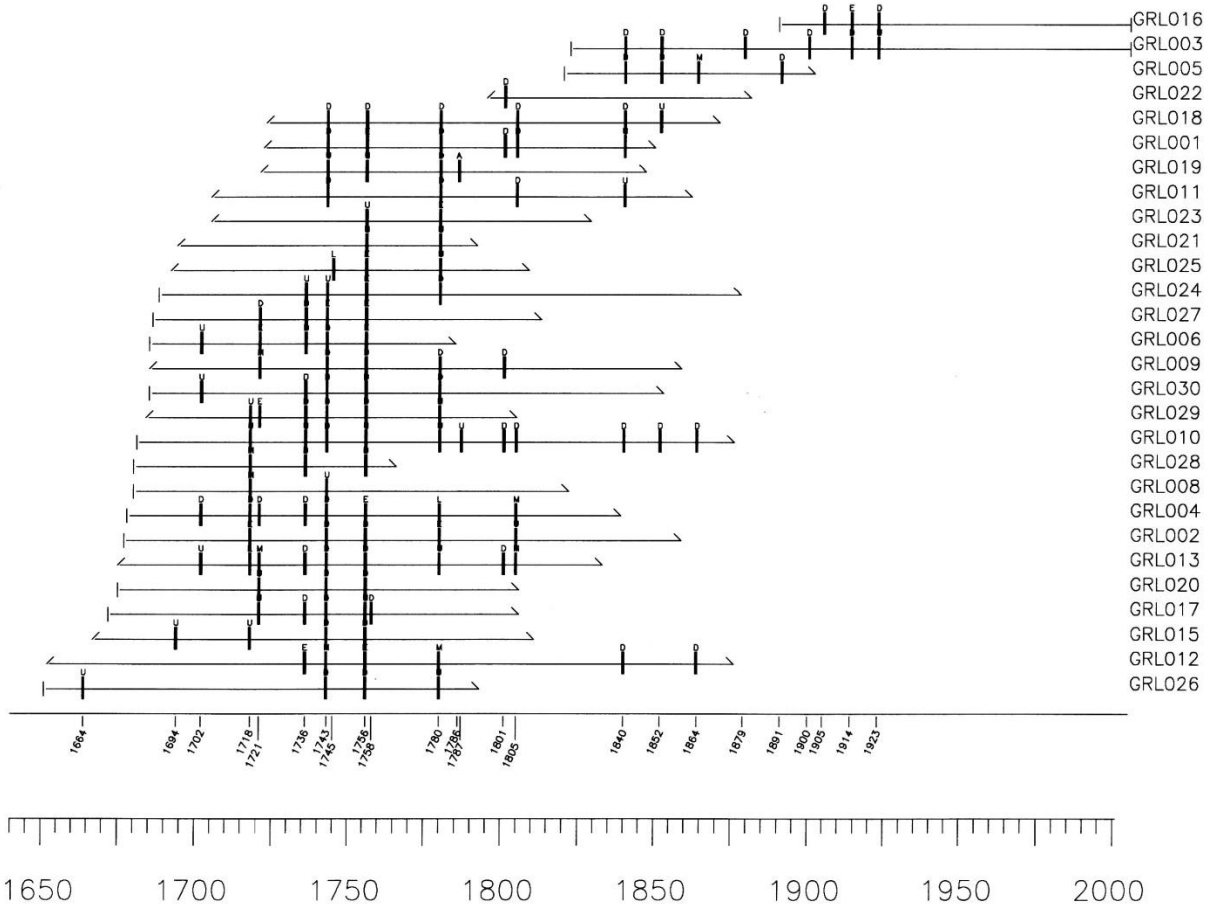
Fire scar history chart from Nye Cabin, Mississippi River Hills, eastern Iowa. Each horizontal line represents the length of the tree-ring record of a white oak (*Quercus alba*). Bold vertical bars represent the year of a fire scar. The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Waubee Lake (WBE), Chequamegon-Nicolet National Forest, WI



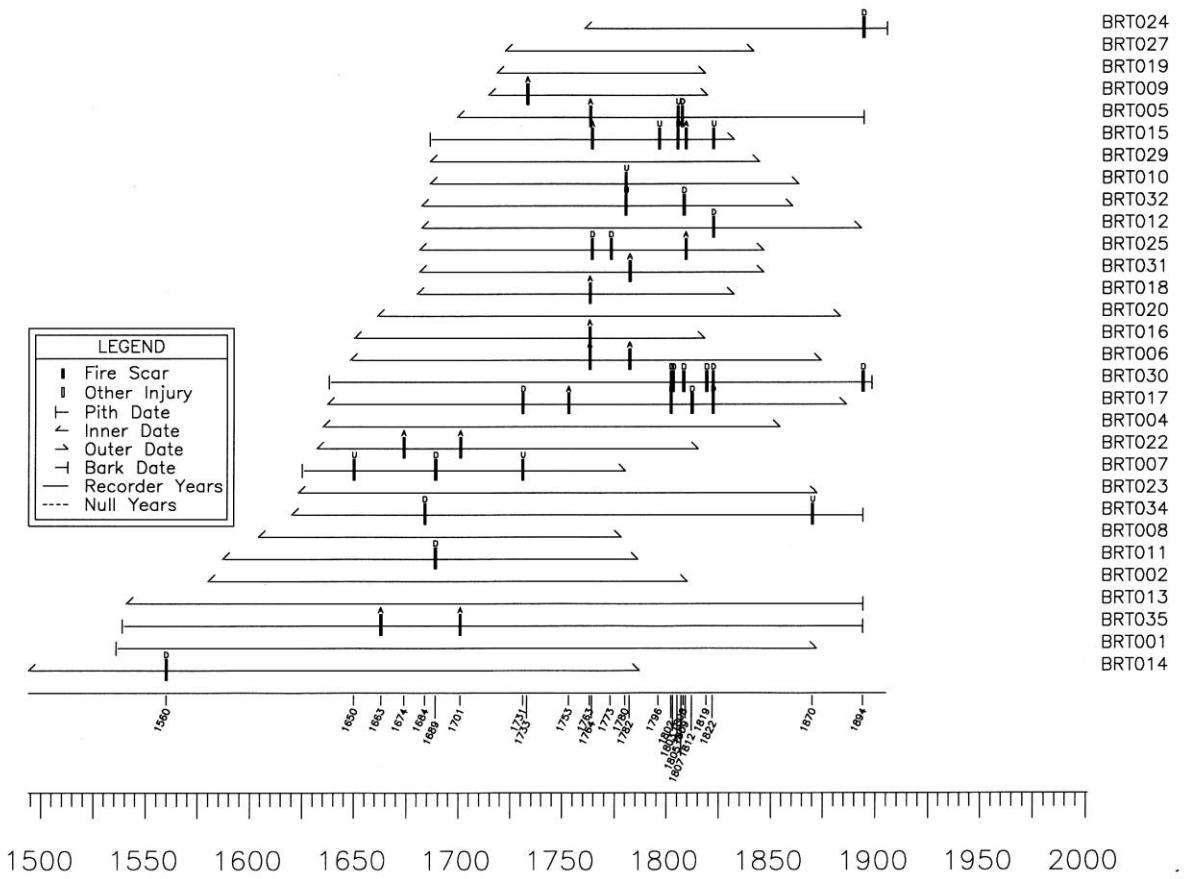
Fire scar history chart for Waubee Lake, Chequamegon-Nicolet National Forest, northern Wisconsin. Each horizontal line represents the length of the tree-ring record of a red pine (*Pinus resinosa*) tree. Bold vertical bars represent the year of a fire scar with the season of the injury coded above each bar (D = dormant season scar, U = undetermined season scar, E = earlywood scar, M = middle earlywood scar, L = late earlywood scar, A = latewood scar). The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Grindel Lake (GRL), Chequamegon-Nicolet National Forest, WI



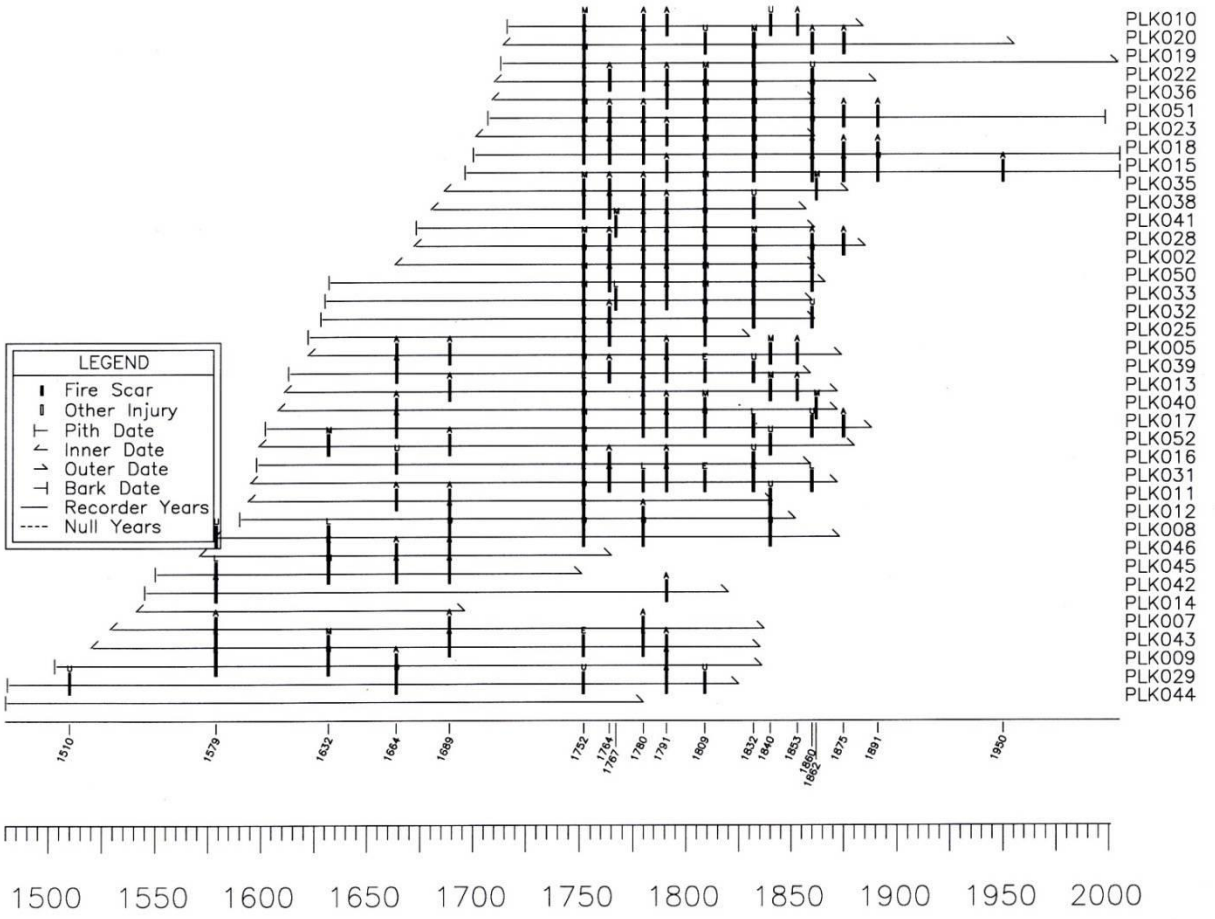
Fire scar history chart for Grindel Lake, Chequamegon-Nicolet National Forest, northern Wisconsin. Each horizontal line represents the length of the tree-ring record of a red pine (*Pinus resinosa*) tree. Bold vertical bars represent the year of a fire scar with the season of the injury coded above each bar (D = dormant season scar, U = undetermined season scar, E = earlywood scar, M = middle earlywood scar, L = late earlywood scar, A = latewood scar). The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Burnt Mountain (BRT), Huron Mountains, MI



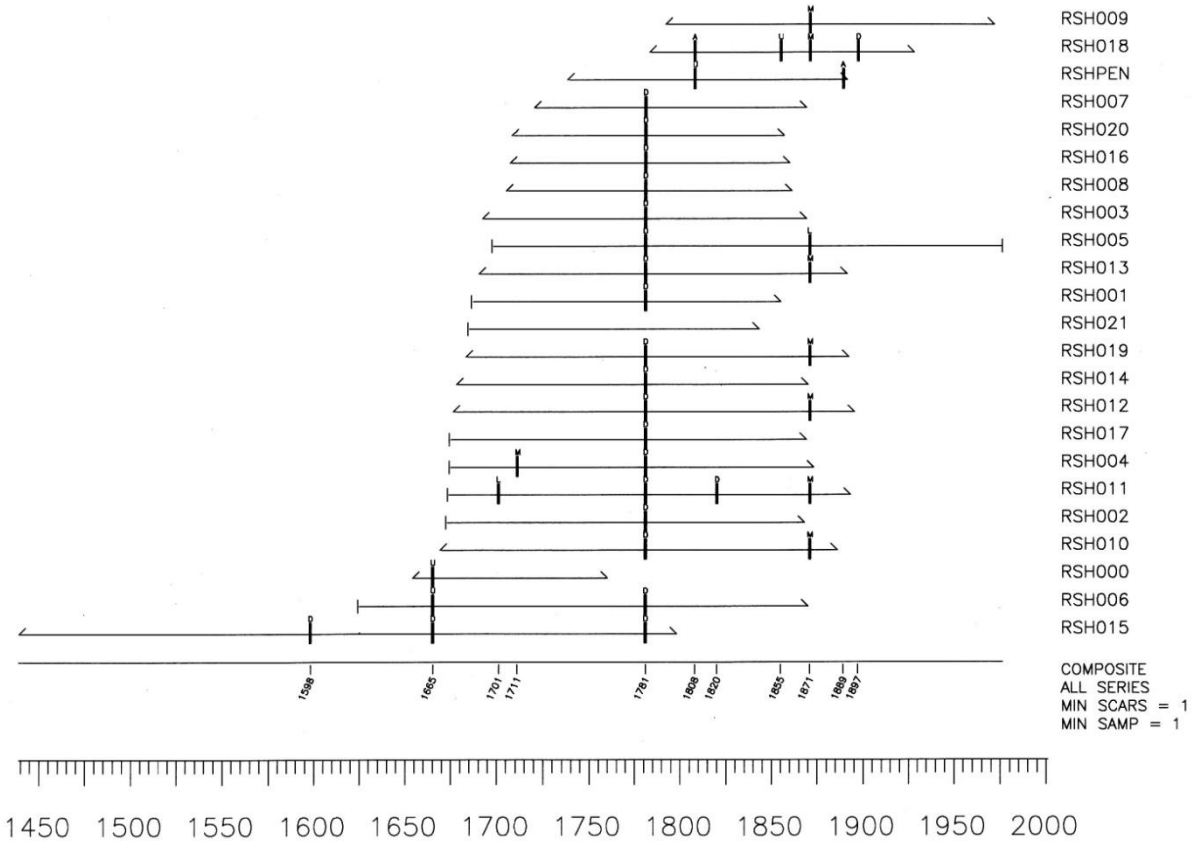
Fire scar history chart for Burnt Mountain, Huron Mountains, Upper Peninsula Michigan. Each horizontal line represents the length of the tree-ring record of a red pine (*Pinus resinosa*) tree. Bold vertical bars represent the year of a fire scar with the season of the injury coded above each bar (D = dormant season scar, U = undetermined season scar, E = earlywood scar, M = middle earlywood scar, L = late earlywood scar, A = latewood scar). The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Pine Lake and River (PLK), Huron Mountains, MI



Fire scar history chart for Pine Lake and River, Huron Mountains, Upper Peninsula Michigan. Each horizontal line represents the length of the tree-ring record of a red pine (*Pinus resinosa*) 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 = earlywood scar, M = middle earlywood scar, L = late earlywood scar, A = latewood scar). The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

Rush Lake (RSH), Huron Mountains, MI



Fire scar history chart for Rush Lake, Huron Mountains, Upper Peninsula Michigan. Each horizontal line represents the length of the tree-ring record of a red pine (*Pinus resinosa*) 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 = earlywood scar, M = middle earlywood scar, L = late earlywood scar, A = latewood scar). The composite fire scar chronology with all fire scar years shown at the bottom of the figure.

IV. Calibration and modeling of climate and fire frequency

A. Introduction

Fire regimes are constrained by climate through the physical chemistry of ecosystems. North America ecosystems are strongly influenced by temperature and precipitation, two important physical-chemical factors controlling the spatial and temporal history of fire regimes (Wright and Bailey 1982, Pyne et al. 1996). The knowledge of fire history provides an ecological basis for past and future management and restoration (Swetnam et al. 1999). Although much has been written and quantified over the last half century about fire regimes, there remain large temporal and spatial gaps in our knowledge of continental fire regimes. Most of North America is without quantitative scientifically-based fire regime information. Large scale models of fire regimes are typically based on the vegetation associations (Keane et al. 2002, Hann et al. 2007) that have resulted from climate and fire. More recent modeling efforts have included climate variables as predictors in modern fire regimes (Westerling et al. 2006, Parisien and Moritz 2009). In many locations site specific fire history may never be obtained owing to a lack of possible charcoal or fire scar chronologies. Therefore, there is great value in a predictive model that synthesizes existing fire history information and formulates mean fire intervals (MFI) models based on physical mechanisms, particularly climate. These models can be useful in assessing the role of climate on fire at a continent level as well as estimating fire frequency for areas lacking in possible fire history information. Here we present a vegetation free modeling effort of the climate forcing of fire frequency in fire regimes.

B. Model Approach

Faced with the problems, prescriptions, and effects of wildland fire, we sometimes overlook that wildland fire is first and foremost a chemical reaction. As such, chemical reactants and reactions in ecosystems are subject to the principles of physical chemistry. Here we use the principles of physical chemistry and fire history data at the ecosystem level to develop, calibrate, and validate equations and models for predicting fire frequency for North America. The logic of the Physical Chemistry Fire Frequency Model (PC2FM) approach and form was inspired by Arrhenius' equation (Figure 1) – a fundamental rate equation in physical chemistry. Our overall approach combines both mechanistic and deterministic modeling for validation and adjustments at the landscape scale. The mechanistic component of the model is represented by using the physical chemistry of Arrhenius' equation as the basis for describing ecosystem rates of fire (mean fire intervals, MFI) (i.e., rate of combustion reactions). One of the important facets of mechanistic models is that causal inference can enable predictions outside the domain of the model and data, which in this case, is represented by millions of acres of land without any known fire histories. Thus, the model is not wholly dependent on spatial distributions of the empirical data, but is dependent on data that represent the wide range of reaction conditions, climates, and ignitions. The deterministic component of the model is represented by the statistical calibration and validation of parameter coefficients using empirical data.

The Arrhenius equation ($k= A_o exp^{-Ea/RT}$) uses molecular collision frequency and reactant concentration (A_o), the reactant activation energy (E_a), the gas constant (R), and temperature (T) to quantify the relationship between reaction rates (k) and environmental and chemical variables. We hypothesize that the relationship between climate (i.e., temperature and precipitation), fuel

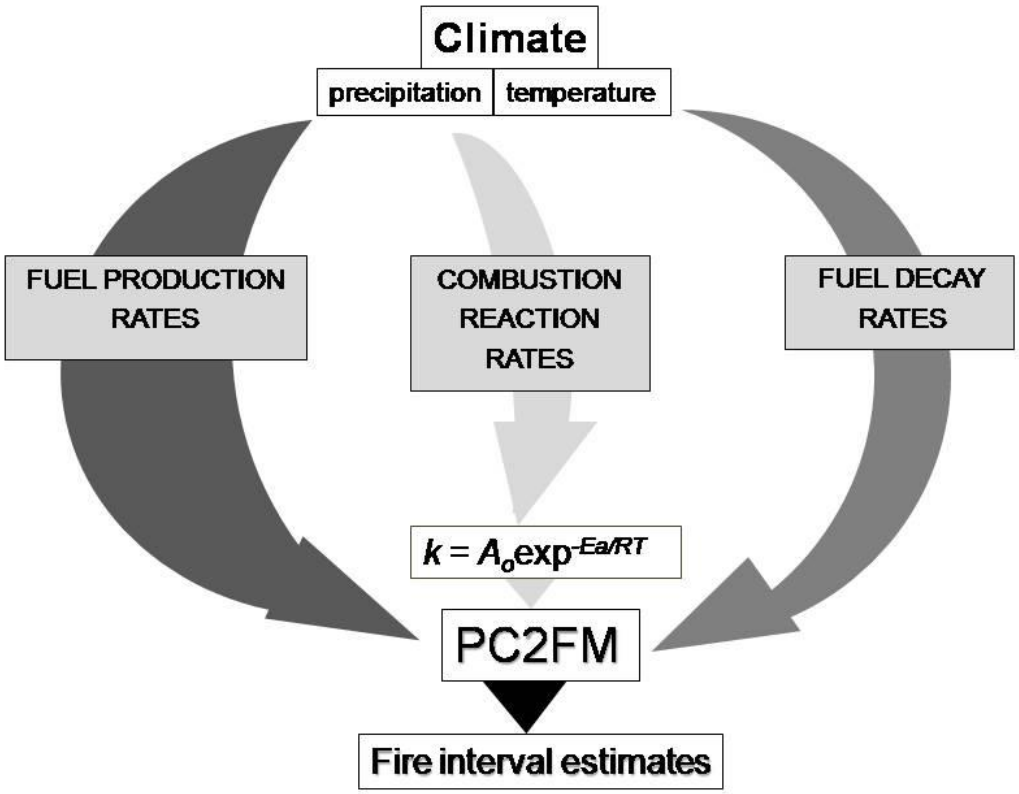


Figure 1. Conceptual diagram describing the relationship of climate to the reaction rates influencing ecosystem processes (fuel production, fuel decay, and combustion reactions) and the Physical Chemistry Fire Frequency Model (PC2FM). Both biological and fire chemistry are embedded in the PC2FM through the effects of climate on the reaction rates that influence fire. Reaction rates (k) are conceptualized here by the parameters of the Arrhenius equation whereby: A_o (molecular collisions and concentration of reactants) represents the landscape-scale distances between fuels, their structure, and quality; E_a (activation energy, the energy required to begin a reaction) is the landscape-scale influence of moisture on fuels and the energy required for ignitions; T (temperature of the reactants) represents fuel and air temperatures. Arrow width represents the relative contribution of climate to the rates of the three processes in fire regimes.

production, structure, and activation energy (Figure 1) can be applicable at the landscape scale using the concepts of the Arrhenius equation. Parameter coefficients for mean fire intervals are essentially (serial) estimates of Arrhenius' coefficients scaled from the laboratory to the landscape (i.e., landscape mean fire interval represents laboratory rate of reaction). For example, both temperature and activation energy (mitigated by fuel moisture) are strongly expressed in Arrhenius' equation (Figure 1). On the other hand, A_o in the Arrhenius (the collision frequency of reactant molecules, e.g. the density or loading of fuels in an ecosystem) is not used in the determinist calibration of the PC2FM because of the difficulty of quantifying this parameter at a coarse scale. In our modified equation, A_o is 'replaced' by a constant (C) derived from the intercept of the regression equation. The gas constant (*R*) is not used in our conceptual translation of the Arrhenius equation to a landscape level model because the historic and landscape level data for predicting MFIs does not have comparable units to the gas constant (J K^{-1} mol^{-1}). Although ignitions are not included in Arrhenius' equation, on the landscape and in the laboratory ignitions are necessary to initiate combustion reactions. Required ignition energy is included as activation energy (E_a). In addition to climate parameters we included human ignitions in this model because 1) they are an important known and generally measurable ignition source, 2) they have been shown to influence and change fire frequency world-wide (Guyette et al. 2006a, Mooney et al. 2007, McWethy et al. 2009), and 3) humans that live and use fire on the landscape have an understanding of fuel moisture (activation energy, E_a) and the fuel concentration (A_o) required to initiate combustion reactions.

We chose to develop and calibrate the PC2FM for the time period prior to widespread Euro-American influence (before ~1850) to minimize the major post-settlement anthropogenic effects on fire frequency such as fire suppression, industrial agriculture, domestic grazing, introduction of invasive and exotic vegetation, recent climate change, and other major land uses that reduce, modify, or fragment fuels. We expect that minimizing these influences would aid in the calibration and parameterization of MFI response and predictor variables. The broad continental scope of observations of MFI, temperature, precipitation, and human population facilitates the detection of spatial patterns in MFI beyond the constraints typically caused by local variation in vegetation and topography. Fire history data are from sites with large temperature and precipitation differences due to elevation, latitude, large water bodies, and other climate controls. In modeling, we used annual climate means because fire seasons vary across the continent. Fire season may typically be in the winter in the southeastern US, spring and fall in many regions of the US, or summer in many cooler parts of the western and eastern US. The season of burning is often unknown in much of the fire history data, and furthermore, it is the effects of temperature during the entire year that can control fuel production and decay.

C. Continental North American Fire History

Tree-ring dated fire scars have provided long-term records of fire frequency and fire-climate interactions from diverse forested sites across North America. For more than 30 years these data and other complementary paleofire evidence (e.g., charcoal sediments) have been the foundation of fire and ecosystem theories (Stokes and Dietrich 1980, Lynch et al. 2004, Whitlock et al. 2004). These spatio-temporal data commonly span more than three hundred years (several generations of trees) and are available for many types of ecosystems via international science

archives[1]. These fire history data have broad applications including providing land managers valuable baseline information about fire regimes in the pre-Euro American period; furthermore fire history data provide ecological insight into plant distribution and succession that underpin ecosystem management and restoration (Swetnam et al. 1999).

Forests and grasslands are exhibiting historically unprecedented changes in fire frequency, fire severity, species composition, and fuels accumulation (McKenzie et al. 2000, Morgan et al. 2001). Therefore in the future, the knowledge gained from fire history studies will likely improve predictive models of fire frequency and help assess fire regime sensitivity to climate change (Westerling et al. 2006, Shapiro-Miller et al. 2007). Our research goal is to develop a model that can bring together and analyze new and existing fire history data for a broad scale characterization of past and future fire regimes.

D. Fire History Data and Site Selection

Fire scar history sites and data were gathered from published scientific studies, data produced for this study, and the International Multiproxy Paleofire Database (NOAA). Sites were included in the database if they satisfied these criteria:

1) Site fire histories were deemed important when they were from very different climates, expanded the range in the length of mean fire intervals in the data set, covered the preindustrial period, and to a lesser extent expanded the geographical range of locations.
2) Site areas were less was than 3 km^2 (except in two cases). For fire scar histories the composite mean fire interval is a robust estimate of the occurrence of fire within a given area (Dietrich and Stokes 1980). This type of fire interval is subject to increasing frequency of fire with increasing area, therefore, comparisons between sites necessitate comparable study areas (Baker and Ehle 2001, Faulk et al. 2007). Fire scar history sites included in this study averaged 1.32 km^2 in area, ranged from < 0.10 to 8.1 km^2, and had a standard deviation of 1.27 km^2. Prior to analysis we found that within this range of site area differences, there is no significant correlation between site areas and mean fire intervals ($r=0.056$, $p= 0.54$) as might be expected by having variable sample areas. The lack of relationship here could be due to the large variation in fire size and frequency among ecosystems across the continent. This area limit was used because increased fire history site areas could distort the 'near point interval estimates' approximated by composite intervals.
3) Data were not included unless they were of high quality. Factors used to judge quality included the number of sample trees, scar dating methodology, and site location in relation to the spatial distribution of sites. For some regions sites were chosen so to include as many ecosystems as possible. If possible, more than one site from a region was included to minimize the effects of local factors (e.g., topography and geology) on biasing mean fire intervals (Heyerdahl et al. 2001). Eastern North America had fewer fire history sites, therefore these data were used despite their quality. For example, one site had only a single tree but provided important fire history data in a region with no other quantitative evidence (Buell et al. 1954). In areas where many fire history studies were available (e.g., Black Hills, Brown and Sieg 1996); western Montana, (Heyerdahl et al. 2006); Cascades, (Everett et al. 2000); Ozarks, (Guyette et al. 2002) the number of sites included was limited to reduce their spatial dominance and auto correlation in the continental analysis.

The fire history database for the PC2FM consisted of 150 fire scar sites. Approximately two-thirds of these sites were from the western U.S and one third from the eastern US. Because trees occupy a stratified sample of ecosystems that meet conditions of moisture and temperature necessary to support tree growth we needed other fire data sources to characterize regions where trees do not grow or are not scarred by fires. Additionally, at large spatial scales, fire scar

[1] National Oceanic and Atmospheric Association (NOAA), International Paleofire Databank (IMPD),

histories are a stratified and biased data set because they come from fire adapted tree species that grow in the part of the landscape where fire intervals are shorter. Thus, we supplemented the fire scar data with charcoal data (3 sites) and expert estimates (7 sites). Despite differences in data types the inclusion of charcoal and expert estimates was necessary because 1) some regions have very long fire intervals that exceed the ages of trees or their scarring dynamics, and 2) variable selection, parameterization, and model development required some data, even at coarse temporal scales, to provide estimates in regions with very long intervals. For desert regions, we also used expert fire regime estimates and reports (Schmidt et al. 2002). Although many charcoal study sites exist, only a few were included to represent treeless and ecosystems with infrequent fire because of their often low temporal resolution compared to fire scars on trees.

E. Modification of the Model Constant for Severity Outputs

Modeling allows for more precise outputs by enhanced data comparisons and extraction. We used a universal modification of the PC2FM constant (C, Equation 1) to roughly differentiate high and low severity fires and to compensate for the differences in the susceptibility of tree species to scarring and to variation in fuel conditions in the fire history data. By universally adjusting the model constant (C) we both enhance model output and avoid comparative differences resulting from species specific responses found in the fire history data such as:

1. The inclusion of fire events that scarred only a single tree or produced weak charcoal formation in years where fires may have incompletely burned the site area or where fire intensity may have been so low as to have scarred few trees.
2. Tree species specific susceptibility to scarring that are based on growth rate, bark thickness, tree size, and stem moisture content.
3. Fuel accumulation and fire intensity vary by decay rates which influence fire severity and the percent of trees scarred.
4. The varied seasonality of fires across the continent is related to stem temperature during the season of burning. Season of burning can make a difference in the fire intensity, ability to scar, and severity of scarring.
5. Fuel moisture (a primary regulator of E_a) and reactant concentration (A_o) differs among environments and sites, which affects fire intensity, tree scarring, and charcoal production. This approach transforms the intercept of the deterministic regression model to the concentration of reactants in the non-linear mechanistic model that is based on the components of the Arrhenius equation. The slope of the regression lines resulting from the change in the C value in Equation 1reflects both the concentration of reactants (A_o) of the Arrhenius Equation and the frequency of fires of different severity.

To estimate and differentiate the frequencies of low and high severity fires, we analyzed a sub group of 30 studies that had data on fire severity based on the number of trees scarred, the spatial distribution of scarring, or indications of stand replacement based on pith dates. These data were used to estimate a ratio of the number of trees scarred to the total tree sample in a given fire year, which indicates fire severity (e.g,, low or high) at each site. The fire history data indicated that about 1 in 6 fires (standard deviation = 3) were high severity and had longer mean fire intervals than low severity high frequency fires. This ratio was used as a weight for the model constant (C in Equation 1). The application of the filter ratio was calculated by the addition of 83 or 17 percent of the equation constant 59.12 to itself (C, Equation 1) to derive two new models differing only in the magnitude of the constant.

F. Model Variables

PC2FM variables were selected and developed based on fire ecology and physical chemistry (i.e., Arrhenius' equation). Model variables were chosen because they were mechanistically and ecologically relevant, statistically significant, and could be mapped using a geographic information system (GIS). We chose four significant covariates of the MFIs: mean maximum temperature (*maxt*) (Daly et al. 2004), human population density (*pop*) (Driver and Massey 1957, Terrell 1971), a moisture index (*moisti*), and annual precipitation (*precip*). Three other climate variables were tested for significance with correlation but not used; minimum mean temperature, mean temperature, and coarse-scale lightning fire frequency. It is possible that mean temperature could have been substituted for *maxt*, however *maxt* consistently explained a greater percentage of variance. The *maxt* parameter used for calibration is a 'proxy' in the sense that the model period (~ 1650 to 1850) it is temporally different than the climate estimate period (1971-2000). Errors caused by the displacement of the period of the climate data and the period of fire history are likely minimal because the long-term temporal differences in temperature from 1750 to 1985 are small (~ 0.4 ^{o}C) compared to the large spatial differences in temperature among sites (26 ^{o}C). We subtracted 0.4 ^{o}C from annual mean maximum temperatures at all the sites compensate for recent warming (Mann et al. 1998).

A key model variable is a simple moisture index (*moisti*). This interaction variable (1/ (annual precipitation / mean maximum temperature)) was developed through iterations of regression modeling with feedback from model-generated maps and expert estimates. The *moisti* variable is suggested in the Arrhenius equation from the division of the E_a and T parameters. This relationship is manifested in fire regimes by the effect of fuel moisture on the activation energy (E_a) required for combustion reactions (Figure 2). Rain forest ecosystems exemplify this relationship in that high fuel moisture contents necessitate high temperatures and multiple or high energy ignitions to start a fire. The function of the *moisti* variable is to switch the direction of influence of moisture with respect to MFI to account for very dry, hot and cold ecosystems. This variable is very sensitive to small differences in precipitation at very low levels; for instance, there were only small differences between the *moisti* of deserts and dry, short grass, and burnable grassland, suggesting that in these types of environments slight differences in precipitation can result in large differences in fire intervals given sufficient continuous and annually reaccumulated fuels.

G. Ignitions: Humans and Lightning

We assigned human population densities to fire history sites using previously mapped estimates of Native Americans in North America at the time of contact with Euro-Americans (Driver and Massey 1957) and supplemented these with more detailed population estimates where available (Kroeber 1925, Mooney 1928, Swanton 1950, Terrell 1971, Denevan 1992, Henige 1998). Precise calibration between fire frequency and population density is difficult at any temporal and spatial scale due to abrupt or slow changes from introduced diseases, war, migration, emigration, as well as the uncertainty of population estimates. Of all the variables used in our analyses, human population density (representing both accidental and purposeful ignitions) is likely the most ephemeral with the ability to change rapidly across many spatial and temporal scales. Additionally, numerous written accounts of purposeful burning may be observer biased (Williams 2001, Barrett et al. 2005). Despite these problems, however, recent quantitative

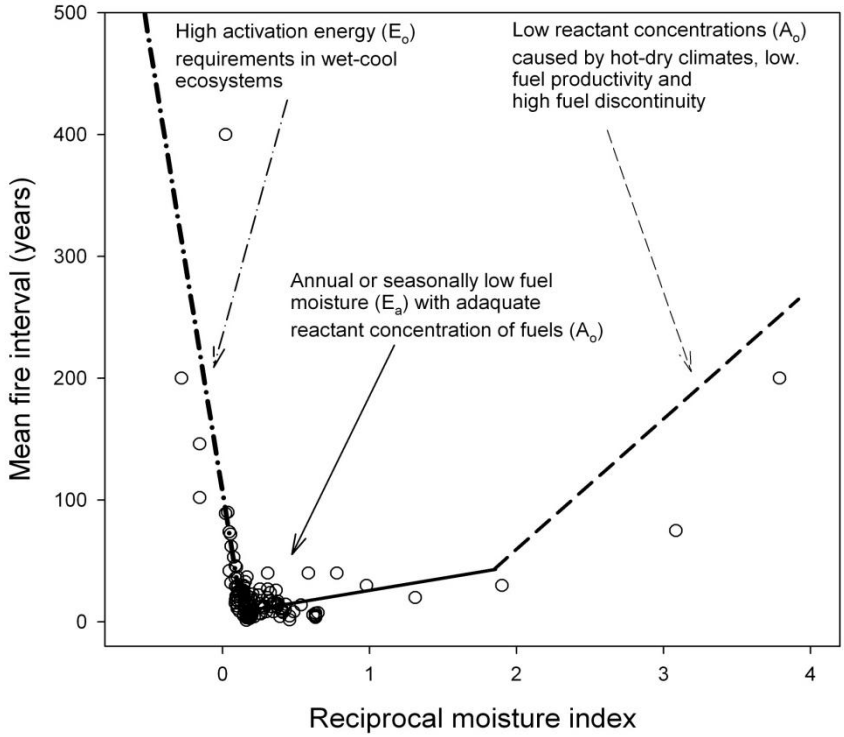


Figure 2. Observed mean fire intervals in this study plotted against the reciprocal moisture index *(moisti)*, used to parameterize the PC2FM. The dotted-dashed line represents regions where high fuel moisture (E_a) is the most important variable controlling fire frequency. The solid line represents regions where fuel production and concentration (A_o) are sufficient and fuel moisture can be low enough to allow low activation energy (E_a). The dashed line represents regions where the low concentration of reactant (A_o) is controlling fire frequency.

studies (Guyette et al 2002, Guyette and Spetich 2003, Guyette et al. 2006a, Stambaugh and Guyette 2008), provide evidence that human ignitions had important effects on historic fire regimes.

Lightning strikes in many regions are an ignition source and affect fire frequency and extent. However, lightning has been excluded from the current version of the PC2FM owing to the limited availability of lightning caused fire data and lightning-fire interval correlations. Lightning ignitions, not frequency, are temporally short and spatially coarse, and thus problematic for model parameterization. The primary concern with lightning data is that most data represent lightning flashes, which do not correlate with wildfire ignitions at broad climate scales. For example, many regions of the continent have frequent lightning strikes but very few lightning ignitions. Conversely, other regions (e.g., high elevations) show that lightning-fire interval correlations are negative (more lightning fires occur in forests with longer fire intervals). Ignitions from dry lightning often occur in high elevation ecosystems where forests have long fire intervals (Rorig and Ferguson 2008). Statistically, our modeling attempts have shown that lightning ignition rates (*sensu* Schroeder and Buck 1970) explain about 1 or 2 percent of the variance in MFIs at the continental scale but with the opposite association for ignitions. Aspects of lightning ignition forcing of fire frequency may be incidentally incorporated in our modeling approach because of the association between lightning and temperature (Ryan 1989, Price 2009). Seasonal, annual, and spatial differences in lightning frequency are positively associated with temperature. Warmer atmospheric conditions correspond to an increased frequency of lightning. Thus, the same warming influences that affect many fire related ecosystem characteristics (e.g. fuel production, combustion rates) may also affect the frequency of lightning ignitions (Figure 1).

H. Model Development, Calibration and Validation

The PC2FM was first regressed using the natural log of the MFIs. This allowed for both deterministic variable selection and a mechanistic transform of the equation. Deterministically, the log transform and formulation met the assumption of mean fire intervals being normally distributed, and allowed for variable selection and estimating the partial r-squares of variables. Mechanistically, this allowed for assessing how the different landscape variables and data were associated with the physical chemistry demonstrated by Arrhenius' equation.

The PC2FM was selected from regressions on randomly selected halves of the data. The PC2FM was selected based on the components of Arrhenius' equation, knowledge of fire ecology, and test statistics such as the variance inflation factor (VIF), correlations, variable stability, and model r-square. The natural logarithmic model was then transformed to its exponential form. Both models resulted in identical estimates (correlation of 1) when the dependent variable was transformed with the appropriate natural log or antilog. The final PC2FM equation was based on 78 observations and tested on random selections of half of the 160 data observations. The distribution of 100 coefficients of determination calculated from randomly chosen halves of the data with replacement indicated that the regression model was stable.

I. Maps based on the PC2FM

PC2FM estimates of MFIs were mapped using ESRI®ArcGIS™ software (ESRI 2005). Gridded mean maximum temperature data (PRISM data, Daly et al. 2004) and a digitized coverage of human population density were applied to Equation 1 to produce maps of MFIs for a pre-Euro American settlement period. Before mapping, population data were spatially smoothed (circular neighborhood means) to more closely reflect the mobility of humans across borders and eliminate abrupt boundaries between population polygons. The mean fire interval error estimates were based on the model (Figure 3).

J. Model Process and Statistics

The PC2FM is described by the exponential equation:

$$\mathbf{MFI = C*exp}^{(-\,(0.139*\boldsymbol{maxt}) + (1.50*\boldsymbol{moisti}) - (2.41*\boldsymbol{pop}) + (0.00763*\boldsymbol{precip}))}, \text{ (Equation 1)}$$

where: **MFI** is the mean fire interval (years),
C is 59.12 (all fires model), 69.17 (low severity fire model), 108.19 (high severity fire model),
exp is 2.718,
maxt is the proxy mean maximum temperature (30 yr mean, ^{o}C),
moisti is the reciprocal moisture index (1/*precip*/*maxt*),
pop is human population density (humans per km^2),
precip is mean annual total precipitation (cm).

All parameters were significant ($p < 0.001$). Multicollinearity among predictor variables was negligible and variance inflation factors were all less than 1.9. Residuals were randomly distributed for predicted MFIs, and were more variable for MFI predictions greater than 60 years. Increased variation may be due to the less accurate expert estimates of long fire intervals or to the greater stochasticity of longer fire intervals. The 95% confidence limit for individual predictions was ± 21 years. The 95% confidence limit for the model mean ranged between about ± 3.5 years to ± 7.5 years (Figure 3).

Based on 100 model runs the average tested model coefficients of determination (r^2) was 0.75 (range 0.63 to 0.91) as tested with the natural log transform of the dependent variable to meet the assumption of normality. From the exponential form of the model, the partial r^2 of the parameters cannot be parceled out because of their addition in the exponent, however, we did estimate the partial r^2 of the independent variables using a natural logarithmic transformation of the dependent variable (MFI). Estimates of partial r^2 were 30 percent for *maxt*, 23 percent for *moisti*, 12 percent for *pop*, and 10 percent for *precip*.

Considerable error remains in the PC2FM estimates and thus mapped estimates (Figures 4 and 5). The coarse-scale model and map estimate the probability of mean fire intervals forced by climate and to a lesser extent human ignition. However, the estimates are normally distributed with the center of the distribution occurring along the regression line (Figure 2b). Shorter mean fire interval estimates (< 20 years) have less variability in prediction (±3.4 years) while longer fire intervals have a much larger prediction interval. Error estimates include all variability imposed by differences in vegetation, fuels, topography and local human population. Evidence for the importance of these variables occurs at finer scales.

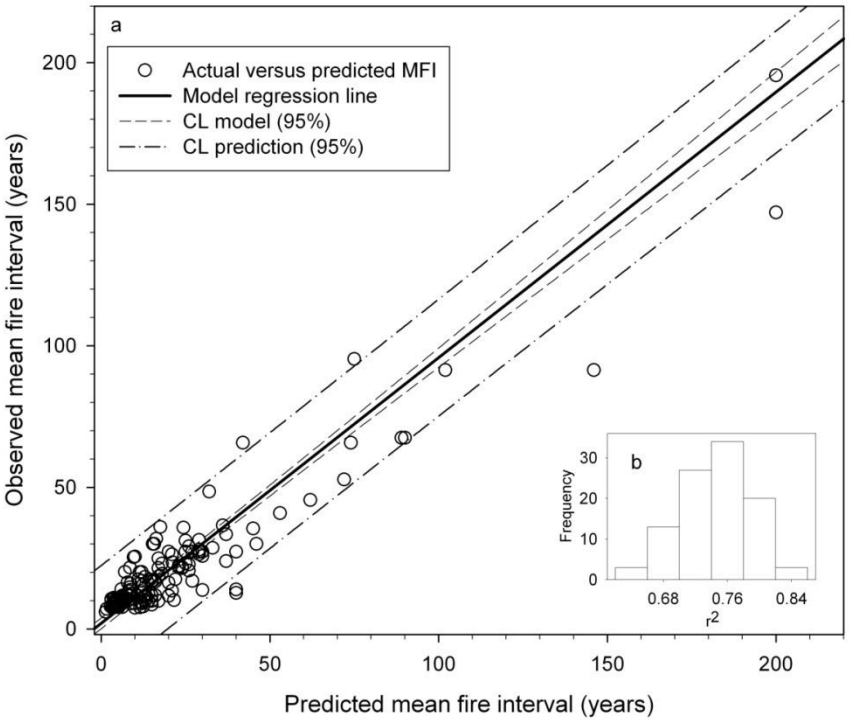


Figure 3. a) Plot of predicted (base PC2FM) and observed mean fire intervals (MFIs) for all fires and their 95 percent model prediction confidence intervals. One predicted MFIs based on an expert estimate of rainforests (433, 400 years) is beyond axes scale, b) frequency distribution of model r-square values from 100 model runs representing random samples of 50 percent of the data with replacement.

K. Model Variables and Approach

Climate and fire are important determinants of long-term vegetation types. Positive feedback may occur between vegetation and fuel types, causing short-term memory in fire regimes. Fire prediction models often incorporate vegetation as the primary determinant of a fire regime. We specifically do not include vegetation in the PC2FM because our main interest was to parameterize climate forcing in fire regimes. The lack of vegetation (i.e., fuel reactants) in the PC2FM may limit its ability to predict fuel produced fine scale fire intervals. The lack of vegetation also increases the confidence limits of the model (Figure 3). Conversely, a benefit of a vegetation-free model is the applicability of the model to make predictions of MFI in situations where vegetation data are unknown, unavailable, not of primary interest, or when current vegetation might differ from historic.

The PC2FM approach is based on a fundamental mechanistic model of physical chemistry, the Arrhenius Equation, which allows for an objective evaluation and assessment of climate forcing in current fire regimes that may be concealed by changing vegetation, landscapes, ignitions, land use, and fire suppression. In other words, most of the parameters and coefficients developed via the mechanistic model and validated with historic data can be used to assess climate forcing without the 'noise' related with many of the present day conditions that mask the effects of climate.

The parameters and approach of this ongoing modeling and mapping effort does have potential limitations. Currently, 33 of the 48 contiguous US states have some fire history data from dated fire scars. Thirteen of these states have only one fire history representing a broad range of fire regimes, historic human population densities, elevation-related temperature gradients, precipitation regimes, and topographies. Fire frequency of landscapes the size of entire states can have nearly as much variability in MFI as the whole continent because of local factors. Due to the overall paucity of fire history data in many regions of the US obtaining finer-scale estimates will likely require much more complex models and many additional study sites.

L. Map interpretations

The maps illustrate MFI as estimated by climate (63 percent) and to a lesser extent, human ignitions (12 percent). Much of the fine-scale complexity of fire regimes in ecosystems was not represented in mapping with this model. Coarse-scale variables are not capable of illuminating fine-scale effects of topography, aspect, and human population (Heyerdahl et al. 2001). For example, the Ozark Plateau is topographically complex but lacks large scale differences in temperature and precipitation. Here, mapped coarse scale PC2FM estimates do not reveal the complex fire history of the region that results from fine-scale topography and vegetation, On the other hand, the PC2FM does well at predicting the regional average of MFIs that occur in this landscape where we have a well documented fire history (Batek et al. 1999, Guyette et al. 2002, Stambaugh and Guyette 2008).

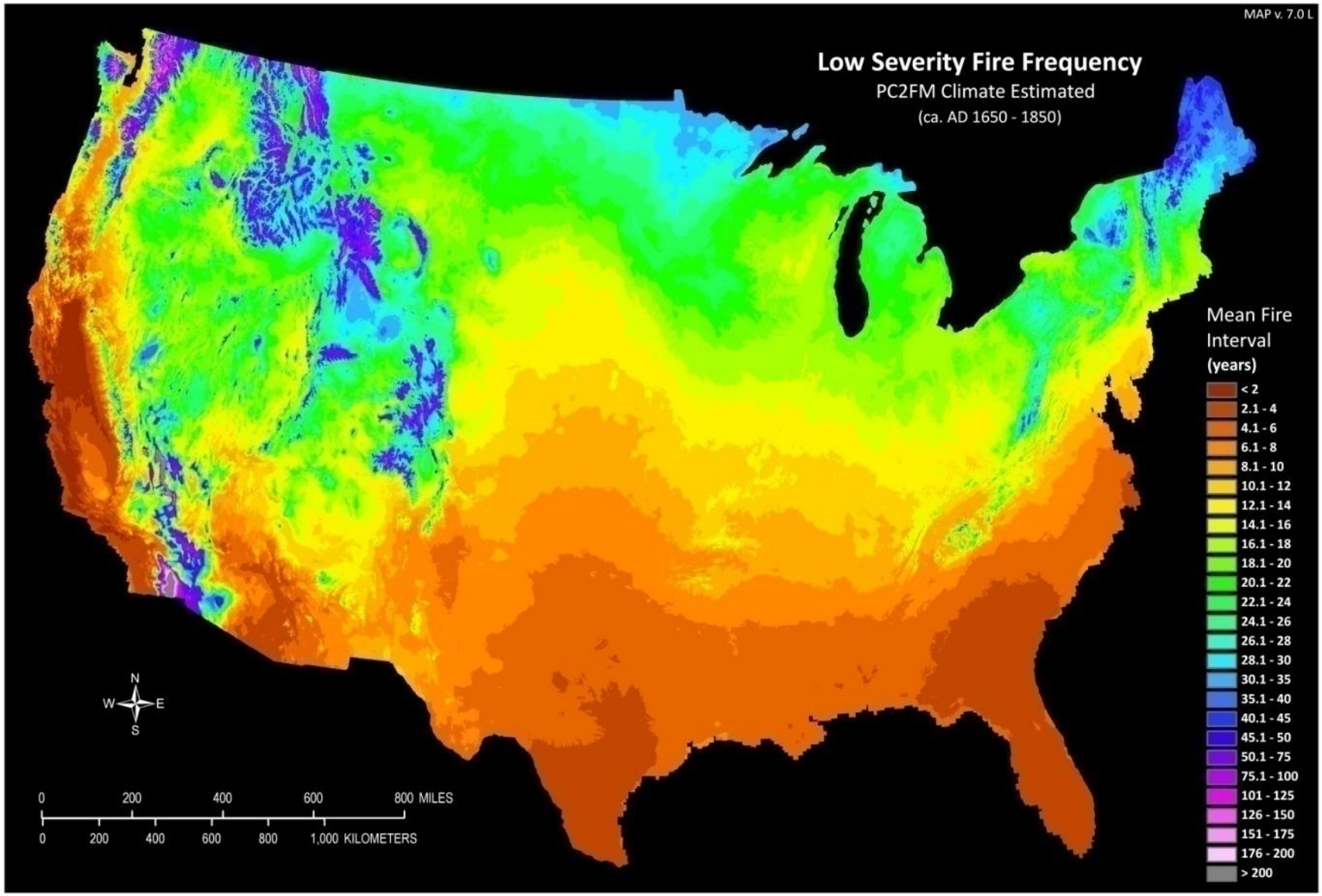


Figure 4. Mapped PC2FM estimates of mean fire intervals (MFIs) for low severity fires based on temperature, precipitation, and human population density (Equation 1). Low severity fire estimates are based on 83 percent of all fire years. Classification intervals are in 2 year classes (1 to 30 years), 5 year classes (31 to 50 years), 25 year classes (50 to 200 years), and a single class for intervals > 200 year.

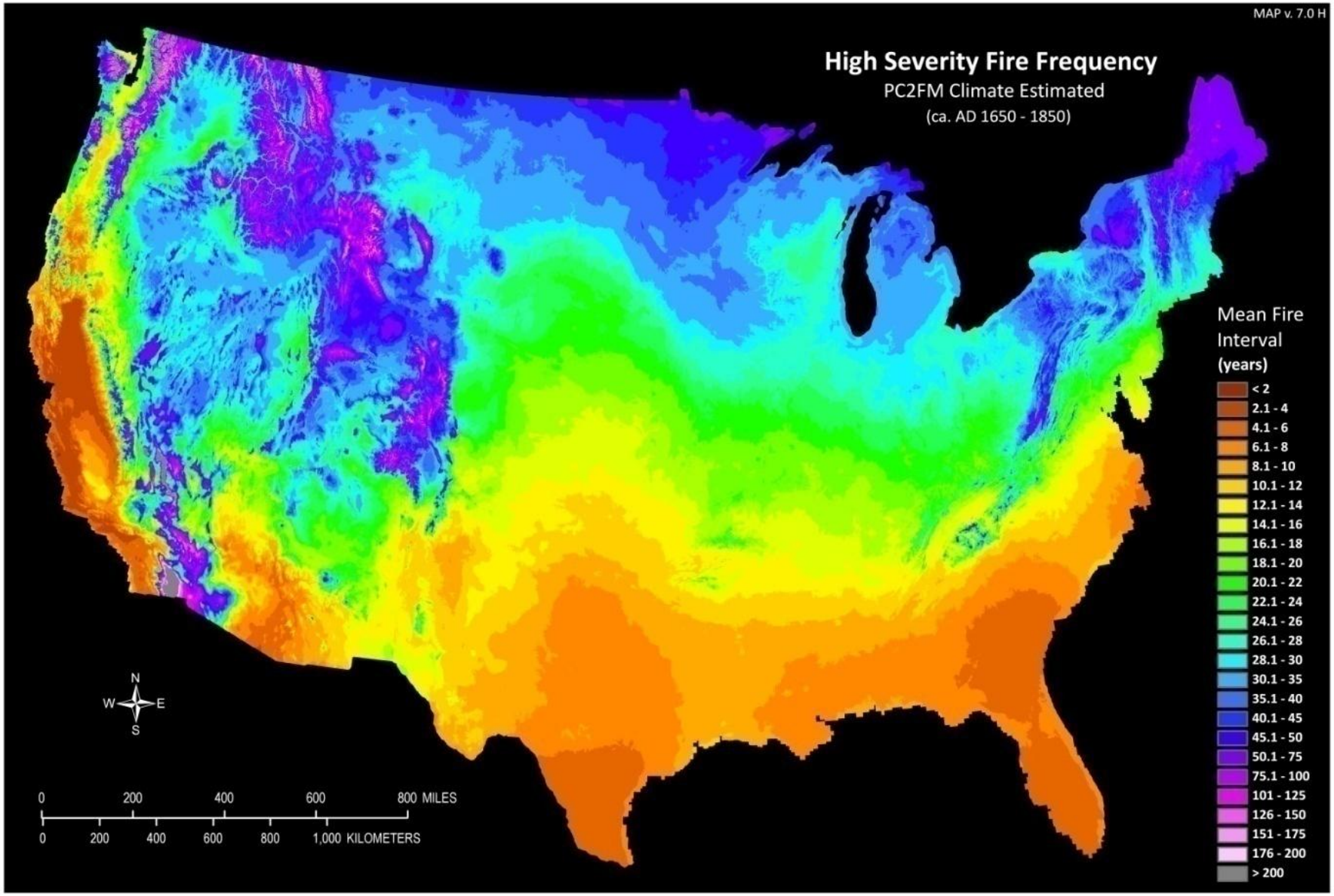


Figure 5. Mapped PC2FM estimates of mean fire intervals (MFIs) for high severity fires based on temperature, precipitation, and human population density (Equation 1). High severity fire estimates are based on 17 percent of all fire years, and do not necessarily include only total stand replacement fires. Classification intervals are in 2 year classes (1 to 30 years), 5 year classes (31 to 50 years), 25 year classes (50 to 200 years), and a single class for intervals > 200 years.

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V. Management implications

This study makes two major contributions to fire science: 1) it provides quantitative local to regional scale estimates of fire frequency that can be used to assess the present state of forests, vegetation and fuels, and species and, 2) it quantitatively and visually depicts coarse-scale fire frequency and elucidates the multiple influences of temperature and precipitation on the fire environment and combustion reactions.

Fire history reports were provided to managers at Land Between the Lakes, Daniel Boone National Forest, Talladega National Forest, Chequamegon-Nicolet National Forest, and Kisatchie National Forest. This fire history information has been used in fuel assessment, public education, and restoration and prescribed fire planning. Restoration of vegetation and habitats with fire is a major concern for many land managers concerned with wildlife and diversity in eastern forests. Fire history studies address restoration questions such as the frequency and perhaps most importantly, the variability in fire frequency that can be used in management. The majority of managed public lands have only generalized information about fire frequency and much information is based on opinion and vegetation. Managers can use model estimates and fire frequency maps as a scientifically-based means of arriving at likely fire frequencies or other fire regime characteristics. These coarse-scale estimates may then be lengthened or shortened based on specific area conditions such as topography or substrate.

The calibration of the PC2FM model is based on parameters that vary both spatially and temporally. This work utilizes a physical-chemistry-based approach to understand climate's influence on fire regimes. An important result of this work is that model parameterization is derived from multi-century data sets that represent diverse fire regimes at a continental extent. Model parameters and coefficients were developed and validated by integrating the science of physical chemistry, statistics, and knowledge of fire ecology. It is our opinion that the model is a very useful tool for identifying climate controls of fire regimes and assessing the influence of climate changes on fire regimes.

VI. Relationship to other recent findings and ongoing work on this topic

There were few quantitative fire histories from fire scars in eastern North America 28 years ago (Guyette et al. 1982). More researchers in the eastern United States have begun working in fire history over the last two decades and we are beginning to recognize and understand the historic

importance of fires. With new data we are beginning to understand the roles of seasonal climate variability, human ignition, and topographic effects. The data, modeling, and mapping of this study support theories and ideas about changing vegetation (Aldrich et al. 2010, Dey and Hartman 2005), human-fire influences (Fesenmyer and Christensen 2010, Delcourt and Delcourt 1994), and information on past fire frequency in eastern regions that has been largely lost by land conversion.

There is some utility in comparing fire intervals defined by vegetation types and the fire intervals estimates forced by climate. The difference between these estimates can be large or small based on a particular vegetation type's ability to enhance or reduce fuel availability during a fire (Romme 2009). For example, pinyon-juniper forests and savannas can have fire intervals that are much longer than predicted by our climate-based model because of the ability of juniper species to reduce available ground and ladder fuels. The comparison of data and hypotheses from these studies may yield insight into complex fire-climate-vegetation interactions in this forest type.

Implicit in the predictor variables of the PC2FM are the effects of ocean-atmosphere circulation on climate and fire frequency. Although general climate parameters of precipitation and temperature have a very broad range in this analysis due to latitude, elevation, and continental climates; ocean and marine climates have long- and short-term effects on fire frequency – especially in coastal regions (Swetnam and Betancourt 1990). The variability due to oceanic mitigation of terrestrial temperature can be observed as the higher fire frequencies that occur from New Jersey to Texas and from southern California to Washington (Figure 4, 5). Future work and prediction of changes in ocean circulation and terrestrial climate may allow coupling of the climate forcing of fire regimes with global climate change models.

This project's modeling and applied research adds a long-term perspective to temperature forcing that spans ecosystems and vegetations ecosystems without past information on fire frequency. Our work may eventually aid in connecting hemispheric scale terrestrial and oceanic climate variability (Conroy et al. 2010) with global climate forcing of fire regimes. The calibration, partial mechanistic approach, and climate forcing aspect of this work may represent its most important contribution because it links fire with global modeling of future temperature and precipitation (Delworth et al. 2006). Despite the usefulness of the map predictions, the coefficients and parameterization of the PC2FM are important because they may aid in the transfer of this approach to other continents and time periods. They also may give us a new way to couple environmental chemistry and ecosystems. We have already found the PC2FM useful in assessing future fire regimes and climate change. We expect small changes in the coefficients as new data and modeling ideas arise.

VII. Future work needed

Future work is needed in two categories 1) fire scar data acquisition from decaying wood and dying older trees in eastern North American and 2) more effort into understanding climate-linkages to fire regimes. In the eastern US many old trees with fire history information are dying from 'old age', disease, and insects. Additionally, preserved pine and oak stumps are decaying. This potential history will be lost forever in a few decades. This is probably the most important single area of needed work. It is especially important for documenting ecosystems and conditions that result in long fire intervals (e.g., 20 to 200 + years).

The success of this projects modeling of ecosystem level combustion reactions with chemistry and topography indicates that more work in this area may be of value in past fire reconstruction and in estimating climate-based future forcing of fire. For example, temperature, precipitation and their interaction prove to be the most important factors control the frequency of fire in ecosystems. Although these relationships are obvious their quantification is challenging, but is becoming more achievable with the breadth of fire history data becoming available. Additionally, the value of models and data that can address fire before and after global changes (temperature, CO_2, and human population) is becoming increasing relevant to society. We can no longer rely on 'expert opinion' to address societal concerns. Reviewer opinions of models in this study have often reflected preconceived notions about fire frequency that are not scientifically based. For example, many reviewers from western U.S. regions refuse the high fire frequency associated with subtropical southeastern U.S. or Lake States regions during pre-industrial periods. Thus, more empirical data such as fire scars on trees are needed to inform scientists and the public about the spatial and temporal variability in U.S. fire regimes.

VIII. Deliverables Cross-Walk

Proposed	**Delivered**	**Status**
Fire scar history data for International Multiproxy Paleofire Database (IMPD)	Twelve fire scar histories from Louisiana, Kentucky, Michigan, Wisconsin, Alabama, Iowa (see data above)	Data submissions for two sites completed. Additional data submissions are in progress. These data have or will be submitted to the IMPD and can be searched by PI names 'Guyette RP' and 'Stambaugh MC'. This website has a delayed posting of data. See recently submitted data page on IMPD website: (http://www.ncdc.noaa.gov/paleo/impd/).
Website of mapped mean fire intervals estimates for pre-European settlement period	(1) Guyette et al. (in review). *Climate calibration of fire frequency in the continental U.S.*	Webpage codes are developed, beta-testing of descriptive webpages has occurred on University of Missouri host website, development of ArcIMS data website and data access in progress and awaiting further development and acceptance of Guyette et al. manuscript (in review) that describes the modeling approach and resulting maps. Website hosting partnership initiated US Forest Service Northern Research Station.
Journal Articles	(1) Guyette et al. (in review). *Climate calibration of fire frequency in the continental U.S.* (2) Stambaugh et al. (in review). *Longleaf pine (Pinus palustris Mill.) fire scars reveal new details of a frequent fire regime.*	(3) Publications in review or preparation. See other publications (theses, abstracts) in additional publications section (below). Access to all publications will be made available through Missouri Tree-Ring Laboratory publications website: (http://web.missouri.edu/~guyetter/pubs.html)

	(3)Muzika et al. (in prep.) *Fire regime dynamics of the Huron Mountains, Upper Peninsula, Michigan*	
Workshops	1) Hosted "Lessons from fire history: past and future" workshop at University of Missouri October 22-26, 2007. Connected 250 fire managers, scientists representing 12 different states. (2) Held informal workshops with personnel at Chequamegon-Nicolet NF (WI), Kisatchie NF (LA) (3) Presented methods and results of fire history at Huron Mountain Club (MI)	All workshops completed. Major workshop was very successful. Details were highlighted in publication Stambaugh et al. 2009 (http://web.missouri.edu/~guyetter/stambaugh_etal_2008a.pdf)
Presentations	21 at professional meetings and seminars	All completed (posted on JFSP website when completed)

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X. Additional Reporting (Appendices and other inputs to JFSP)

A. Input into Findings Database (available from www.firescience.gov)

B. Digital Photos (Photos available on CD upon request)

C. First Look (Jan. 2008): Filling in the Blanks: Developing Fire Scar Histories in the Southern and Eastern United States.
(http://www.firescience.gov/New_Research/Developing_Fire_Scar_Histories_South_and_Eastern_US.pdf)

D. Deliverables Citation Database (items entered into the JFSP Citation Database through May 10, 2010)

Final Report

Guyette, R.P., Stambaugh, M.C., Dey, D.C. 2010. Developing fire histories in the eastern U.S. Final Project Report (JFSP Project Number: 06-3-1-16). May 10, 2010.

Professional Presentations and Invited Talks

2009

Stambaugh, M.C. and R.P. Guyette. Perspectives and comparisons of smoke emissions from historic and modern fires: taking the elephant out of the closet and putting it into the stadium. Tall Timbers 24th Fire Ecology Conference, Tallahassee, FL (Plenary).

Stambaugh, M.C., R.P. Guyette, and J.M. Marschall. Confirmation of a long-term frequent fire regime in a longleaf pine-bluestem ecosystem. 4th International Fire Ecology and Management Congress, Savannah, GA (poster).

Stambaugh, M.C., R.P. Guyette, and D.C. Dey. Perspectives and comparisons of smoke emissions from historic and modern fires: taking the elephant out of the closet and placing it into the stadium. 4th International Fire Ecology and Management Congress, Savannah, GA (oral presentation).

Guyette, R.P. and M.C. Stambaugh, Great Plains fire frequency modeling and climate calibration. 4th International Fire Ecology and Management Congress, Savannah, GA. (oral presentation).

Muzika, R., R.P. Guyette, and M.C. Stambaugh. Fire history of the Huron Mountains landscape. 4th International Fire Ecology and Management Congress, Savannah, GA. (oral presentation).

Guyette, R.P., M.C. Stambaugh, R. Muzika, and D. Dey. Future continental- and global-scale climate forcing of fire frequency using the PC2FM model. 4th International Fire Ecology and Management Congress, Savannah, GA. (oral presentation).

Guyette, R.P., M.C. Stambaugh, R. Muzika, and D. Dey. Calibration and mapping of historic and future fire frequency in the continental United States. 4th International Fire Ecology and Management Congress, Savannah, GA (poster).

Stambaugh, M.C. and R.P. Guyette. Climate forcing of historic and future fire frequency in the continental United States. PAGES 3rd Open Science Meeting, Corvallis, OR (poster).

Guyette, R.P. and M.C. Stambaugh. Historic and future climate forcing of fire frequency in the southern plains and comparisons with North America. American Assoc. for the Advancement of Science (AAAS) – Southwest and Rocky Mtn. Division Annual Meeting, Tulsa, OK (oral presentation).

Stambaugh, M.C. and R.P. Guyette. Fire scar history confirmation of a long-term frequent fire regime in a longleaf-bluestem ecosystem, Kisatchie Hills Wilderness, Louisiana. Tall Timbers 24th Fire Ecology Conference, Tallahassee, FL (oral presentation).

Guyette, R.P. and M.C. Stambaugh, and R.M. Muzika, R.M. Estimates of historic fire intervals In the North Central U.S. Prescribed Fire: Learning From the Past Planning for the Future. Prescribed Fire Council, Stevens Point, WI (plenary oral presentation).

2008

Stambaugh, M.C. 2008. New fire histories from the eastern U.S. and Great Plains regions. The Nature Conservancy Fire Learning Network, St. Francis National Forest, Marianna, AR (oral presentation).

Stambaugh, M.C. 2007. Multiple uses of fire history information. Lessons from fire history: past and future workshop. University of Missouri, Columbia, MO (oral presentation).

Stambaugh, M.C. 2006. Defining historic fire regimes using tree-ring science. 2006. U.S. Forest Service, Shawnee National Forest fire planning meeting, Anna, IL (oral presentation).

Guyette, R.P. and Stambaugh, M.C. Quantitative estimates of historic fire intervals for the Pacific Coast and North America Pacific Coast Fire Conference: Changing Fire Regimes, Goals and Ecosystems. Dec., San Diego, CA. (oral presentation).

Guyette, R.P., Stambaugh, M.C., and Dey, D.C. An empirical calibration and comparison of fire intervals in the Southwest and contiguous U.S. Fire in the Southwest: Integrating Fire into Management of Changing Ecosystems, Nov. Tucson AZ. (oral presentation).

2007

Stambaugh, M.C., R.P. Guyette, and D.C. Dey. Continental and landscape-scale approaches to modeling historic spatio-temporal variability in fire frequency from fire scar data. IAWF 2nd Fuels and Fire Behavior Conference, Destin, FL (poster).

Guyette, R.P., M.C. Stambaugh, and D.C. Dey. A calibration of temperature and fire frequency. American Geophysical Union (AGU) Fall Meeting, San Francisco, CA (oral presentation).

2006

Stambaugh, M.C., R.P. Guyette. Continental- and landscape-scale approaches to modeling historic spatio-temporal variability in fire frequency from fire scar data. 7th International Conference on Dendrochronology, Beijing, China (poster).

Guyette, R.P., M.C. Stambaugh, R.M. Muzika, and D.C. Dey. Mapping historic fire intervals in North America using fire scars, temperature, precipitation and human population. Ecological Society of America annual meeting, Memphis, TN (poster).

Guyette, R.P., M.C. Stambaugh, and D.C. Dey. Mapping historic fire intervals in North America using fire scars, temperature and human population. International Association of Landscape Ecologists Workshop, Beijing, China (oral presentation).

Graduate Education

Bale, A.M. 2009. Fire effects and litter accumulation dynamics in a montane longleaf pine ecosystem. M.S. Thesis, University of Missouri-Columbia (Advisor: Dr. Richard Guyette). http://edt.missouri.edu/Spring2009/Thesis/BaleA-051109-T950/research.pdf

Publications in Print/in Press

Stambaugh, M.C., R.P. Guyette, E.R. McMurry, and D.C. Dey. 2008. Lessons from fire history, past and future: a regional workshop on eastern U.S. fire history. Missouri Wildlife 69(2):6. (http://web.missouri.edu/~guyetter/stambaugh_etal_2008a.pdf)

Bale, A.M., Guyette, R.P. and M.C. Stambaugh. 2008. Fire regime of a montane longleaf pine ecosystem, Alabama. Pages 54-59 In: Third Montane Longleaf Conference Proceedings; 2008 March 11-12; Auburn, AL. School of Forestry and Wildlife Sciences, Auburn University. http://web.missouri.edu/~guyetter/bale_etal_2008.pdf

McMurry, E.R., M.C. Stambaugh, R.P. Guyette, and D.C. Dey. 2007. Fire scars reveal source of New England's 1780 Dark Day. International Journal of Wildland Fire, 16(3): 266-270. http://web.missouri.edu/~stambaughm/2007_McMurry_DarkDay.pdf

Publications under review

Guyette, R.P., M.C. Stambaugh, D.C. Dey, and R. Muzika. In review. Climate forcing of fire frequency on a continental scale.

Stambaugh, M.C., R.P. Guyette, and J. Marschall. In review. Longleaf pine (*Pinus palustris* Mill.) fire scars reveal new details of a frequent fire regime.

Publications in preparation

Bale, A.M., Guyette, R.P., and Stambaugh, M.C. In prep. Fire effects and litter accumulation dynamics in a montane longleaf pine ecosystem.

Stambaugh, M.C. and R.P. Guyette. In prep. Contrasting fire histories at The Land Between the Lakes, Kentucky.

Muzika, R., Guyette, R.P. and Stambaugh, M.C. In prep. Fire regime dynamics of the Huron Mountains, Upper Peninsula, Michigan.

Archived Fire History Data

Paleoecological data are archived at: IGBP PAGES/ World Data Center for Paleoclimatology Data. NOAA/NGC Paleoclimatology Program, Boulder, CO, USA. http://www.ncdc.noaa.gov/paleo/paleo.html. These data constitute annually resolved historic fire event dates.

Submitted
Hatton Ridge (HTN), Kentucky, Daniel Boone National Forest
Kisatchie Hills (KIS), Louisiana, Kisatchie National Forest