# FIRE SCARS REVEAL VARIABILITY AND DYNAMICS OF EASTERN FIRE REGIMES

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**Abstract.**—Fire scar evidence in eastern North America is sparse and complex but shows promise in defining the dynamics of these fire regimes and their influence on ecosystems. We review fire scar data, methods, and limitations, and use this information to identify and examine the factors influencing fire regimes. Fire scar data from studies at more than 40 sites in Eastern North America document fire regimes in forests with oak. Fire frequency was highly variable in both time and space even at regional scales (less than 500,000 ha). Many sites burned frequently (2- to 3-year mean fire intervals) while nearby sites (less than 40 km distant) burned infrequently (mean fire intervals more than 20 years). The fire scar record shows that major factors controlling temporal differences in fire regimes are changes in human population density, culture, and annual drought. Spatial differences in fire regimes are influenced by regional temperature, human population density, and topographic resistance to the spread of fire. Severe fire years (more than 10 percent of trees scarred at the sites) were associated with strong regional droughts that covered most of the Eastern United States and southern Ontario, Canada. Major fire years in Eastern North America occurred about 3.6 times per century before suppression efforts in forests with an oak component. Fire regimes with numerous human ignitions were more influenced by droughts. We synthesize mean fire intervals during the pre-European settlement period using an empirically derived regression model. The model was developed using two variables to predict broad scale spatial differences in fire frequency based on fire interval data derived from dendrochronologically dated fire scarred trees. Sixty-three percent of the variance in mean fire intervals was explained by mean maximum temperature and 12 percent by mapped human population density and historical documentation. The model is used to map coarse scale fire intervals in forested regions of the Eastern United States.

## INTRODUCTION

Wildland fire is an important disturbance influencing oak forests (Johnson et al. 2002; Wade et al. 2000). Changing forest composition and fire risk have given the history of wildland fire regimes new relevance. Owing to the longevity of trees, forest composition often changes slowly in response to fire and at time scales well beyond the lifespan of single human observers. To understand how and why forests are changing, we often can benefit from a longer-term perspective. Dendrochronology can provide this perspective with high resolution spatio-temporal data for periods of more than 300 years (several generations of trees) in Eastern North America. This period spans changes in human societies from subsistence to fire suppression. Tree-ring dating of fire scars and climate reconstructions from the width of tree rings provide long records of fire dates, fire locations, and drought. We examine fire history in forests of Eastern North America during the last three centuries, emphasizing forests that have an oak (*Quercus* spp.) component. We document and analyze fire regimes using dated fire scars and examine variables that are hypothesized to influence these fire regimes. Fire scar data from more than 60 sites in 16 states and the province of Ontario (Table 1) are used to document fire regimes and examine their temporal and spatial variability. To present a more balanced regional analysis and overview, we excluded a considerable amount of data from Missouri (more than 20 fire history sites).

Dendrochronological analysis of fire scars and the reconstruction of fire history from scar data have many positive and precise features as well as limitations. Fire scars on oaks provide a detailed record of fire events, such as exact locations and dates (Guyette and Stambaugh 2004; Smith and Sutherland 1999). Each fire scar potentially has a spatial resolution of less than 1 m and a temporal resolution of less than one year. These characteristics generally set this method apart from other

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**Table 1.—Mean fire intervals from fire scar studies in eastern North America (NH = northern hardwoods, CH = Central Hardwood, SP = Southern Pine-Hardwoods, PT = Prairie-Forest Transition; na = not available)**

| Site name | State | Forest Type | Trees and forest type | Pre-Euro-fire interval | Post- Euro-fire interval | Site data reference |
|---|---|---|---|---|---|---|
| Green Mts. | VT | NH | red pine forest | na | 18 | Engstrom and Mann 1991 |
| Basin Lake | ON | NH | pine-oak woodland | 21 | na | Guyette and Dey 1995a |
| Papineau L. | ON | NH | oak-pine forest | 29 | 7 | Dey and Guyette 2000 |
| Opeongo | ON | NH | pine-hardwoods | 29 | 25 | Guyette and Dey 1995b |
| Bracebridge | ON | NH | red oak forest | 11 | na | Guyette and Dey 1995c |
| Joko | ON | NH | pine hardwoods | 13 | na | Dey and Guyette 2000 |
| Seagan | ON | NH | pine hardwoods | 17 | na | Dey and Guyette 2000 |
| Sault Ste. Marie | ON | NH | pine hardwoods | 26 | 73 | Alexander et al. 1979 |
| Big Bay | MI | NH | pine- hardwoods | 25 | na | Torretti 2003 |
| Itasca SP | MN | NH | conifer hardwood | 25 | 36 | Spurr 1954 |
| Itasca SP | MN | NH | conifer-hardwood | 29 | 13 | Clark 1990 |
| Itasca SP | MN | NH | conifer-hardwoods | 30 | 9 | Frissell 1973 |
| Costal sand | MI | NH | costal pine forests | 18 | 88 | Loope and Anderton 1998 |
| Upland sand | MI | NH | upland pine forests | 23 | 29 | Loope and Anderton 1998 |
| Savage Mt. | MD | CH | oak forest | 8 | 8 | Shumway et al. 2001 |
| Oreton | OH | CH | white oak forest | na | 4 | Sutherland 1997 |
| Pike Knob | WV | CH | white oak forest | na | 14 | Schuler and McClain 2003 |
| Lemm Swamp | TN | CH | oak woodlands | 5 | 8 | Guyette and Stambaugh 2005 |
| Saltwell | TN | CH | oak woodlands | 6 | 8 | Guyette and Stambaugh 2005 |
| Richland Creek | TN | CH | oak woodlands | 5 | 4 | Guyette and Stambaugh 2005 |
| Huckleberry | TN | CH | oak woodlands | 6 | 4 | Guyette and Stambaugh 2005 |
| Boone Barrens | IN | CH | oak savanna | 19 | 5 | Guyette et al. 2003 |
| Brush Mt. | VA | CH | pine – hardwood | na | 8 | Sutherland et al. 1992 |
| Mill Hollow | MO | CH | oak-pine forest | 6 | 2 | Guyette and Cutter 1997 |
| MOFEP 4 | MO | CH | oak –pine forest | 3 | na | Guyette and Stambaugh 2004 |
| MOFEP 5 | MO | CH | oak –pine forest | 4 | na | Guyette and Stambaugh 2004 |
| Mahans Crk. | MO | CH | oak –pine forest | 3 | 4 | Guyette and Cutter 1997 |
| Mill Creek | MO | CH | oak-pine forest | 4 | 4 | Guyette and Cutter 1997 |
| Hartshorn | MO | CH | oak-pine woodland | 3 | 2 | Guyette and Cutter 1997 |
| Shannondale | MO | CH | oak forest | 13 | 4 | Guyette and Cutter 1997 |
| Gee Creek | AR | CH | oak-pine forest | 15 | 2 | Guyette and Spetich 2003 |
| Gobblers Knob | AR | CH | oak-pine forest | 16 | 2 | Guyette and Spetich 2003 |
| Vermillion | MO | CH | pine-oak forest | 3 | na | Guyette 1997 |
| Rd1645 | MO | PT | oak woodland | 4 | 8 | Cutter and Guyette 1994 |
| Pleasant Prairie | WI | PT | oak savanna | na | 7 | Wolf 2004 |
| Ava Glades | MO | PT | redcedar-oak glades | 6 | 11 | Guyette and McGinnes 1982 |
| White Ran. | MO | PT | oak woodland | 4 | 8 | Dey et al. 2004 |
| Caney Mt | MO | PT | oak savanna | 5 | 7 | Guyette andCutter 1991 |
| Loess Hills | MO | PT | bur oak woodland | 8 | 4 | Guyette and Stambaugh 2005 |
| Granny Gap | AR | SP | pine–oak forest | 5 | 4 | Guyette and Spetich 2003 |
| Chigger Rd | AR | SP | pine-oak forest | 13 | 2 | Guyette and Spetich 2003 |
| GSMNP | TN | SP | pine – oak forests | na | 13 | Harmon 1982 |

**Table 2.—Methods of documenting fire history, their data acquisition and characteristics**

| Method | Sources | Resolution | Time depth | Limitations and advantages |
|---|---|---|---|---|
| Dendrochronology | Crossdated fire scars from trees, remnant wood. Also ring widths, stand age | Seasonal to annual with high precision | Commonly two to four centuries, rarely more | Stand replacement fires not well documented, high resolution in time and space |
| GLO notes | Historical archives | None | About 150 to 200 years ago | Inferential, spatially explicit information |
| Charcoal sediment | Lakes, peat | Variable, decadal to centuries | Centuries to 12,000+ years | Local sources and low resolution, long-term data |
| Written accounts | Historical literature and travel accounts | Low to daily in journals | About 500 years | Nonquantitative, often biased, includes cultural information |
| Alluvial charcoal | Alluvial sediments | About 500 years or the limits of carbon dating | 1000 to 20,000+ years | Low resolution, record of large, intense, sediment-producing fires |

fire history methods (Table 2). However, a number of problems may arise when developing and interpreting the fire scar record. A woody growth increment without a scar is only weak evidence of "no fire" because many trees are resistant to scarring. In Eastern North America, challenges often arise when constructing fire scar histories, such as the limited availability of preserved fire scars, limited abundance of closely spaced recorder trees, differences in record length, and sampling methods that are defined by the limits of the resource. However, even studies with the most severe sampling problems rise above the alternative: an absence in our knowledge of fire history. Problems in developing fire history from fire scars (and how we address them in this paper) include:

1. *Problem:* Many trees have thick bark and are not scarred in fires. Thus, the lack of a scar does not mean the absence of fire. *Solution:* Minimize the use of studies based only on a single or several trees.

2. *Problem:* Stand replacement fires are not included in fire scar studies because all fire scars occur on survivor trees. *Solution:* Infer from the number of trees scarred when larger and more severe fires occurred.

3. *Problem:* Tree species differ with respect to recording fire history. This can result in errors when comparing histories. *Solution:* Sample a sufficient number of trees to develop a composite fire interval that reflects the actual frequency of fire in an area.

4. *Problem:* Spatial extent of a study site influences the inferred fire frequency. *Solution:* Confine analysis to sites of several hundred hectares (less than 4 $km^2$)

5. *Problem:* The number of sample trees in any given year may affect the number of fires detected. *Solution:* Truncate data from early periods when there were few recorder trees in the record.

6. *Problem:* Many fire scar chronologies have long, open-ended intervals that cannot be interpreted as true intervals. *Solution:* Estimate mean fire intervals as years per fire.

The goals of this review and synthesis are to examine the long-term and large-scale factors that affect the spatial and temporal variability of fire regimes in Eastern North America. Specific objectives are to examine climate,

**Table 3.—Number of fire scar history studies and sites by Ecoregion**

| Ecoregion | Forest type | Studies | Sites |
|---|---|---|---|
| Warm continental | Northern hardwoods | 13 | 17 |
| Hot continental | Central hardwoods | 25 | 60 |
| Subtropical | Southern pine hardwoods | 1 | 1 |
| Prairie | Forest prairie transition | 6 | 6 |

human, and landscape influences on fire regimes using data from existing fire scar histories in the eastern oak forests. We present a preliminary synthesis via regression modeling, using the effects of temperature and human population on fire regimes.

## REVIEW

Numerous studies (Table 1) have used fire scar data to reconstruct fire history from the four major oak ecoregions and forest types of Eastern North America (Bailey 1997; Johnson et al. 2002). The number of quantitative fire scar histories varies widely among ecoregions (Table 3). Both a lack of scientific inquiry and the scarce availability of datable fire scarred materials contribute to this disparity. Northern Hardwood studies are located in Minnesota (Frissell 1993; Clark 1990; Heinselman 1973; Spurr 1954), Michigan (Torretti 2003), Ontario (Dey and Guyette 2000; Cwynar 1977), and Vermont (Engstrom and Mann 1991). Central Hardwood studies are located in Missouri (Guyette and Kabrick 2003; Guyette et al. 2002; Batek et al. 1999; Guyette and Cutter 1997), Indiana (Guyette et al. 2003), Tennessee (Guyette and Stambaugh 2005; Harmon 1982; Armbrister 2002), Ohio (Sutherland 1997), West Virginia (Schuler and McClain 2003), Virginia (Sutherland et al. 1992), and Maryland (Shumway et al. 2001). Although there are studies for the southern pine-oak region (DeVivo 1991, Van Lear and Waldrop1989), few are fire history studies from fire scars. There are three fire scar sites on the edge of the southern pine-oak region in the Lower Boston Mountains of Arkansas (Guyette and Spetich 2003). Forest-prairie transition sites are on the edge of the Great Plains (Guyette and Stambaugh 2005), the oak savannas of Wisconsin (Wolf 2004), the oak woodlands and savannas of south-central Missouri (Cutter and Guyette 1994; Guyette and Cutter 1991; Dey et al. 2004), and redcedar glades of southwestern Missouri (Guyette and McGinnes 1982).

The Warm Continental-Northern Hardwoods region has several robust fire histories, though most are in forest types with moderate to low oak abundance. Several of these were not based on fire scars or derived from precisely crossdated tree rings (Whitney 1986; Heinselman 1973). Nine studies in this region had an average mean fire interval (MFI) of 23 years, with a range from 11 to 33 or more years before European settlement (ca. 1650 to 1850).

The Hot Continental-Central Hardwoods region is fairly well represented, especially in its western half. Here, many studies indicate a high frequency of burning in oak and oak-pine forests. Fifteen studies had an average MFI of 8 years, with a range from 3 to 21or more years before European settlement. However, in some areas of the Ozarks, high variability in fire frequency can be found within small extents (e.g., 3 km) (Guyette et al. 2002).

Unfortunately, little quantitative fire scar data are available for the Subtropical-Southern Pine-Hardwoods (Table 3). For this review we used sites (Guyette and Spetich 2003) on the edge of this ecoregion in Arkansas. Three upland forest sites in Arkansas had an average MFI of 11 years, with a range from 5 to 16 or more years before European settlement. The topographic roughness and low population density of these sites during this period probably do not represent the region as a whole. However, the southern pine-oak region has a number of species and ecosystems with potential fire scar data, and represents excellent future opportunities for documenting fire history. "Yellow pine" species often have resinous wood that preserves well for at least a

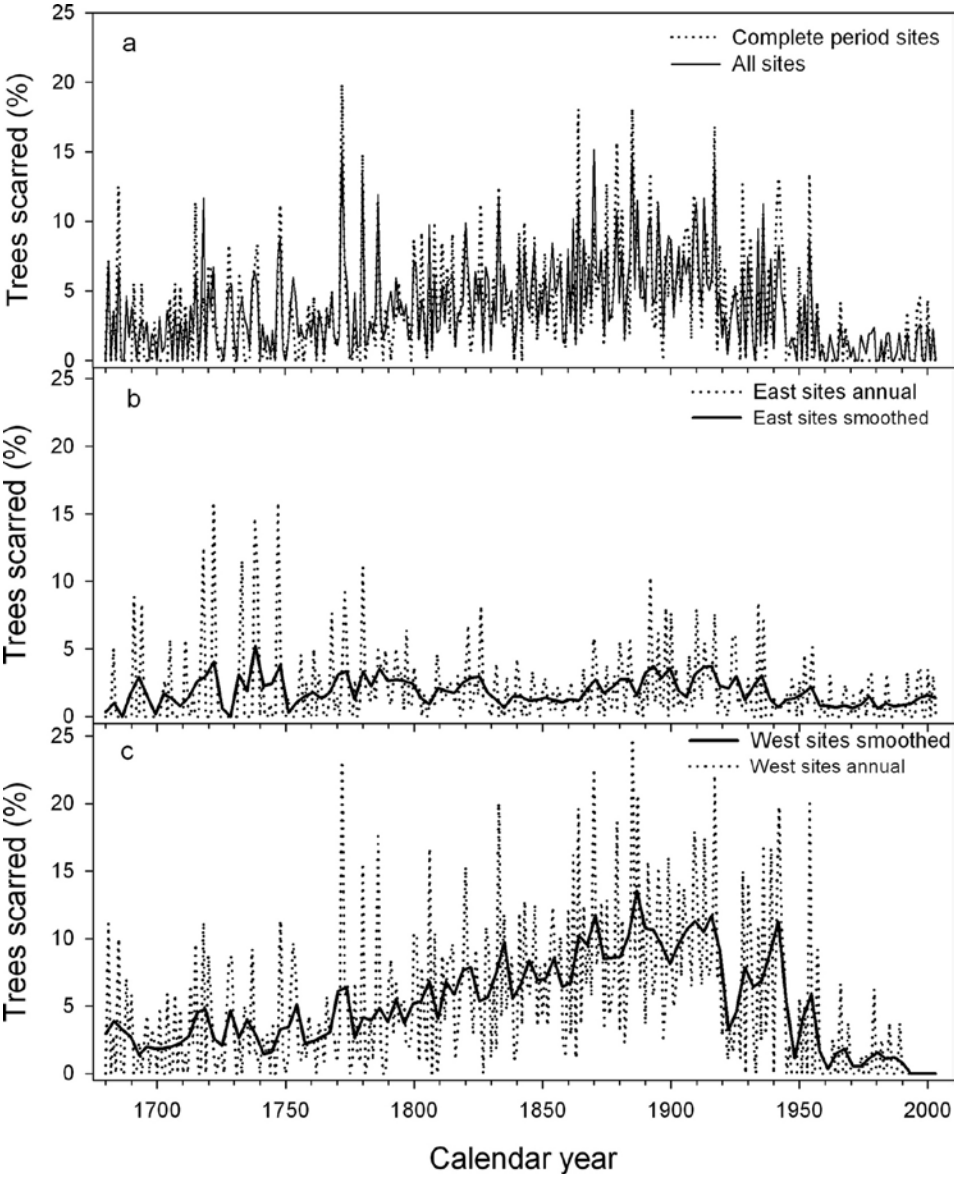


Figure 1.—Time series of percent trees scarred at sites in or near forests with an oak component in Eastern North America. The "complete period site" chronology (a, doted line) is compiled from fire scar chronologies that cover the whole or nearly the whole time period. The "all sites" chronology (a, solid line) is compiled from all fire scar chronologies regardless of length. The eastern chronology (b) is from sites in Ontario, Maryland, Indiana, Tennessee, West Virginia, Virginia, and Ohio. The western chronology (c) is from Arkansas, Missouri, Wisconsin, Minnesota, and Michigan. See Table 1 for Eastern North American site references.

century after the death of the tree. Live and recently dead oaks of the white oak group also can provide excellent fire histories.

The forest-prairie transition region is represented by several studies in Missouri and Wisconsin, that focus on conditions from oak woodlands and savannas to cedar glades. Five sites in the forest prairie transition had an average MFI of 5 years, with a range from 3 to 8 years or more years before European settlement.

The fire scar record (Fig. 1a-c) as indicated by the studies cited, provides the timing and magnitude of fire events that can be linked to climate. However, the timing of annual fire dates is less than exact within a given year due to the nature of tree growth and fire scars. Fires

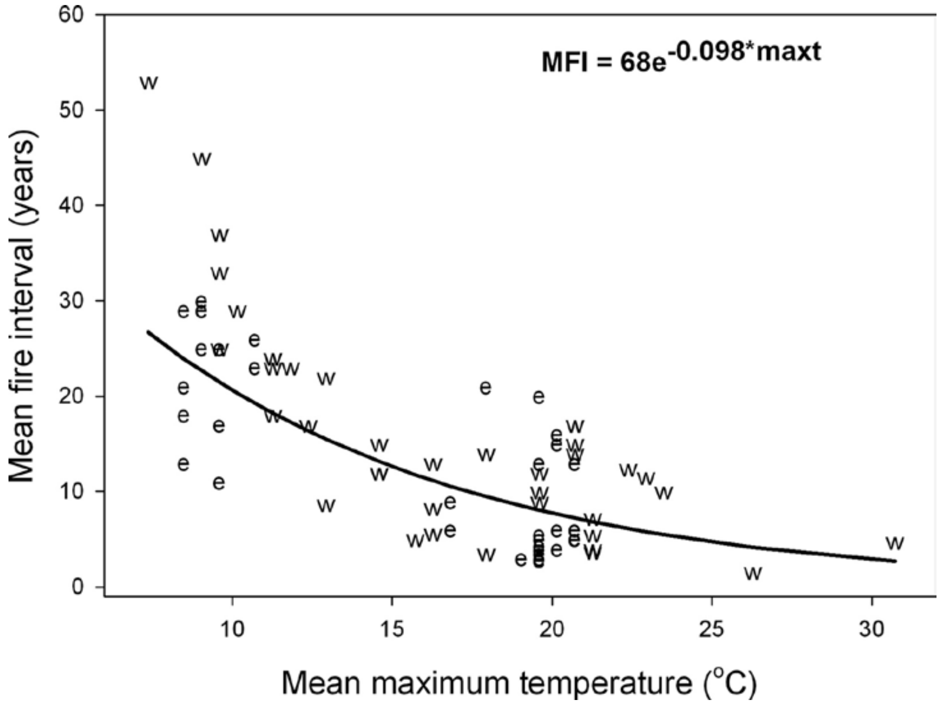


Figure 2.—Mean fire intervals (MFI) predicted from proxy mean maximum temperature (maxt). Mean fire intervals are for the pre-Euro American period (ca.1650 to 1850). Temperature is the average annual mean maximum temperature for 1971 to 2000 minus 0.4 ºC for North American warming. Eastern North American sites are denoted by "e:" while western North American sites are denoted by "w"; fire scar data are from 79 sites with more than 1,500 trees and 10,000 fire scars. See Table 1 for Eastern North American (e) site references and the Model Development section of this paper for western North American (w) site references. The equation in the upper right describes the regression line.

can be dated to the early, mid, and late parts of the growing season or to the dormant season (generally October through April). Fire scar evidence from eastern forests indicates that fires in oak ecosystems occur most frequently during the dormant season of tree growth. Of the 60 or more study sites in eastern North America in which the authors have been involved, about 95 percent of the fire scars occurred between annual rings during the dormant season. This probably results from surface fuel characteristics such as the quantity of leaf litter, its density and arrangement, and its potential moisture content all of which increased during leafoff and can lead to more pyrogenic conditions. The season of burning is greatly restricted by primary fine fuels as the controller of fire propagation. Surface fuels in deciduous forests have more and potentially drier litter when the leaves have fallen. Full summer canopies mitigate the loss of litter moisture and fuel temperature by decreasing solar exposure.

## Factors influencing fire intervals

### Spatial and Temporal Climate Differences

Climate is a pervasive factor in all fire regimes and has complex effects at multiple spatial and temporal scales. Spatially, we address regional climate differences as well as the effects of year-to-year climate variability on fire history sites. The duration of fuel conditioning, the duration of snow cover, the length and intensity of the warm season, and primary productivity are tied to temperature and precipitation. The correlation between annual mean maximum temperature (proxy period: 1971 to 2000) and pre-European settlement mean fire intervals at 38 sites (Table 1) is significant ($p < 0.001$) and strong ($r = -0.73$, Fig. 2), indicating that temperature likely influences many biotic and abiotic factors that control fire regimes. Precipitation also was significantly correlated ($r = -0.56$, $p < 0.01$) with fire intervals. The negative correlation value reflects the association of shorter intervals between fires occurring at sites with higher amounts of precipitation. In some ways this is counterintuitive since wetter conditions can create shorter fire windows and higher fuel moisture; however, increased precipitation generally leads to higher primary productivity and potential more rapid fuel accumulation. Thus, regional climate parameters, particularly mean maximum temperature and precipitation, may have a major influence on fire regimes.

Temporally, the effects of yearly to monthly differences in climate, particularly drought, are obvious and important to fire occurrence and fire regimes. Equally important in eastern deciduous forest ecosystems are

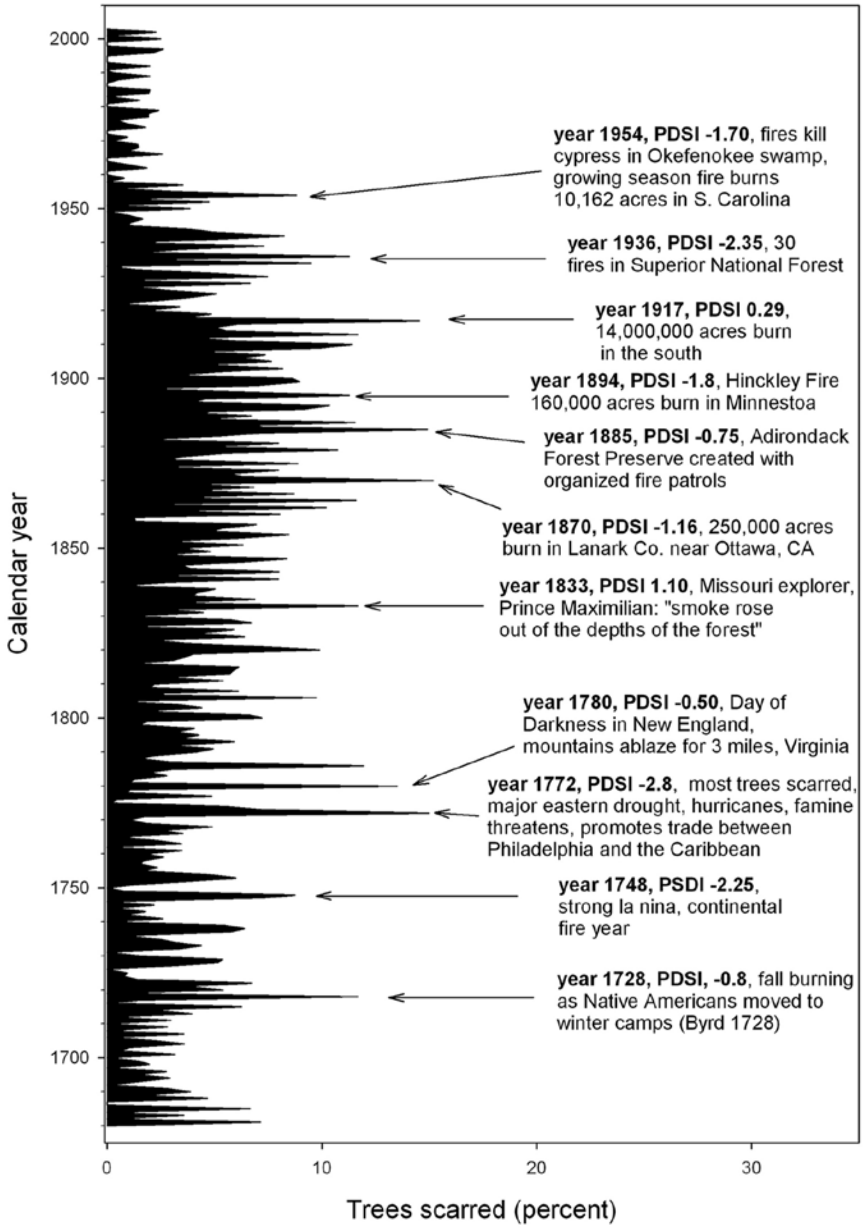


Figure 3.—Percentage of trees scarred at sites with fire scar chronologies in Eastern North American, illustrating the connection between the fire scar record and historical documentations of fire history. PDSI is the reconstructed Palmer drought severity index (Cook et al. 1999). Negative values denote increasing drought.

conditions during leafoff, particularly spring and fall season drought. Our preliminary correlation analysis of drought and fire extent and severity (percent trees scarred) shows that annual reconstructed drought indices (Cook et al. 1999) are weakly ($r < 0.2$) but significantly ($p < 0.05$) associated with the percentage of trees scarred at various sites in Eastern North America, particularly those in the western portion. Fire occurrence and percent trees scarred in eastern oak forests were only weakly related to reconstructed annual drought over the past three centuries. This probably results from limitations of drought reconstructions and their resolution, and asynchrony between fire occurrence (dormant season) and the bases of reconstructed drought (growing-season ring width). However, in years when many sites and trees were scarred in Eastern North America, there is evidence for widespread drought that continues through growing and dormant seasons (Fig. 3). Eight of ten of the largest fire years occurred during severe droughts. We judge by the percentage of trees scarred (years with twice the average percent trees scarred) that major fire years in Eastern North America occurred about 3.6 times per century before fire suppression efforts in forests with an oak component. These large fire years often are associated with historical documentation (Fig. 3) of smoke, wildfire, and fire prevention.

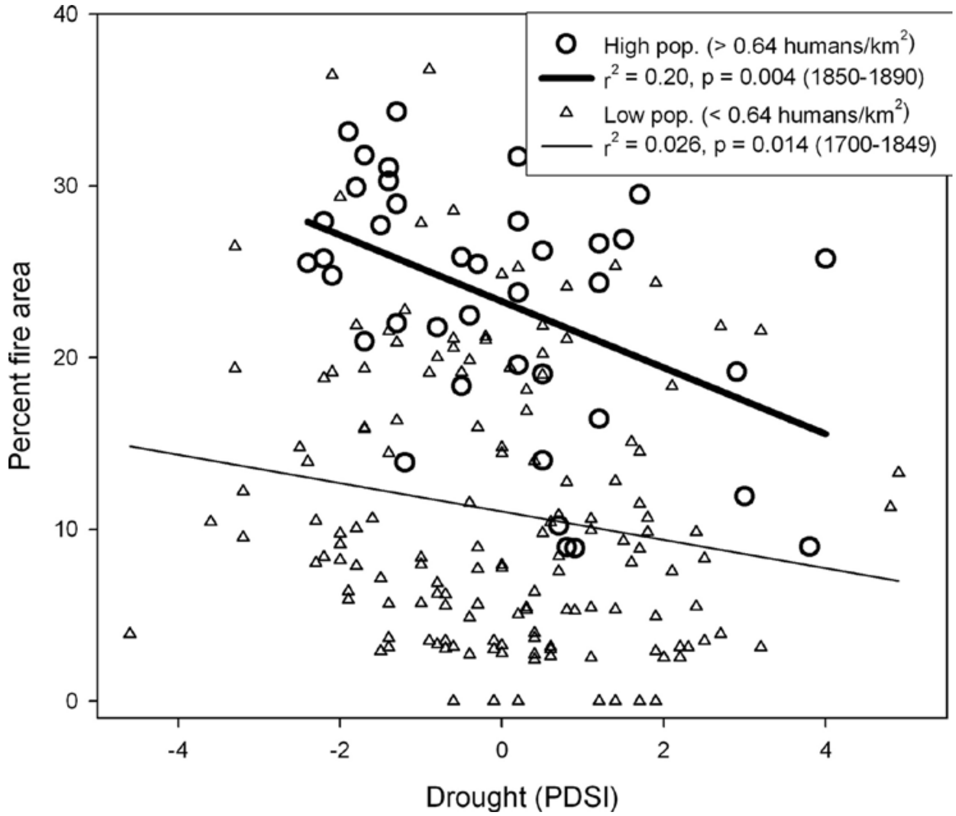


Figure 4.—Regression lines indicate the increased strength of the drought-fire relationship during periods of high versus low human population density. Fire data are from more than 2500 dated fire scars at 27 sites in the Current River region of the Ozark Highlands between 1700 and 1890. Fire area is based on the product of the percent of trees and the percent of sites burned annually. PDSI is the reconstructed Palmer drought severity index (Cook et al. 1999).

The fire scar record illustrates that drought-fire associations are not fully realized in the absence of numerous ignitions, as many severe droughts result in no fire events. Human population density influences the relationship between drought and wildfire by increasing ignitions. In fire regimes with few lightning ignitions, the effects of drought on fire occurrence often are unrealized until human ignitions become abundant. For example, in the Ozark Highlands, the extent of wildfire is moderately correlated (r = -0.44, p = 0.004) with drought during periods with abundant anthropogenic ignitions (1850 to 1890) but weakly correlated (r = -0.15, p = 0.014) during periods with low human population density (1700 to 1849) (Fig. 4). This supports the hypothesis that humans may have played a significant role in past fire regimes.

When interpreting fire scar records, a common assumption is that years with a higher percentage of trees scarred result solely from the effects of drought on fuels and scarring. However, it is possible that many past wildfires were the result of climate-conditioned fuels *and* numerous drought-inspired human ignitions. While one might expect an increase in fires owing to accidental ignitions during drought periods, there is no necessary causation between drought and the number of intentional fires. This theory is supported by consistent correlations between drought and arson documented by the modern fire record. For example, fire season drought is significantly correlated with the number of arson fires in the Eminence Fire Protection District (1970 to 1989) in the Missouri Ozarks (*r* = -0.76). On a larger scale, drought and the number of arson fires summarized by

**Table 4.—Relationship between number of arson fires and drought by state (Drought data are the annual Palmer Drought Severity Index; the lower the value of this index, the more severe the drought; thus, the negative correlation between drought and arson; correlation coefficients in bold are significant at ($p<0.05$); fire data: U.S. Dep. Agric. 1940-1997)**

| State | Correlation (No. arson fires and drought) | Mean no. arson fires | Mean no. lightning fires | No. of years of data |
|---|---|---|---|---|
| Missouri | -0.39 | 1069 | 20 | 48 |
| Arkansas | -0.61 | 1638 | 85 | 48 |
| Illinois | -0.49 | 46 | 0.72 | 48 |
| Indiana | -0.29 | 36 | 1.7 | 48 |
| Tennessee | 0.04 | 1148 | 12 | 48 |
| S. Carolina | -0.36 | 1918 | 58 | 48 |
| Florida | -0.42 | 2769 | 580 | 48 |

**Table 5.—Effects of topographic roughness on mean fire intervals at increasing human population densities (topo-resistance refers to the resistance of a landscape to the propagation of fire); details on the calculation of topographic roughness indices found in Guyette et al. 2002; Peak mean fire intervals are for the first decades of most frequent burning**

| Site Group | Number sites | Topo-resistance | Roughness index | MFI at peak | Population at peak no./km$^2$ | Year at peak |
|---|---|---|---|---|---|---|
| Boston Mts., AR | 6 | high | 1.08 | 2.7 | 5.5 | 1875 |
| Current River, MO | 10 | moderate | 1.020 | 3.5 | 0.64 | 1850 |
| Highland Rim, TN | 4 | low | 1.0004 | 2.3 | 0.50 | 1770 |

year and state are significantly correlated (Table 4) (U.S. Dep. Agric. 1940-1997). Thus, during much of our history, and even during the recent period of societal pressure and legal penalties for arson, humans are still purposefully burning landscapes during droughts.

## Topographic Resistance to Fire Propagation

The frequency of fire is a function of two types of ignitions: local and neighboring. For example, fires at a site 1 to 3 km$^2$ in area result from ignitions produced locally (new ignitions within the site) or from the propagation of ignitions into the site by a spreading fire. Thus, fire frequency at a site is both a product of local ignition and the resistance of the surrounding landscape to the propagation of fire. Part of this resistance is a function of topographic features such as hills, valleys, and bodies of water that disrupt the continuity of fuels (Guyette and Stambaugh, in press). For example, the highly dissected topography of the Current River watershed in Missouri has been shown to be related to the frequency of fires during periods of low human population density, when anthropogenic ignitions were limited in number (Guyette et al. 2002; Guyette and Dey 2000). In topographically rough terrain, low-intensity surface fires are impeded by steep slopes, discontinuous fuels, and variability in fuel moisture and fuel loading. In addition, topographic roughness likely mitigates the effect of increasing anthropogenic ignitions as many more human ignitions are required to maintain the same mean fire interval compared to less topographically rough regions (Table 5). Thus, at the time of Euro-American settlement, short fire intervals (1 to 3 years) in topographically rough landscapes occur at later dates as human populations increased. Before

1875, about 10 times as many humans were required to maintain a fire frequency of less than 3 years in the topographically rough Boston Mountains, Arkansas, as were required in the Oak Barrens of the Highland Rim in middle Tennessee (Table 5).

## Fire and Culture

Of all of the cultural aspects affecting wildland fire, none have been as profound and effective as suppression efforts enabled by the modern technologies of ground and air transportation. Although grazing, landscape fuel fragmentation, intentional burning, and other cultural influences have been detected in fire scar records, these effects are not as pronounced as fire suppression in modern industrial societies. All but a handful of fire scar chronologies show a significant decline in fire frequency in the mid to late 20th century. The few fire scar chronologies that do not have a decline in fire frequency often are derived from private lands with owners who have a tradition of burning, or are in remote regions with long response times in fire protection (Jenkins 1997).

Before fire suppression, cultural values concerning wildland burning are not evident in the fire scar record and may be secondary to increasing anthropogenic ignitions as a function of human population density. In many environments, humans are a fire obligate species. Accidental ignitions, purposeful ignitions, machine fires, and debris burning are a few of the hundreds of human activities that can result in wildland fires. The sheer number of humans in an ecosystem may be more important than their cultural attitudes about the use of fire. Unlike fire frequency, which is tempered by fire suppression, fuel fragmentation, and reduction, the number of ignitions continues to rise with increasing human population.

The fire scar record suggests that *Homo sapiens* is a keystone species in many fire regimes. A keystone species influences the "environmental balance of an area or habitat" through a chain of events (e.g., trophic, reproductive, or abiotic modifications). Keystone species have a disproportionate influence on community structure in excess of their abundance. The fire scar record indicates that even at low population densities, humans had a profound effect on fire regimes and vegetation (Batek et al. 1999; Guyette and Kabrick 2003). The influence of a keystone species is derived from the ability to control the most competitive species (i.e., tree species). Temporally and spatially, fire scar frequency has been associated with the presence of humans. The absence of a keystone species releases highly competitive plants (trees) from the limiting effects of fire and allows them to exclude other plants and their herbivores. In forested regions, fire scar frequency increases rapidly as humans culture the forest for both wild and domestic large herbivores. The theory that humans are a keystone species in fire regimes may be especially relevant in Eastern North America, where climate windows suitable for burning often are short and the probability of natural ignitions is low. The fire scar record in Eastern North America is only weakly related to the abundance of lightning fires as documented later in this paper. Unlike lightning, humans can target their ignitions with respect to fuel conditions and location.

## Population Density and Anthropogenic Ignition Rates

Since the entry of *Homo sapiens* into North America more than 12,000 years ago, humans have been the dominant ignition factor in many ecosystems. Although some have argued that there were not enough humans to impact flora and fauna at regional levels, the fire scar evidence suggests otherwise. Few humans are necessary to add a significant level of fire disturbance. The topographically rough Missouri Ozarks reach ignition saturation at about 0.64 human per km$^2$ or less (Guyette and Dey 2000). The rougher Boston Mountains of Arkansas reach ignition saturation at about four or five humans per km$^2$. The smooth oak flats of the Highland Rim in middle Tennessee reach ignition saturation at about 0.50 human per km$^2$. Even at relatively low human population densities in a moderately dissected landscape (e.g., Missouri Ozarks) mean fire intervals of 10 years were supported by populations of less than 0.10 human per km$^2$ during a "depopulated" period (1680 to 1800).

A theoretical analysis of scenarios of human population density, ignition type, and culture illustrates the potential influence of anthropogenic ignitions in past fire regimes and consistency with the fire scar record. The population of North America (north of Mexico) has been estimated to be from 1 million to more than 10 million at the time of first contact and before population reductions by a variety of agents, e.g., introduced diseases. We chose the conservative estimate of about 1 million humans for this analysis. We used 500,000 humans for the estimate of population in the Eastern United States and southeastern Canada. The study area in eastern North America is about 3,024,000 $km^2$. We then subtracted the area of the Great Lakes (245,000 $km^2$) to obtain an area of 2,779,000 $km^2$. Although rough, this estimate is more precise than population estimates. Thus, population density roughly averaged 1 person for every 5.5 $km^2$, or 0.18 human per $km^2$ (500,000 humans/2,779,000 $km^2$). Given this population density, we generate quantitative scenarios of the rates of purposeful and accidental ignitions. Present-day rates of human-caused fires in forested areas of the Missouri Ozarks average one wildfire per 350 humans per year (0.0029 fire/human/yr). This rate occurred during an era of fire suppression (1991 to 2003), laws and societal pressures against burning, relatively few open fires (e.g., camp fires) per person, and limits on fire propagation imposed by land fragmentation. This rate applies to all arson (31 percent) and accidental fires (66 percent). Prior to European settlement, if the people of a culture viewed fire neutrally, the rate of ignitions by humans might be 10 times this amount (0.029 fires/human/yr). Thus, based on a pre-European settlement population and a neutral fire culture, the rate for human ignitions would be 0.0052 human-caused fires per $km^2$ per year (i.e., 0.029 fire/human/yr multiplied by 0.18 human per/$km^2$). This translates to a single human ignition for every 190 $km^2$ per year. If the people of a culture purposely used wildland fire as a tool (for many possible reasons) the rate of human ignitions might be 100 times greater, or 0.052 human ignition per $km^2$/year (i.e., 0.29 fire/human/yr multiplied by 0.18 human per/$km^2$). This translates to a single human ignition for every 19 $km^2$ per year. This rate (0.052 human-caused fire/$km^2$/yr) is about 200 times the rate of lightning ignition in the Central Hardwoods region (0.00025/ $km^2$/year) (Schroeder and Buck 1970). For example, if the average fire size was 1.9 $km^2$, this rate of ignition would maintain a fire rotation interval of about 10 years. This scenario and fire interval is not unlike the rate of burning (13 percent sites scarred annually) that occurred in 1790 in the moderately rough Current River landscape at population levels of about 0.017 human/$km^2$ (Guyette et al. 2002). The anthropogenic ignition rate is potentially much greater if intentional burning occurs (Williams 2000, Williams 2001). We conclude that even low levels of human population density combined with a culture of landscape burning were sufficient to provide levels of ignitions needed to maintain the fire frequencies we document with fire scars in Eastern North America.

## SYNTHESIS AND MODELING OF PRE-EUROPEAN FIRE INTERVALS

Quantitative and empirically derived models of fire regimes can be used in many ways. Models allow past fire regimes to be estimated for ecosystems that have no on-site fire history information. Models can be used in conjunction with soil, geology, and species data to reconstruct past and potential flora and fauna. Thus, land managers interested in returning ecosystems to pre-European settlement conditions (including fuels) using prescribed fire can utilize models to estimate components of fire regimes including fire frequency. Researchers can use equations of this type to create a continuous landscape overlay of past fire frequency. Models without vegetation input also can be useful for independently estimating fire frequency at research vegetation plots, and for making inferences about possible changes in future fire regimes due to changes in population and climate. The preliminary results of the modeling that follows should be used with caution as they are temporally and spatially coarse scale, requiring additional validation and data from many regions of Eastern North America. Perhaps the most important aspect of fire interval models and fire history may not be the information provided on fire regimes but the perspective provided on the long-term interactions between humans and their environment.

### Model Development

A preliminary model that predicts mean fire intervals for eastern oak forest ecosystems before European settlement was developed from fire scar data. The first iteration of the model was empirically derived from available fire scar data at 38 sites in Eastern North America (Table 1, col. 5). Although this data set showed predictive power, the eastern fire history data alone was inadequate in the range and distribution of the variables and did not meet the assumption of statistical normality. Thus, we used pre-European fire scar interval data from an additional 41 sites in the Western United States (Brown and Sieg 1996; Brown et al. 1997; Caprio 1998; Caprio and Swetnam 1995; Donnegan et al. 2001; Finny and Martin 1989; Fulé et al. 2003; Heyerdahl et al. 2001; Kipfmueller 2003; Miller and Rose 1999; Moir 1982; Swetnam et al. 1989 ; 1991).

These additional data extended the range of temperature and fire interval observations, increased the normality of the distribution of temperature means, more than doubled the degrees of freedom, and served to examine the hypothesis and model under a much broader set of conditions. We used published mean fire intervals, though in several cases we divided the period of record by the number of fires to estimate mean fire intervals. This was necessary when data were not expressed as mean fire intervals, data were not presented in FHX2 format (Grissino-Mayer 2001), fire dates were not published, long fire intervals were open ended, or the fire scar dates were not crossdated. Since the variables we used in this analysis are being refined and additional fire data are needed and forthcoming in many regions, we present this model as a work in progress with updated versions expected in the future. The two predictor variables of mean fire intervals are mean maximum temperature (*maxt*) and human population density (*pop*). Multicollinearity among predictor variables was negligible. Of the possible intercorrelations among variables, none was significant. The largest variance inflation factor (VIF) was 1.19, well below a VIF of 10, which would indicate that multicollinearity was influencing least squares estimates. The model is described by the regression equation:

$$MFI = -12.7 + 64.5e^{-0.098*maxt} - (6.3*\ln[pop]), \quad \text{(Equation 1)}$$

where MFI is the mean fire interval, *maxt* is the proxy mean maximum temperature (30 year average in degrees Celsius),
ln[*pop*] is the natural log of human population density (humans per $km^2$),
df = 78, $r^2 = 0.75$, all variables are significant ($p < 0.01$).

We tested the model's stability and predictive power by sampling half data with replacement 30 times. Variance explained ($r^2$) ranged from 0.63 to 0.83, the standard deviation of the coefficient of determination was 0.05; the $r^2$ mode was 0.75. The model and predictor variables tested significant ($p < 0.01$) in all model runs. The model predictions did not rely on extreme or rare sets of observations and did not vary greatly by the set of observations tested. On the basis of these results, the predictive power of the model as measured by the coefficient of determination proved stable.

The model predicted the mean fire intervals (Fig. 5) for the presence of fire in a 1- to 3-$km^2$ area during the 150 years before Euro-American settlement. Due to a westward progression of European settlement, this period varies by settlement date and the length of the fire scar record of each site, but generally begins from about 1650 to 1750 and ends between 1780 and 1850. The prediction period for this model also was restricted because the relationship between humans and fire scar frequency was positive only when ignitions were limited (Guyette et al. 2002). During later periods when human population density is high, this relationship becomes more complex and may even be negative. Also, the regression model does not predict or include stand replacement fires (the data are based entirely on survivor trees) or extend to prairies or regions where fire intervals are longer than the lives of recorder trees.

The useful components (predictor variables) of this preliminary model and map also are its caveats. One of the advantages of this model is that it is based on variables that change and can be used to examine different scenarios, for example, landscapes without humans or possible effects of climatic warming or cooling. One disadvantage is that spatial predictions probably are more static than actual (and often unknown) conditions due to the difficulty of variable quantification. This is especially true for the effects

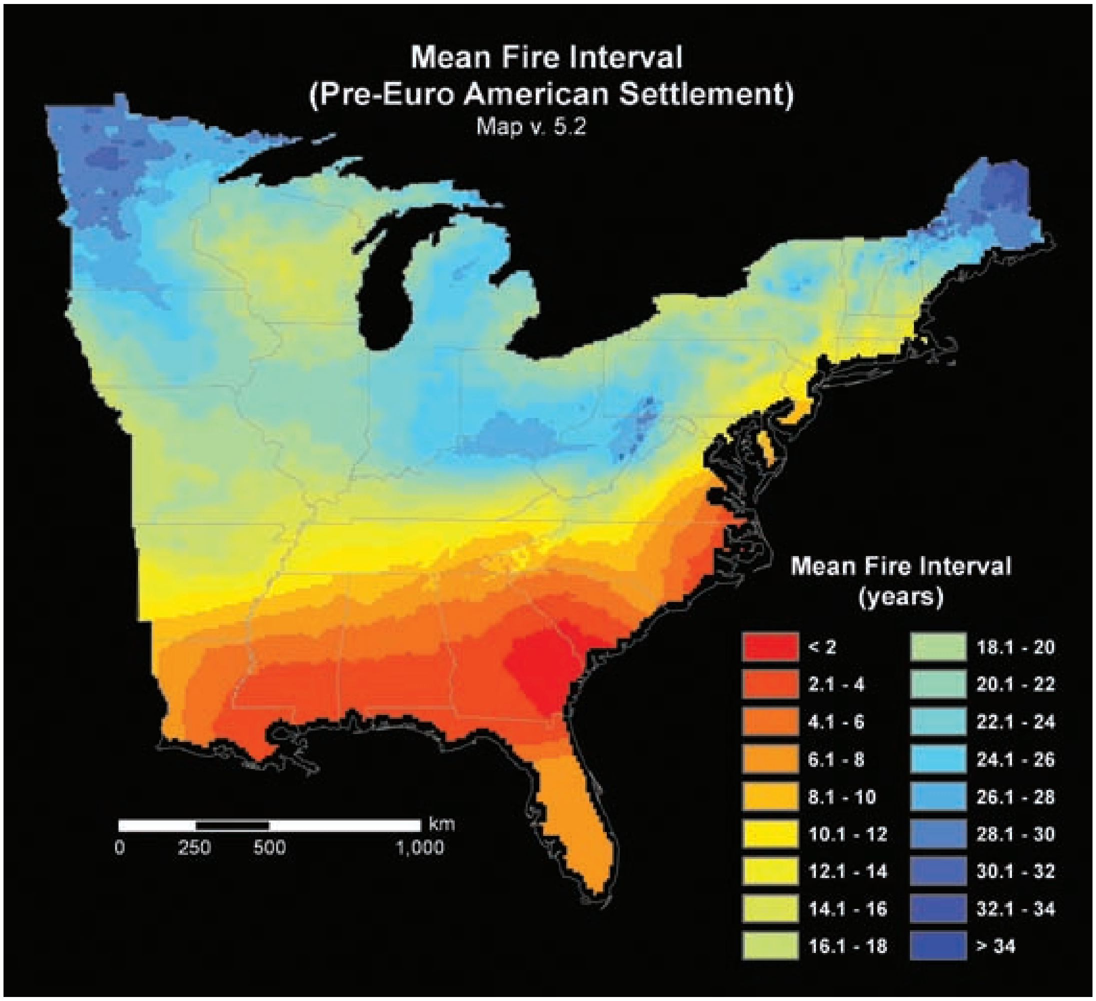


Figure 5.—First approximation of coarse scale mean fire intervals in the Eastern United States as predicted by mean maximum temperature and human population density (Equation 1). The mapped mean fire intervals are based on fire scar histories and model results generated from forested landscapes and nonstand replacement fire events. Mapped estimates are not valid for wetlands, grasslands, and other vegetation types where trees do not grow. The pre-Euro American period is based on fire scar intervals between 1650 and 1850. Estimates near ocean edges are unclassified (black). Mapped mean fire interval estimates are only as stable as human populations (e.g., several centuries earlier, the concentrated populations of the Mississippian cultural phase would have shortened fire intervals in the Mississippi and Ohio River Valleys).

of human-caused ignitions, which can be highly and abruptly variable through time and space.

## Mean Maximum Temperature Proxy

We used annual mean maximum temperature (Daly et al. 2004), a precisely measured and modeled quantity compared to fire intervals, as a predictor of mean fire interval in Eastern North America. Because our period of interest (pre-Euro American settlement) for fire history and mean maximum temperature (1971 to 2000) are not temporally matched, we subtracted 0.4°C from the mean maximum temperature values to compensate for the effects of recent warming (Mann et al. 1998). Error caused by the non-temporal overlap of the temperature record with fire scar history will be minimal because the scale of temperature change between 1750 and 1985 (0.4°C) is small (about 35 times less) compared to differences among sites (about 14°C). Mean maximum temperature probably influences and controls many biotic and abiotic components that influence fire regimes and fire intervals such as fuel moisture, fuel production, and combustion. For example, the length of the fire season, as determined by the number of months in which 90 percent of the acres are burned in the four oak ecoregions (National Fire Occurrence Database and GIS Coverage 2005), is strongly correlated with maximum temperature ($r = 0.77$, $p = 0.01$). We speculate that mean maximum temperature is related to fire intervals and regimes in many ways, including:

1. The length of the fire season as influenced by snow cover at northern latitudes and high-elevation sites.

2. The length of the fire season as determined by the drying rate of fuels.

3. The direct effect of temperature in combustion reactions.

4. Mean *maximum* temperatures most often occur during the most fire-prone time of day.

5. The amount, types, and decay rates of fuels in an ecosystem are determined in part by temperature.

Other basic climate variables were considered as predictors. Precipitation, mean minimum temperature, and mean average temperature were included in the analysis but did not enter the stepwise multiple regression equation as significant. The fact that precipitation did not enter the model in stepwise regression probably reflects the potential complexity of the response of fire regimes to precipitation in hot versus cool climates. For instance, fire can be frequent in both hot-wet (Florida) and hot-dry (southern Arizona) climates. Also, we found that lightning ignition rates based on generalized maps of lighting ignitions of forest fires (Schroeder and Buck 1970) did not enter the stepwise regression, and that correlations between mean fire intervals and lightning ignitions were not significant ($r = 0.16$, $p = 0.16$). However, separation of the data into eastern and western sites yielded a significant correlation ($r = 0.40$, $p < 0.01$) with lightning fires in Western but not Eastern North America ($r = 0.12$, $p = 0.46$). This result partially reflects the lack of fire history sites in the in the lightning and fire-prone Southeastern United States.

## Population Density and Ignition Proxy

We used human population density as a proxy for the number of anthropogenic ignitions. Although the estimation of Native American populations is fraught with problems (Henige 1998), progress has been made in assessing estimates and observations made by early workers (Denevan 1992; Mooney1928). We used mapped population density classes of Native Americans in North America (Driver and Massey 1957) and more detailed population estimates in the Ozarks (Guyette et al. 2002). We used population class variables to facilitate the quantification of pre-census estimates of human population density, which have a large degree of potential error and may never be known precisely. These estimates are consistent with conservative estimates of Native American population (Waldman 1985). However, temporal continuity in population density estimates is variable. Driver and Massey's mapping of human population is not unlike the *relative* spatial distribution of human population density in 2000 (U.S. Census Bur. 2000), illustrating that suitable human habitat (and spatially relative population densities) is somewhat consistent through time. For example, population densities are high during both periods along coastal areas, in the Northeast, near the Great Lakes, in localized areas of the Southwest, and near Appalachia. Also, spatial error in population estimates may be no greater than the variance in population density owing to the migration, immigration, and decline of populations of humans (Thornton 1987) during the two centuries of the pre-Euro American settlement fire scar record. Although these factors make precise calibration between fire frequency and population density difficult over large temporal and spatial scales, their significant ($p < 0.01$) correlation ($r = -0.45$) supports the theory that humans had large-scale effects on fire regimes.

## Mapping Fire Intervals

The model results were mapped using ESRI®ArcGIS™ software (Environ. Syst. Res. Inst. 2005). Gridded mean maximum temperature data (Daly et al. 2004) and coverage of human population density (Driver and Massey 1957) were applied to Equation 1 to produce estimates of mean fire intervals for a pre-Euro American settlement period (about 1650 to 1850).

Prior to mapping, population data were smoothed using a circular (25-km radius) neighborhood mean to more closely reflect the mobility of humans. Mapped coarse scale fire intervals have error based on the model (Equation 1). The model error indicates that the 95-percent model confidence interval is about ±3 years while the 95-percent prediction interval is about ±11 years (less for shorter intervals). These error estimates include all the variability in vegetation, topography, and local human population not evident in the predictor variables that can affect fire frequency at finer spatial scales. During periods that precede model calibration, the model may work within limits but the mapped estimates of mean fire intervals must be based on temporally appropriate predictor variable data.

## CONCLUSION

The quantitative history of wildland fire derived from fire scar studies in Eastern North America provides several insights into past and future fire regimes. Seemingly important variables such as precipitation did not explain variance in mean fire intervals beyond what was explained by temperature. Variables relevant to fire regimes and fire intervals in eastern oak forests were identified and include mean maximum temperature, human population density, extreme drought events, and topographic resistance to the spread of fire. Some of these variables are dynamic, such as human population and temperature, and their potential change in the future may influence fire regimes. Understanding how these variables interact to influence fire regimes will aid in assessing future fire risk with changes in fuel continuity, temperature, extreme climate events, human culture, and population density.

The interaction between drought and intentional human ignitions will make future fire regimes potentially unstable and difficult to predict. Human populations are increasing and will provide more ignitions, making fire regimes more responsive to drought. This will be countered to some extent by improved suppression response time and new technologies. The stability of fire regimes in changing climates may be low, particularly in landscapes with a low resistance to fire propagation and changes in the number and distribution of human ignitions. Drought has inspired purposeful human burning both in the past and present. It is doubtful that this relationship will cease to exist in the future.

The effects of topography on the propagation of fire have been understood by humans for a long time. Fire scar data quantified this effect at a general landscape level. The mitigation of fire by topography has been relatively static over geologic time scales compared to the ephemeral changes caused by the frequency of human ignitions. Thus, in terms of temporal scale, topographic roughness is by far one of the most consistent and important variables affecting the frequency of fire.

Fire history modeling and mapping from fire scars can provide estimates of fire intervals for restoration and reference conditions (Maclean and Cleland 2003; McKenzie et al. 2000; Morgan et al. 2001). However, the quality of any model or map is dependent on the quality of the data from which it is derived. In this study, we mapped large regions of the Southern and Eastern United States for which pre-European settlement fire scar histories were unavailable. Therefore, estimates for these regions are uncalibrated and approximate but might be improved by future studies and data collection.

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## LITERATURE CITED

Alexander, M.E.; Mason, J.A.; Stocks, B.J. 1979. **Two and a half centuries of recorded forest fire history.** Sault St. Marie, ON: Environment Canada Great Lakes Forest Research Centre.

Armbrister, M.R. 2002. **Changes in fire regimes and the successional status of table mountain**

**pine (*Pinus pungens* Lamb.) in the southern Appalachians.** Knoxville, TN: University of Tennessee. Ms. thesis.

Bailey, R.G. 1997. **Ecoregions of North America.** 1:15,000,000 scale map (rev.) Washington. DC: U.S. Department of Agriculure, Forest Service.

Batek, M.J.; Rebertus, A.J.; Schroeder, W.A.; Haithcoat, T.L.; Compas, E.; Guyette, R.P. 1999. **Reconstruction of early nineteenth century vegetation and fire regimes in the Missouri Ozarks.** Journal of Biogeography. 26: 397-412.

Brown, P.M.; Foster, J.; Holzman B.; Hurd, S.; Kitchen, S.; Miller, R.; Schoennagel, T.; Solomon, A.; Wadleigh, L. 1997. **A dendrochronological assessment of fire history in a ponderosa pine forest of the eastern Cascades.** Research Report, International Dendrochronological Field Week.

Brown, P.; Sieg, C.H. 1996. **Fire history in interior ponderosa pine communities of the Black Hills, South Dakota, USA.** International Journal of Wildland Fire. 6(3): 97-105.

Caprio, A.C. 1998. **Fire history.** In: Mineral King Risk Reduction Project – 1998 Annual Report. pp. 48-56.

Caprio, A.C.; Swetnam, T.W. 1995. **Historic fire regimes along an elevational gradient on the west slope of the Sierra Nevada, California.** In: Brown, J.; Mutch, R.; Spoon, C.; Wakimoto, R., tech coords. Proceedings: symposium on fire in wilderness and park management. Gen Tech. Rep. INT-320. Odgen, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 173-179.

Clark, J.S. 1990. **Fire and climate change during the last 750 yr in northwestern Minnesota.** Ecological Monographs. 60(2): 135-159.

Cook, E.R.; Meko, D.M.; Stahle, D.W.; Cleaveland, M.K. 1999. **Drought reconstructions for the continental United States.** Journal of Climate. 12: 1145-1162.

Cutter, B.E.; Guyette, R.P. 1994. **Fire history of an oak-hickory ridge top in the Missouri Ozarks.** American Midlands Naturalist. 132: 393-398.

Cwynar, L.C. 1977. **The recent fire history of Barron Township, Algonquin Park.** Canadian Journal of Botany. 55: 1524-1538.

Daly, C.; Gibson, W.P.; Doggett, M.; Smith, J.; Taylor, G. 2004. **Up-to-date monthly climate maps for the conterminous United States.** Proceedings of the 14th American Meteorological Society conference on applied climatology and 84th annual meeting;2004 January 13-16; Seattle, WA. Boston, MA: American Meteorological Socitey.

Denevan, W.M. 1992. **The native populations of the Americas in 1492.** Madison, WI: University of Wisconsin Press. 353 p.

DeVivo, M.S. 1991. **Indian use of fire and land clearance in the southern Appalachians.** In: Nodvin, S.C.; Waldrop, T.A., eds. Fire and the environment: ecological and cultural perspectives. Proceedings of an international symposium. Gen. Tech. Rep. SE-069. Ashville, NC: U.S. Department of Agricluture, Forest Service, Southeastern Forest Experiment Station: 306-310.

Dey, D.C.; Guyette, R.P. 2000. **Anthropogenic fire history and red oak forests in south-central Ontario.** Forestry Chronicle. 76: 339-347.

Dey D.C.; Guyette, R.P.; Stambaugh, M.C. 2004. **Fire history of a forest, savanna, and fen mosaic at White Ranch State Forest.** In: Spetich, M.A., ed. Upland oak ecology symposium: history current conditions, and sustainability. Gen. Tech. Rep. SRS-73. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 132-137.

Donnegan, J.A.; Veblen, T.T.; Sibold, J.S. 2001. **Climatic and human influences on fire history in Pike National Forest, Central Colorado.** Canadian Journal of Forest Research. 31: 1526-1539.

Driver, H.E.; Massey, W.C. 1957. **Comparative Studies of North American Indians.** Transactions of the American Philosophical Society. 47: 165-465.

Engstrom, F.B.; Mann, D.H. 1991. **Fire ecology of red pine (*Pinus resinosa*) in northern Vermont, U.S.A.** Canadian Journal of Forest Research. 21: 882-889.

Environmental Systems Research Institute. 2005. **ArcGIS software v. 9.1.** Redlands, CA: Environmental Systems Research Institute.

Finny, M.A.; Martin, R.E. 1989. **Fire history in a *Sequoia sempervirens* forest at Salt Point State Park, California.** Canadian Journal of Forest Research. 19: 1451-1457.

Frissell, S.S. 1973. **The importance of fire as a natural ecological factor in Itasca State Park.** Minnesota. Quaternary Research. 3: 397-407.

Fulé, P.Z.; Heinlein, T.A.; Covingtion, W.W.; Moore, M.M. 2003. **Assessing fire regimes on Grand Canyon landscapes with fire-scar and fire-record data.** International Journal of Wildland Fire. 12: 129-145.

Grissino-Mayer, H.D. 2001. **FHX2—software for analyzing temporal and spatial patterns in fire regimes from tree rings.** Tree-Ring Research. 57(1): 115-124.

Guyette, R.P. 1997. **Fire history of MOFEP site 7.** Missouri Ozark forest ecosystem project data base. Jefferson City, MO: Missouri Department of Conservation.

Guyette, R.P. 2002. **Fire history of MOFEP site 4.** Missouri Ozark forest ecosystem project data base. Jefferson City, MO: Missouri Department of Conservation.

Guyette, R.P.; Cutter, B.E. 1997. **Fire history, population, and calcium cycling in the Current River Watershed.** In: Pallardy et al., eds. Proceedings of the 11th central hardwood forest conference. Gen. Tech. Rep. NC-188. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 355-373.

Guyette, R.P.; Cutter, B.E. 1991. **Tree-ring analysis of fire history of a post oak savanna in the Missouri Ozarks.** Natural Areas Journal. 11: 93-99.

Guyette, R.P.; Dey D.C. 2000. **Human, topography, and wildland fire: the ingredients for long-term patterns in ecosystems.** In: Yaussey, D., ed. People, fire, and the central hardwood landscape. Gen. Tech. Rep. NE-274. U.S. Department of Agriculture, Forest Service, Northeastern Research Station: 28-35.

Guyette, R.P.; Dey, D.C.; Stambaugh, M.C. 2003. **Fire history of a barren-forest mosaic in Southern Indiana.** American Midlands Naturalist. 149: 21-34.

Guyette R.P.; Dey, D.C. 1995a. **A history of fire, disturbance, and growth in a red oak stand in the Bancroft District, Ontario.** For. Res. Inf. Pap. 119. Saulte Ste. Marie, ON: Ontario Ministry of Natural Resources and Ontario Forest Research Institute.

Guyette, R.P.; Dey, D.C. 1995b. **A dendrochronological fire history of Opeongo Lookout in Algonquin Park, Ontario.** For. Res. Rep. No. 134. Saulte Ste. Marie, ON: Ontario Forest Research Institute.

Guyette R.P.; Dey, D.C. 1995c. **A pre-settlement fire history of an Oak-Pine Forest near Basin Lake, Algonquin Park, Ontario.** For. Res. Rep. No. 132. Saulte Ste. Marie, ON: Ontario Forest Research Institute.

Guyette, R.P.; Kabrick, J. 2003. **The legacy of forest disturbance, succession, and species at the MOFEP sites.** In: Shifley, S. et al., eds. Proceeding of the second Missouri Ozark forest ecosystem project symposium. Gen. Tech. Rep. NC-227. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 26-44.

Guyette, R.P.; McGinnes, E.A. 1982. **Fire history of an Ozark Glade.** Transactions of the Missouri Academy of Scienceh. 16: 85-93.

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

Guyette, R.P.; Spetich, M. 2003. **Fire history in the Lower Boston Mountains.** Forest Ecology and Management. 180: 463-474.

Guyette, R.P.; Stambaugh, M.C. 2002. **Fire history of MOFEP site 5.** Missouri Ozark forest ecosystem project data base. Jefferson City, MO: Missouri Department of Conservation.

Guyette, R.P.; Stambaugh, M.C. 2004. **Post oak fire scars as a function of diameter, growth, and tree age.** Forest Ecology and Management 198: 183-192.

Guyette, R.P.; Stambaugh, M.C. **In the heart of roughness: Pioneer forest.** Proceedings of the pioneer forest conference; St. Louis, Missouri. USDA Forest Service General Technical Report.

Guyette, R.P.; Stambaugh, M.C. 2005. **Fire history and stand age at Arnold Air Force Base, Highland Rim, Tennessee.** Interim project report for CH2MHILL and the United States Air Force. 89 pp.

Harmon, M. 1982. **Fire history of the westernmost portion of Great Smoky Mountains National Park.** Bulletin of the Torrey Botanical Club. 109(1): 74-79.

Heinselman, M.L. 1973. **Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota.** Quaternary Research. 3: 329-382.

Henige, D. 1998. **Numbers from nowhere.** Norman, OK: University of Oklahoma Press. 532 p.

Heyerdahl, E.K.; Brubaker, L.B.; Agee, J.K. 2001. **Spatial controls of historical fire regimes: a multiscale example from the interior west.** Ecology. 82: 660-678.

Jenkins, S.E. 1997. **Spatial demography of an Ozark savanna.** Ph.D. Dissertation, Univ. of Missouri-Columbia. 116 pp.

Johnson, P.S.; Shifley, S.R.; Rogers, R. 2002. **The ecology and silviculture of oaks.** CABI publishing. 503 pp.

Kipfmueller, K.F. 2003. **Fire-climate-vegetation interactions in subalpine forests of the Selway-Bitterroot Wilderness Area, Idaho and Montana, USA.** Tucson, AZ: University of Arizona. 94 p. Ph.D. dissertation.

Loope, W.L.; Anderton, J.B. 1998. **Human vs. lightning ignition of presettlement surface fires in coastal pine forests of the upper Great Lakes.** American Midlands Naturalist. 140: 206-218.

Maclean, A.L.; Cleland, D.T. 2003. **Determining the spatial extent of historical fires with geostatistics in Northern Lower Michigan.** In: Omi, P.N.; Joyce, L.A., tech. coords. Fire, fuel treatments and ecological restoration: conference proceedings. USDA Forest Service Proceedings RMRS-P-29. pp. 289-299.

Mann, M.E.; Bradley R.S.; Hughes, M.K.1998. **Global scale temperature patterns and climate forcing over the last six centuries.** Nature. 392: 779-787.

McKenzie, D.; Peterson, D.L.; Agee, J.K. 2000. **Fire frequency in the Columbia River Basin: building regional models from fire history data.** Ecological Applications. 10: 1497-1516.

Miller, R.F.; Rose, J.A. 1999. **Fire history and western juniper encroachment in sagebrush steppe.** Journal of Range Management. 52: 550-559.

Moir, W.H. 1982. **A fire history of the High Chisos, Big Bend National Park, Texas.** Southwestern Naturalist. 27(1): 87-98.

Mooney, J. 1928. **The Aboriginal population of America north of Mexico**, edited by J. Swanton, Smithsonian Miscellaneous Collections, 80(7):1-40. Smithsonian Institution: Washington. D.C.

Morgan, P.; Hardy, C.C.; Swetnam, T.W.; Rollins, M.G.; Long, D.G. 2001. **Mapping fire regimes across time and space: understanding coarse and fine-scale fire patterns.** International Journal of Wildland Fire. 10: 329-342.

National Fire Occurrence Database and GIS Coverage. 2005. **Federal and State Lands, 1986-1996, v1999.** Available at: http://www.fs.fed.us/fire/fuelman/fireloc.htm.

Schuler, T.M.; McClain, W.R. 2003. **Fire history of a ridge and valley oak forest.** Res. Pap. NE-724. U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 9 p.

Schroeder, M.J.; Buck, C.C. 1970. **Fire weather.** Agric. Handb. 360. Wasghington, DC: U.S. Department of Agriculture. 288 p.

Shumway, D.L.; Abrams, M.D.; Ruffner, C.M. 2001. **A 400-year history of fire and oak recruitment in an old-growth oak forest in western Maryland, U.S.A.** Canadian Journal of Forest Research. 31: 1437-1443.

Smith, K.T.; Sutherland, E.K. 1999. **Fire-scar formation and compartmentalization in oak.** Canadian Journal of Forest Research. 29: 166-171.

Spurr, S.H. 1954. **The forests of Itasca in the nineteenth century as related to fire.** Ecology. 35: 21-25.

Sutherland, E.K. 1997. **History of fire in a southern Ohio second-growth mixed-oak forest.** In: Pallardy, S. et al., eds. Proceedings of the 11th central hardwood forest conference. Gen. Tech. Rep. NC-188. U.S. Department of Agriculture, Forest Service, North Central Experiment Station: 172-183.

Sutherland, E.K.; Grissino-Mayer, H.; Woodhouse, C.A.; Covingtion, W.W.; Horn, S.; Huckaby, L.; Kerr, R.; Kush, J.; Moorte, M.; Plumb, T. 1992. **Two centuries of fire in a southwestern Virginia *Pinus pungens* community.** Proceeding of the 4th annual dendrochronological fieldweek. Pemborke, VA: Mountain Lake Field Station.

Swetnam, T.W.; Touchan, R.; Baisan, C.H.; Caprio, A.C.; Brown, P.M. 1991. **Giant sequoia fire history in Mariposa Grove, Yosemite National Park.** In: Yosemite centennial symposium proceedings. Natural areas and Yosemite: prospects for the future. Denver, CO: U.S. Department of the Interior, National Park Service: 249-255.

Swetnam, T.W.; Baisan, C.H.; Brown, P.M.; Caprio, A.C. 1989. **Fire history of Rhyolite Canyon, Chiricahua National Monument.** Tech. Rep. No. 32. Cooperative National Park Resources Studies Unit. 54 p.

Thornton, R. 1987. **American Indian holocaust and survival.** Norman, OK: University of Oklahoma Press. 292 p.

Torretti, R.L. 2003. **Traditional stories from non-traditional stories: tree-rings reveal historical use of fire by Native Americans on Lake Superior's southern shore.** Marquette, MI: Northern Michigan University. M.S. thesis. 40 p.

U.S. Census Bureau. 2000. **Redistricting data** (PL 94.171) summary file, population division. Washington, DC: U.S. Census Bureau.

U.S. Department of Agriculture 1940-1997. **Wildfire statistics.** Washington, DC: U.S. Department of Agriculture.

Van Lear, D.H.; Waldrop, T.A. 1989. **History, uses, and effects of fire in the Appalachians.** Gen. Tech. Rep. SE-54. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 24 p.

Wade, Dale D.; Brock, Brent L.; Brose, Patrick H.; Grace, James B.; Hoch, Greg A.; Patterson, William A, III. 2000. **Chapter 4: Fire in eastern ecosystems.**

In: Brown, J.B.; Smith, J.K., eds. Wildland fire in ecosystems: effects of fire on flora. Gen. Tech. Rep. RMRS 42. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 53-96.

Waldman, C. 1985. **Atlas of the North American Indian.** New York. Fact on File. 276 pp.

Whitney, G.G. 1986. **Relation of Michigan's presettlement pine forests to substrate and disturbance history.** Ecology. 67: 1548-1559.

Williams, G.W. 2000. **Introduction to Aboriginal Fire Use in North America.** Fire Management Today. 60(3): 8-12.

Williams, G.W. 2001. **References on the Native American use of fire in ecosystems.** http://www.wildlandfire.com/docs/biblio_indianfire.htm.

Wolf, J. 2004. **A 200 year fire history in a remnant oak savanna in southeastern Wisconsin.** American Midlands Naturalist. 152(2): 201-213.