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Abstract

Human interaction with fire and vegetation occurs at many levels of human population density and cultural development, from subsistence cultures to highly technological societies. The dynamics of these interactions with respect to wildland fire are often difficult to understand and identify at short temporal scales. Dendrochronological fire histories from the Missouri Ozarks, coupled with human population data, offer a quantitative means of examining historic (1680–1990) changes in the anthropogenic fire regime. A temporal analysis of fire scar dates over the last 3 centuries indicates that the percent of sites burned and fire intervals of anthropogenic fires are conditioned by the following four limiting factors: (a) anthropogenic ignition, (b) surface fuel production, (c) fuel fragmentation, and (d) cultural behavior. During an ignition-dependent stage (fewer than 0.64 humans/km^2), the percent of sites burned is logarithmically related to human population (r^2 = 0.67). During a fuel-limited stage, where population density exceeds a threshold of 0.64 humans/km^2, the percent of sites burned is independent of population increases and is limited by fuel production. During a fuel-fragmentation stage, regional trade allows population densities to increase above 3.4 humans/km^2, and the percent of sites burned becomes inversely related to population (r^2 = 0.18) as decreases in fuel continuity limit the propagation of surface fires. During a culture-dependent stage, increases in the value of timber over forage greatly reduce the mean fire interval and the percent of sites burned. Examples of the dynamics of these four stages are presented from the Current River watershed of the Missouri Ozarks.

Key words: human population density; Ozarks; Missouri; disturbance; dendrochronology; fire regimes.

Introduction

Anthropogenic, or human-caused, fire has influenced ecosystem processes for millennia, and at broader scales has been an important determinant of landscape character and global carbon cycles (Pyne 1995; Delcourt and Delcourt 1997; Bird and Cali 1998). Despite progress in recent years in understanding how the spatial and temporal dynamics of wildfire shape natural ecosystems (Swetnam 1993; Agee 1993; Whelan 1995), we know little about the ways in which changes in human population and culture alter the use of anthropogenic fire and consequently how that dynamic affects ecosystem processes and attributes.

Anthropogenic fire occurs throughout a range of human-related activities and settings, from widely scattered populations living in subsistence cultures to densely settled urban societies; therefore, anthropogenic fire is both temporally and spatially dynamic. Within a region, a temporal dynamic in anthropogenic fire is driven by changes in population and culture that occur over decades and centuries. In North America, dramatic temporal changes in the frequency of anthropogenic fire over the past 400 years have resulted from the displacement of aboriginal cultures and populations by high-density European populations and industrial economies (Pyne 1982; Williams 1989). Human ac-

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tivities strongly influence fire frequencies in such areas as Patagonia (Veblen and others 1999) and the Amazon basin (Kauffman and Uhl 1990); and human populations account for variation in landscape-level fire regimes in North America (Turner and Romme 1994; Guyette and Dey 2000; Dey and Guyette 2000). In the Midwest, historical narratives suggesting the use of fire by aboriginal people have been summarized by Ladd (1991), and archaeological evidence supports the presence of human populations in Missouri for many thousands of years (Marriott 1974; Price and others 1987; O'Brien and Wood 1998).

Many fire ecologists and historians have defined the concept of fire regime (Pyne 1982; Agee 1993; Whelan 1995; Pyne and others 1996). According to Pyne and others (1996), "A fire regime is intended to characterize the feature of historic, natural fires that have been typical for a particular ecosystem or set of ecosystems." In many regions, such as the Ozark physiographic province in midwestern North America, human presence on the landscape (O'Brien and Wood 1998) predates contemporary forest–vegetation associations and climatic conditions (Delcourt and Delcourt 1987, 1991); therefore, any characterization of the "natural" fire regime should incorporate all organisms in the ecosystem and all sources of fire, including humans and their ignitions. For the purposes of this analysis, we define an anthropogenic fire regime as patterns of wildland fire shaped by the dynamic interactions of vegetation (fuels) and human populations (ignitions). This definition is functional and consistent with the standard dictionary definition of a regime as "a system of rules", or in our case, factors that govern the frequency and intensity of fire. Although fire regimes are often defined for specific ecosystems that have a particular combination of vegetation (fuels), climate, and a certain frequency of ignition, the perception that an anthropogenic fire regime is a static combination of these factors may be unrealistic because of the extreme variability in time and space of fluctuating human populations and cultures.

The goal of the research presented here is to demonstrate that change in human population density and culture has been one of the major factors influencing the frequency and effects of wildland fire over the last 320 years in southeastern Missouri. The objectives of this paper are to (a) describe the historic changes in an anthropogenic fire regime; and (b) elucidate the limiting factors that affect these changes through time, including the relationships among human population density, culture, and fuels as determinants of fire regimes. To fulfill these objectives, we used dendrochronological fire histories coupled with data on human population density from AD 1680 to 1998 in the Current River watershed, a topographically highly dissected section of the Ozark Highlands in Missouri, USA.

A Temporal Anthropogenic Framework

The oak-pine forests of the Ozark Highlands offer an appropriate setting to document changes in human–fire interactions over hundreds of years. Schroeder and Buck (1970) estimated that less than one lightning fire per 4000 km^2 occurs annually in the Missouri Ozarks. Missouri State Fire Protection records between 1970 and 1989, summarized by Westin (1992), indicate that an average of 108 fires per year per 4000 km^2 occurred in the region of the Current River watershed. Of these, less than 1% were of lightning ignition origin; therefore, the overwhelming majority of these fires were caused by humans. The lack of "natural" fires in the Current River region, a temporally variable human population, and variable topography make this region ideal for studying change in anthropogenic fire regimes and its effects on ecosystems. Fire scars from primarily low-intensity surface fires offer high-resolution spatial–temporal data on fire frequency and extent and can be tree-ring–dated on survivor trees and woody remnants (Guyette and McGinnes 1982; Guyette and Cutter 1991; Guyette and Dey 1997a; Jenkins and others 1997). Finally, a highly dissected topography inhibits the propagation of fire, thus making mean fire intervals and the percent of sites burned sensitive to the number and distribution of anthropogenic ignitions. The foregoing evidence suggests a close association between humans and fire in the Ozarks. We hypothesize that identified changes in the percent of sites burned can be attributed to changes in human population density and cultural behavior. Consequently, we propose that a temporal framework can be used to describe these changes. In this analysis, we examine whether fire frequency is a function of ignitions (anthropogenic), fuels, and cultural behavior based on economics and technology.

Study Area

The study area is in the upper Current River watershed (including the Jack Fork River), is heavily forested (more than 80%), and measures about 4316 km^2 in area (Figure 1). The study area is located near the western edge of the eastern deciduous forest and is dissected by steep ridges and numerous streams. The slope of the sample sites

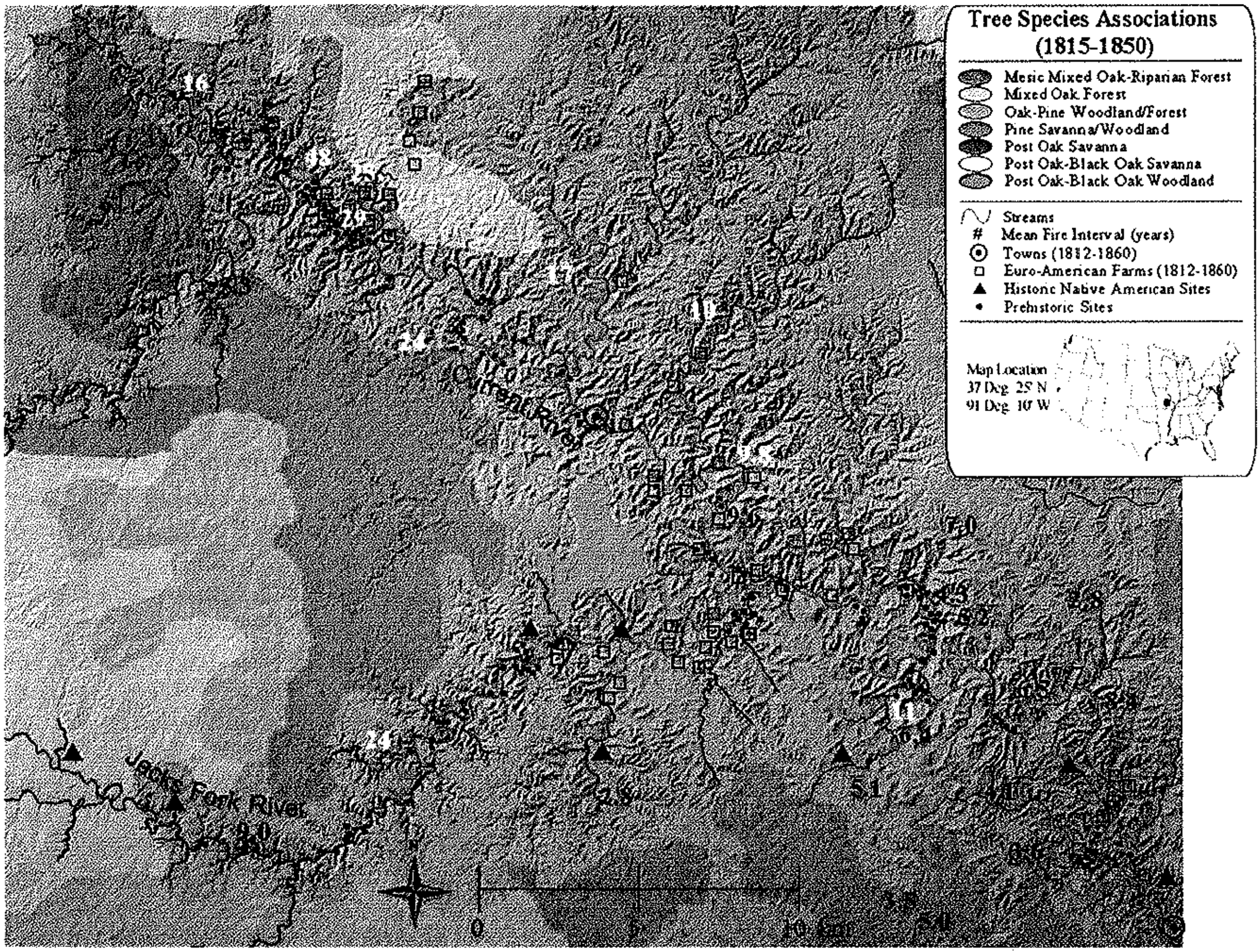

Figure 1. Study area, with fire history sites, historic tree species associations, mean fire intervals, topography, archeological sites, and historic sites. The location of the fire history sites and their mean fire intervals (1700–1850) are indicated by the mapped numbers in black and white. Mean fire intervals in white text represent sites where the interval decreased by more than 10 years during the ignition-dependent stage; mean fire intervals in black indicate a decrease of 0–10 years. The percent of canopy closure defines forests (more than 75%), woodlands (25%–75%), and savannas (less than 25%). *Mesic mixed oak-riparian forest* is more than 25% mesic species or more than 25% riparian species; *mixed oak forest* is more than 75% oak and hickory; *oak-pine woodland/forest* is oak with more than 25% and less than 65% pine; *pine savanna/woodland* is more than 65% pine; *post oak savanna* is more than 75% post oak; *post oak–black oak savanna* is more than 75% post and black oak. Tree species associations are based on General Land Office Survey Notes as interpreted by Porter (1998), Batek and others (1999), and Hughes and Nigh (2000). Archaeological and historic sites are based on data from Price and others (1987), Lynott (1989), and Stevens (1991).

averages 18° and ranges from 10° to 32°. Elevations in the study area range from 140 to 414 m a.s.l. The climate of the study area is humid and continental. Precipitation ranges from 60 to 152 cm and averages 115 cm per year. Spring is the wettest season, followed by fall, summer, and winter. During the fall, winter, and spring of most years, dry warm weather during only a few days may be sufficient to dry surface fuels and permit the spread of surface fires. Fires during the growing season are rare but do occur during very hot and dry summers. Natural ignition is rare despite an abundance of thunderstorms (50–70 thunderstorm days per year) (Baldwin 1973).

Methods

Fire History Development

Site locations within the study area were chosen based on the presence of fire-scarred wood, and the majority of fire-scarred wood was found in steep terrain. Thus, the sites are not necessarily truly representative of the area as a whole. Twenty-three

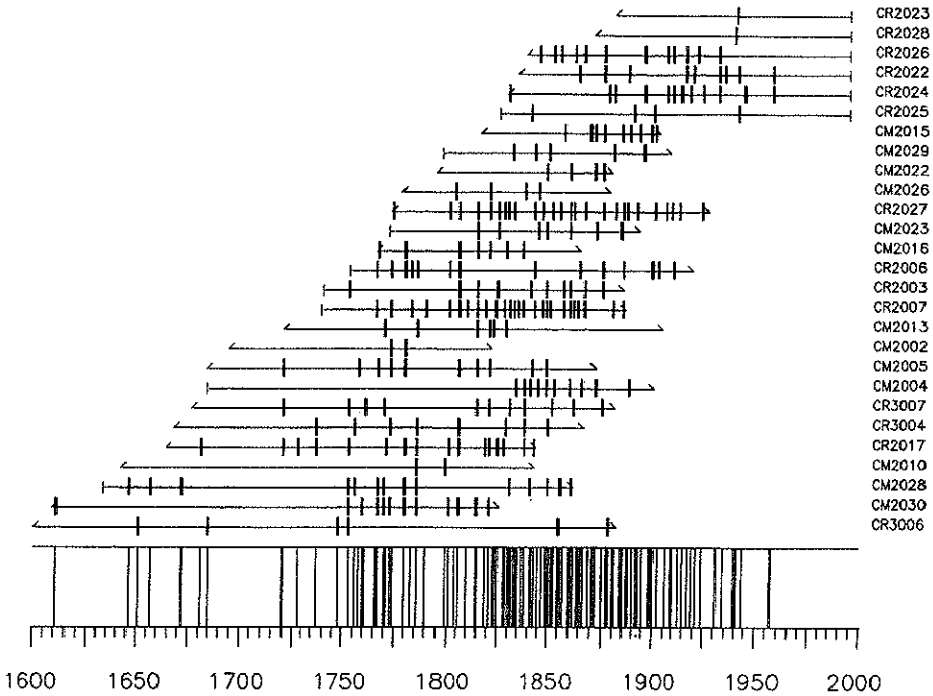

Figure 2. Fire scar data plotted by tree sample and calendar year for a 1-km^2 area near Blue Spring along the Current River in Missouri. Each horizontal line represents the tree-ring record of a fire-scarred shortleaf pine tree, stump, or natural snag. Dendrochronologically dated fire scars are represented by vertical lines. A composite fire scar chronology (all fire scar dates) is plotted at the bottom of the graph.

of the sites were located in areas dominated historically by oak (*Quercus* species) forests; four other sites occurred in forests historically dominated by shortleaf pine (*Pinus echinata*) (Batek and others 1999). Oak has become a dominant species in the overstory of all the fire history sites.

Cross sections of more than 257 shortleaf pine remnants (cut stumps, natural snags, downed trees) were cut between ground level and 30 cm. Wedges were cut from the scar face of live trees. Fire scars were identified by callus tissue, traumatic resin canals, and cambial injury. All samples had charcoal present on the scarred exterior. Scars were dated to the 1st year of cambial injury. Ring-width series from each sample were measured and plotted by year. Ring-width plots were used for visual cross-dating (Stokes and Smiley 1968; Guyette and Cutter 1991). The COFECHA computer program (Grissino-Mayer and others 1996) was used to assist in ensuring the accuracy of both relative and absolute dating of the samples by correlation analysis. Absolute dating of the pine remnants was accomplished by cross-dating with a ring-width chronology (Guyette 1996) based on live shortleaf pine growing in Shannon County, Missouri, within the study area. Over 2500 scars were identified and dated from 27 sites. Site-level data were averaged into a regional composite of the percent of sites burned. An 11-year moving average was applied to percent of sites burned to reduce variability in the time series due to changes in annual climate and to enhance long-term trends in the data. An 11-year moving average was chosen because it preserved variability on a decadal scale, it is symmetrical, and it corresponds to the decadal census data. Correlation coefficients between the percent of sites burned and human population density were calculated without the moving average and were adjusted for autocorrelation in the time series of the percent of sites burned. A representative subset of the data from a site in the study watershed (Figure 2) is graphed using FHX2 software (Grissino-Mayer 1995) and illustrates the structure of the data and the changing fire return interval over nearly 4 centuries.

Topographic Roughness

Irregularities in the landscape, or "topographic roughness", can contribute to the fire behavior in an area of highly dissected topography. The rate of spread of a low-intensity surface fire may decrease because fire burns slower down steep slopes; because fuel continuity is broken by creeks, rivers, and rocky outcrops; or because fuel moisture content increases on northern aspects.

Indexes of topographic roughness were used to reflect topographic inhibition of the propagation of fire across the landscape. These indexes were developed by comparing surface area measurements made with two different-sized scales. A circle 5000 m in diameter is marked on a digital elevation map. The surface area of the earth circumscribed by this circle is calculated from pixels that are 30 m on a side. Their slope and a trigonometric conversion are used to estimate the area of the uneven land surface. The pixels are summed to estimate the surface area of the landscape enclosed by the circle. This measure is then divided by the planimetric surface area (the large scale in this case) of a circle that is 5000 m in diameter. This ratio of the actual surface area to the planimetric surface area is the Index of Topographic Roughness. A correlation analysis was used to document changes in the influence of topographic roughness on mean fire intervals by stage of the anthropogenic fire regime.

Human Populations

Population since 1820 was derived for the study area from United States Census data (Shannon County, Missouri) and population estimates and maps in Stevens (1991) and Rafferty (1982). Historic Native American population density was estimated from many sources (Table 1 and references therein). The population density of each group in the Current River watershed was calculated by dividing their historical population estimates by the area of a circle whose radius was the distance between their population center and the watershed. Changes in the location and territory of populations documented in the historical literature were also used to estimate population trends of groups. Although this method does not take into account the great variation of population density within a tribal territory, it does provide an estimate of changes in population density through time that have affected the population of the Current River watershed. These population density estimates are consistent with aboriginal population densities (0.07–6 humans per km^2) given for the Great Lakes region and eastern North America (Kroeber 1934; Dobyns 1983; Ramenofsky 1987; Thornton 1987) and with mapped estimates by Paullin (1932) for the period after 1790. The relative spatial distribution of population within the watershed has remained consistent over time and reflects spatial patterns in past fire occurrence and the recent population of towns (Guyette and Dey 2000). Linear interpolation was used to estimate annual population from decadal census data.

Discussion

The Dynamics and Sequence of the Fire Regime

A historic and sequential interpretation of fire, human population, and culture (Figure 3) is essential to an understanding of the events that have occurred in the study area over the last 350 years. Although fire history research often ends with the identification of fire intervals and ecological relationships, such findings represent only a first step in identifying the processes and variables underlying changes in ecosystem processes. When population and fire data identical to those in Figure 3 are plotted with axes that are independent of time (Figure 4a), the resulting pattern reflects critical changes in the relationships between humans and the environment (fire). The changing slope and direction of the plotted data reflect four temporal stages that are built upon the interaction among ignitions, fuels, and topography as a function of human population density.

The temporal progression of limiting factors defining these stages in the anthropogenic fire regime involves (a) human ignitions >, (b) fuel availability >, (c) fire propagation and fuel continuity >, and (d) cultural values. Consequently, these factors define four stages: ignition-dependent, fuel-limited, fuel-fragmentation, and culture-dependent (identified in Figure 4a). All stages are linked to population density in the way that population affects ignitions and fire frequency (the percent of sites burned), as well as the ways in which that relationship is modified by culture. Descriptions of these stages, based on limiting factors and interpretations, follow.

Ignition-dependent (Stage 1). The anthropogenic fire regime is population-dependent during this stage and directly related to human population. Human population density is one of the most important factors in an anthropogenic fire regime, especially in early stages or at low levels of human population density. Consequently, ignition sources are the most limiting factor influencing the percent of sites burned during this period. During this stage (before 1850), low population densities (fewer than 0.64 humans/km^2) limited the frequency and distribution of anthropogenic sources of ignition in the Current River watershed. Correlation between percent of sites burned and human population density (nontransformed data) is strongest during this stage (Table 2). Verification of this relationship is demonstrated by a positive nonlinear relationship between the percent of sites burned and human population density. During the ignition-dependent stage, percent of sites burned is related ($r^2 = 0.67$, $P < 0.01$) to the natural logarithm of human population density at low levels (fewer than 0.64 humans/km^2) by:

$$F^{\%} = 0.32 + 0.069(\ln[P]) \qquad (1)$$

Table 1. Population Densities (Humans per km^2) Estimated and Measured by Decade and Cultural Group

Date	All	Quapaw	Osage	Cherokee	Delaware	Shawnee	European
1650	0.047	0.0421[a]	0.0049[f]				
1660	0.047	0.0421	0.0049				
1670	0.050	0.0421	0.0082[g]				
1680	0.052	0.0421	0.0099				
1690	0.053	0.0421	0.0115				
1700	0.027	0.0139[b]	0.0132				
1710	0.027	0.0126	0.0148				
1720	0.038	0.0113	0.0264				0.0001
1730	0.038	0.0084	0.0297				0.0007
1740	0.042	0.0084	0.0331				0.0014
1750	0.045	0.0063[c]	0.0364				0.0028
1760	0.048	0.0049[d]	0.0397				0.0041
1770	0.061	0.0044	0.0430[h]	0.0046[l]	0.0002[n]	0.0033[r]	0.0055
1780	0.1340	0.0039	.0397	0.0185	0.0320	0.0320	0.0082
1790	0.167	0.0034	0.0364[i]	0.463	0.0320	0.0384	0.0110[t]
1800	0.2210	0.0029	0.0347	0.0927	0.0320	0.0449	0.0137
1810	0.2020	0.0029	0.0331	0.0648	0.0320[o]	0.0513	0.0179
1820	0.662	0.0024	0.0198[j]	0.0289[m]	0.3012[p]	0.0926[s]	0.2175[u]
1830	0.371	0.0009[e]	0.0066	0.0231	0.0033[q]	0.0926	0.2447
1840	0.294		0.0001[k]	0.0154		0.0066	0.2719
1850	0.642						0.6420[v]
1860	0.873						0.8736
1870	0.899						0.8998
1880	1.323						1.3237
1890	3.423						3.4231
1900	4.326						4.3268
1910	4.402						4.4022
1920	4.564						4.5645
1930	4.191						4.1910
1940	4.551						4.5515
1950	3.638						3.6389
1960	2.726						2.7264
1970	2.886						2.8853
1980	3.033						3.0334
1990	3.073						3.0738

The sum of the densities is given in the column labeled "All."
Superscripts refer to source data and type by period.
Not all figures are significant.
[a]*Population estimate (Baird 1980)*
[b,c,d]*Population reductions by disease (Ramenofsky 1987; Baird 1980)*
[e]*Migration out of the watershed (Baird 1980)*
[f]*Territory just west of Current River (Bailey 1973; Wiegers 1985)*
[g]*Acquisition of horse (Wiegers 1985; Waldman 1985)*
[h]*Maximum expansion of territory (Bailey 1973; Wiegers 1985)*
[i]*Population estimates (Marriott 1974; Banks 1978)*
[j]*Territorial reduction (Wiegers 1985) and movement west by treaty (Marriott 1974; Banks 1978)*
[k]*Last Osage removed from Missouri (Wiegers 1985)*
[l]*Population estimates, trends, movement into Missouri (Gilbert 1996; Stevens 1991)*
[m]*Migration to Arkansas (Pitcaithley 1978)*
[n]*Movement into east Missouri (Stevens 1991)*
[o]*Population estimates (Marriott 1974)*
[p]*Migration across Missouri River, population estimate, and encampment on the Jacks Fork of the Current River (Weslager 1978)*
[q]*Movement out of Current River watershed (Stevens 1991; Weslager 1978)*
[r]*Movement into east Missouri (Stevens 1991)*
[s]*Movement out of southeast Missouri (Howard 1981)*
[t]*Spanish census data (Gerlach 1986)*
[u]*Early settlement (Stevens 1991)*
[v]*Shannon County census data (Stevens 1991)*

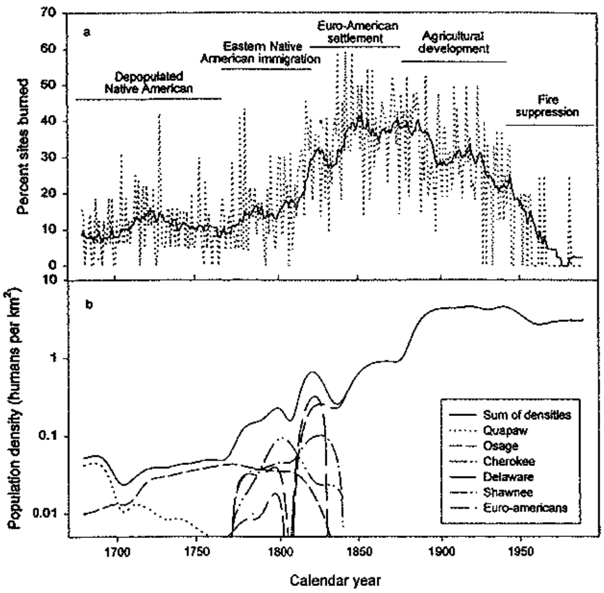

Figure 3. (a) The percent of 26 fire history sites in the Current River watershed that were burned each year (*dotted line*) and an 11-year moving average of the percent of sites burned annually (*solid line*) plotted by calendar year. The text above the graph identifies the corresponding cultural periods. (b) A record of the human population density and the population densities of individual cultural groups (see Table 1) in the Current River watershed and the Ozark Highlands (log scale) by calendar year.

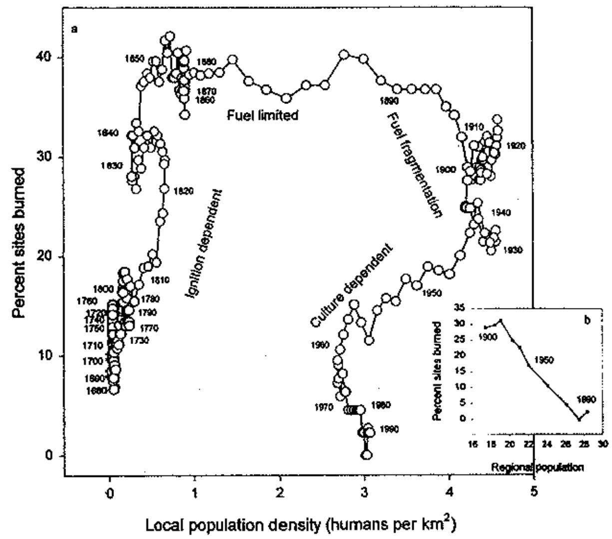

Figure 4. (a) Scatterplot illustrating the change in the relationship between the percent of sites burned annually and human population density through time. These relationships help to identify the stages in an anthropogenic fire regime. Data points in the scatterplot are labeled with decadal calendar dates to identify the temporal sequence. The scatterplot data are the same data represented by the solid lines in Figure 3a and b. (b) The regional and exogenous population density (state of Missouri) plotted with the percent sites burned during the 20th century contrasts with the endogenous population trends of the Current River watershed.

where $F^{\%}$ is the percent of sites burned and P is the human population density.

Topographic roughness inhibits the spatial extent and spread of fire during this stage. The degree of topographic roughness and the frequency of fire at each site are inversely correlated (Table 2). Both endogenous and exogenous factors play roles during this stage, since population levels at the study sites were controlled by local human reproduction, human migration, technological development, and introduced disease (Table 2). This stage is the longest in duration over the past 3 centuries and includes notable fire years (see Appendix).

Fuel-limited (Stage 2). The anthropogenic fire regime is limited by fuel availability in this stage; within limits, population has no effect. Fire reduces surface fuels in Missouri by more than 50% for up to 2.5 years (Scowcroft 1965). During the fuel-limited stage (1850–90), human population exceeded 0.64 humans/km^2 in the study area, and the percent of sites burned became independent of increases in human population density. The percent of sites burned during this stage is limited by the availability and production of surface fuels. Frequent fire created open woodlands with grassy–herbaceous understories; therefore, biomass accumulation was limited by the short fire return interval. But by 1850 a threshold in population density (0.64 humans per km^2) was reached in terms of burning and fuels wherein the environment became ignition-saturated and the fire regime was fuel limited. The great number of ignitions during this stage nullified the effects of topographic roughness in inhibiting the propagation of fire; hence, topographic roughness became less important as a factor controlling fire (Table 2), as illustrated by the lack of significant correlations in stages 2, 3, and 4 of the fire regime. During this stage, endogenous factors that limit fire frequency change from human ignitions to fuel production. This is the shortest of the four stages; it is less than 25% as long as the previous stage. Within the fuel-limited stage, a broad range of human population densities can maintain a consistently short fire interval; however, permanent fuel elimination does not characterize this stage.

Fuel-fragmentation (Stage 3). During the fuel-fragmentation stage (1890–1940), regional trade,

Table 2. Attributes and Interactions of a Four-phased Anthropogenic Fire Regime

Interactions and Attributes	Stage 1: Ignition-dependent (1680–1850)	Stage 2: Fuel-limited (1851–90)	Stage 3: Fuel-fragmentation (1891–1940)	Stage 4: Culture-dependent (1940–90)
Key Factors Limiting Fire	Number of human ignitions	Amount and production of fuels	Discontinuity of fuels, propagation of fire	Cultural attitude, fire suppression, value of wood over forage
Origin and Examples of Factors that Influence Development	Endogenous: human population change Exogenous: human migration, introduced disease	Endogenous: fuel production, ignition saturation	Endogenous: fuel continuity, human incursions Exogenous: regional economics, resource exploitation	Exogenous: cultural value of forests, value of timber versus forage
Population (humans km^{-2})	<0.03–0.64	0.64–3.4	3.4–4.6	4.6–2.7
Average and Range of Mean Fire Intervals[a] (y)	10 (2.3–45)	3.5 (1.5–6.8)	5.8 (1.7–19)	>20 (6.8–50)
Mean and Range (Percent Sites Burned Annually)[b]	12 (0–60)	38 (10–55)	29 (0–51)	10 (0–32)
Correlation (Population, Percent Sites Burned)	$r = 0.63$, $P<0.01$	$r = -0.05$, $P>0.05$	$r = -0.30$, $P<0.05$	$r = 0.52$, $P<0.01$
Culture (price ratio: (timber/livestock)	Insufficient data	2.1	4.3	7.2
Correlation: (Topography and Mean Fire Interval)[c]	(1580–1700) $r = -0.71$ (1701–1850) $r = -0.43$ $P<0.05$	$r = 0.14$, $P>0.05$	$r = 0.15$, $P>0.05$	Insufficient data
Ca in Wood[b] (μg/g)	678	755	700	650
Pine Abundance[d]	51 stems per ha		17 stems per ha	
Culture and Land Use	Aboriginal American, hunting, and gathering	Euro-American settlement and agriculture	Euro-American, logging, grazing, and agriculture	American, forestry, recreation, and agriculture

[a] *Guyette and Cutter 1997; Batek and others 1999*
[b] *Guyette and Cutter 1997*
[c] *Guyette and Dey 2000*
[d] *Guyette and Dey 1997b*

Table 3. Agricultural Statistics Indicating Increases in Land Uses that Fragmented the Continuity of the Surface Fuel Environment Between Stage 2 and Stage 3[a]

Decade	Hogs per km^2	Cattle per km^2	Improved land[a] (%)
1850	0.87	0.38	1.3
1860	2.5	1.8	2.2
1870	4.1	1.7	2.2
1880	8.6	2.2	6.3
1890	7.8	5.2	11.6
1900	8.4	2.6	14.2
1910	8.1	7.3	17.5
1920	6.6	8.4	19.7
1930	4.0	7.4	17.2
1940	6.2	7.3	26.7

[a] *"Improved land" includes pasture fenced land, orchards, crops, and fallow fields (Jacobson and Primm 1997).*

railroads, and markets allowed population densities to increase above 3.4 humans/km^2. A peak in human population density within the watershed (about 4.6 km^2) was reached in the 1920s. Increases in human population density led to increases in the number of artificial fuel breaks caused by livestock grazing, road building, and the conversion of field and forest to crop land and pasture (Table 3). This development led in turn to a reduction in the percent of sites burned because it inhibited the propagation of low-intensity surface fires, the mode of fire in the previous two stages. The percent of sites burned became inversely related to population density ($r^2 = 0.18$, $P < 0.05$) because the continuity of wildland fuels became fragmented by agricultural and rural development. A decrease in the percent of sites burned coincided with increasing population density between 1890 and 1940. Thus, the percent of sites burned, once a function of the ability of fires to spread and increase in size, was limited by the decreased propagation of surface fires across the landscape due to fragmentation of the fuel environment. The fragmentation stage can be followed in subsequent stages by the elimination of wildland fuels, as might occur through urban or agricultural development.

Culture-dependent (Stage 4). During this stage, cultural values, practices, and technology influence human–environmental interactions. Cultural attitudes toward the benefits, costs, and dangers of wildland fire are second only to gross population density in importance to anthropogenic fire regimes. During the culture-dependent stage (1940–96), increases in the value of timber (to a growing exogenous human population) (Figure 4b) relative to that of pasture resulted in attitudes and cultural constructs that reduced the frequency of fire. The price ratio of wood products (Anonymous 1965; Gregory 1972) to livestock (data provided by the Missouri Agricultural Statistical Service) was highly correlated with the percent of sites burned and probably reflects changes in attitudes about the value of forests versus livestock range. The low forage value of forest lands for livestock and increasing demand for wood products were important factors that inspired education on the economic destructiveness of wildland fire, the desire to protect forested lands, and the institution of fire suppression over the last 60 years in the Ozark Highlands.

Attributes of the Stages

Throughout all four of the stages of the anthropogenic fire regime, the factors that limit fire change along the temporal framework. Both causal and resulting factors exert varying influences on the character of the fire regime, depending on the stage. We have identified several components of the anthropogenic fire regime that figure prominantly in determining the stage or represent a substantial response in any or all stages. Although the implications of changing fire regimes are numerous, we will focus here on a few interactions, effects, and attributes that are useful in elucidating the complexity of the human–fire interaction.

Endogenous and Exogenous Factors. A classification of important endogenous and exogenous factors by stage (Table 2) shows that endogenous factors predominate in early stages, and that exogenous factors become more important in later stages. For the purposes of this perspective, we consider humans to be an integral part of the Current River ecosystem; therefore, anthropogenic factors within the ecosystem are endogenous, and anthropogenic factors outside the ecosystem are exogenous. Significant endogenous factors during early stages include indigenous human population growth and technological innovation. Introduced diseases, however, were a major exogenous factor during the ignition-dependent stage. Endogenous factors pertinent in the early stages of development include fuel abundance, fuel type, and vegetative change and succession. The fuel-limited stage is the only stage where there are no important contributions by exogenous factors. Exogenous factors resulting from human population changes, predominantly migration and population growth, contribute to the fuel-fragmentation and culture-dependent stages. Throughout the stages, the change from endogenous to exogenous influence is accompanied by increases in human population, transportation, and communication.

Vegetation–Fire Interactions. There are several tree species that provide particularly useful evidence of the effects of the stages of the fire regime on vegetation because of their longevity and fire sensitivity. Using data compiled from land survey records (circa 1830), the mean fire interval at 23 sites (Batek and others 1999) in the Current River watershed was positively and significantly correlated with the abundance of *Pinus echinata* and negatively correlated with the abundance of *Quercus velutina* (black oak). These relationships imply that fire frequency may have been a factor influencing vegetation during stage 1 (Table 2). Reductions in the mean fire interval during stages 2 and 3 (1820–1940) to near annual burning in some areas (Guyette and Cutter 1997), combined with the logging of pine, may have inhibited pine regeneration, reduced the abundance of advanced (prelogging) reproduction, and decreased the amount of mature pine (Record 1910). Currently, pine abundance is only 34% of its historic levels in some areas of the Current River watershed (Guyette and Dey 1997a).

The past and present distribution of *Juniperus virginiana* (eastern redcedar), a fire-sensitive species, may reflect the intensity and frequency of fires during the ignition-dependent stage. Circa 1840, surveyors noted redcedar on sites with long fire intervals but made no mention of redcedar on sites with a short fire interval (Batek and others 1999). Old (200+ years) redcedar persist to the present day on sites that had longer fire intervals during the ignition-dependent stage, as documented by the fire scar record. In contrast, there are no old and few young eastern redcedar on sites that had short fire intervals during the ignition-dependent stage. Abundance of *Quercus stellata* (post oak), a fire-tolerant and shade-intolerant species, as determined from surveyor notes, is significantly correlated with mean fire intervals during the ignition-dependent stage. The ignition-dependent stage has the greatest spatial and temporal variability in the percent of sites burned and mean fire intervals (Table 2); it is the disturbance regime under which recent vegetation associations have developed for centuries.

Stage-related Calcium Dynamics. Wildland fire is a chemical process that can cause sudden changes in the nutrient status of a site. Calcium (Ca) is a necessary plant macronutrient whose bioavailability has been shown to increase after fires (DeBano and others 1977; Zinke 1977; Agee 1993) and over longer periods by increasing the rate of Ca cycling in

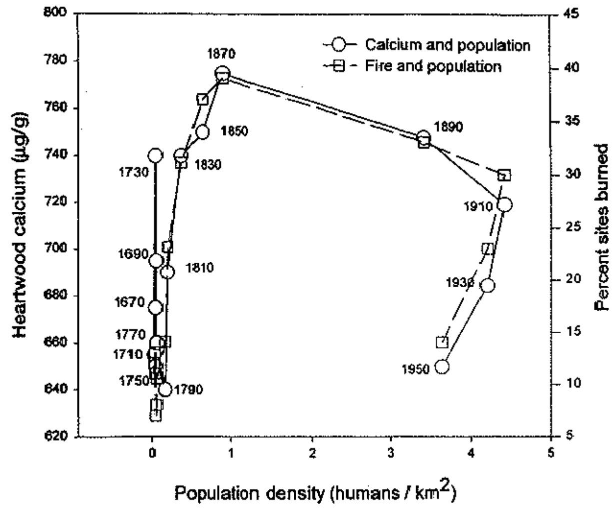

Figure 5. Scatterplots illustrating the similarity in pattern between the percent sites burned and heartwood calcium concentration (*Juniperus virginana*) as related to human population density. Labels on the graph data points represent bidecadal calendar years.

organic debris that is frequently burned (Alban 1977; Binkley and others 1992). An association between trends in Ca availability and mean fire intervals over a 340-year period was inferred from Ca in growth increments of eastern redcedar heartwood growing in the Current River watershed (Guyette and Cutter 1997). Although eastern redcedar is a fire-sensitive species, old individuals of this species persist where they have some protection from the lethal effects of fire—for example, on rhyolite glades, where there is extensive barren rock surface and fire intensity is low. In addition, eastern redcedar has many anatomical and ecological characteristics uniquely suited for dendrochemical studies (Cutter and Guyette 1993) and has been used to reconstruct many changes in environmental chemistry (Guyette and others 1989, 1991, 1992; Guyette and Cutter 1994).

The association between heartwood Ca and human population density (Figure 5) suggests that the stages of the fire regime may have different effects on nutrient cycling. The Ca chronology of dated redcedar heartwood increments was highly correlated with the 20-year grouped means of the percent of sites burned ($r = 0.81$) and trees scarred ($r = 0.77$). During the ignition-dependent stage, Ca is variable and increases steadily with small increases in human population density. Ca concentrations in the heartwood are highest during the fuel-limited stage, the period with the lowest mean fire interval and the greatest percent of sites burned (Table 2). During this stage, the availability of Ca increases owing to the release of Ca in organic litter by the rapid abiotic decomposition mechanism of frequent low-intensity fires. As fire frequency declines in subsequent stages, Ca concentrations decrease in wood.

Human Population Density and Topographic Interactions. Certain stages in an anthropogenic fire regime are the result of complex interactions between human population density and topographic roughness. At low population densities, the percent of sites burned increases with population density (Figure 4a). Topographic controls on the frequency of fire become less important as population density and the frequency and distribution of anthropogenic ignitions increases (Table 2). The forcing factor of the ignition-dependent and fuel-limited stages is the interaction of human population density and topographic roughness. A topographically smooth landscape, such as a large plain or plateau (often prairies), might require only a few humans to reach and maintain a fuel-limited stage. On the other hand, many topographically rough landscapes, such as forests in the Ozark Highlands, require a relatively high human population density to reach and maintain a fuel-limited stage.

Culture and Fire Stages. In the later stages that we have identified, factors controlling the regime change from environmental to cultural. Fuel and local human population density, possibly irrespective of ignition motivation, govern the fire regime in the early stages. Subsequently, during the fuel-fragmentation stage, cultural artifacts—such as roads and agricultural development—begin to affect the spread, frequency, and size of fires. Artificial fire breaks in an ignition-saturated environment are now replacing the natural role of topographic roughness as an inhibitor of the spread of fire. Economic values, coupled with the technology of fire suppression, become dominant during the cultural-dependent stage and account for the lowest frequency of fire across all stages.

Human Risk and Fire Stages. The culture-dependent stage may be unstable. During this stage, the cultural separation of ignitions and fuels continues to have increasingly serious implications for human societies that live in environments with highly volatile fuels, particularly those with growing human populations. The accumulation of fuel, ignition potential, and increasing human occupation of the landscape act together to increase the potential risk to human life and property. The most important factors affecting the dynamics of the stages and their associated risk to human life and property are conceptualized using the dynamic interactions of humans and fuels (Figure 6a, b, c). Using a theoretically extended temporal framework, we developed a conceptual model to examine the overall risk to humans (Figure 6d). The square of human population density is the dominant variable in this model. The exponential nature of this variable is derived from the dual effect of human population density on fire regimes. One significant effect is that increases in human population density increase ignition potential; the other effect is that higher human population density across the landscape increases the likelihood that wildland fire will damage human life and property. Fuel fragmentation is the only physical factor in this conceptual model of risk that reduces the risk of wildland fire for humans. Fuel fragmentation, however, may be outweighed by the exponential effects of human population and the accumulation of fuels.

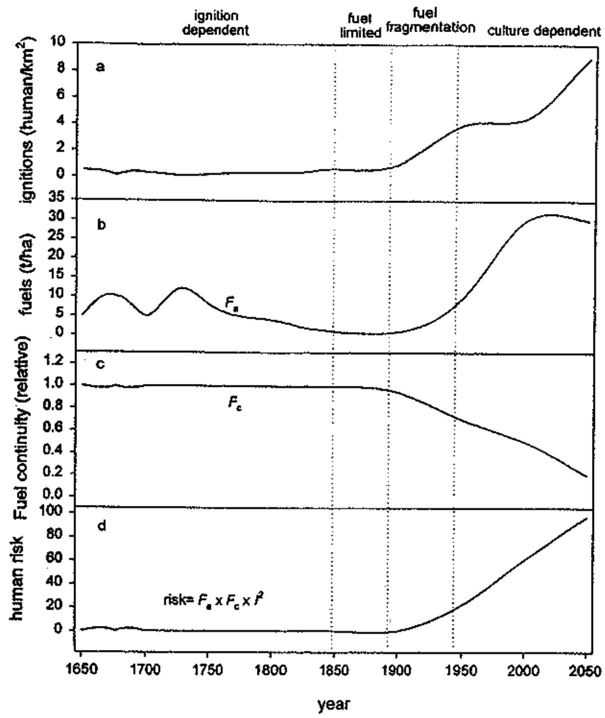

Figure 6. Theorized time series of factors influencing the dynamics of the stages of the fire regime (a, b, c). The variables associated with each of the stages include I: human population density, F_a: total surface fuel accumulation, and F_c: relative fuel continuity. The conceptual model of risk (d) to humans, based on calculations from the formula presented, represents the contribution of these three variables.

Synthesis

Dendrochronological histories allow the quantitative analysis of the role of humans in an ecosystem and show that this role is part of an ecological dynamic controlled by changes in factors that limit the occurrence of fire. Temporal trends in the percent of sites burned and human population density, coupled with historic information on human cultures, allow us to define four stages within an anthropogenic fire regime in the Current River watershed in Missouri.

The stability of any stage in the fire regime is dependent on exogenous human-related factors—for example, war, migration, and introduced disease—as well as changes in endogenous factors, such as fuel accumulation. Some stages may persist and appear to be somewhat stable. In North America, for example, the culture-dependent stage may be a prolonged endpoint under continued fire suppression. The apparent stability of this stage, however, is subject to stochastic phenomena—for example, extreme climate events, which could result in catastrophic or frequent fires. The separation of ignitions and fuels (fire suppression) that occurs during a culture-dependent stage creates an inherently unstable condition.

Fire histories reveal many examples of the influence of exogenous human-related factors on the initiation and termination of anthropogenic fire stages. In Patagonia, the link between humans and fire frequency suggests a sequence of human–fire interactions wherein climatic influences are significant in determining fire frequency on a short-term basis, but the role of humans is significant when examined over decades and centuries (Veblen and others 1999). Bird and Cali (1998) have presented evidence of fire from sediments that demonstrates the influence of humans on fire regimes in sub-Saharan Africa over a time scale of hundreds of thousands of years. Charcoal accumulation rates from sediments in the southern Appalachian Mountains also suggest a strong correspondence between human population density (based on the number of archaeological sites) and fire (based on charcoal accumulation) (Delcourt and Delcourt 1997).

The extension of these stages to other ecosystems has limitations. Topographic roughness mitigates the spread of fire and is an integral component of the stages we have identified in our landscape. The effect of human ignitions could be mitigated by topographic roughness or the frequency of water bodies, nonvegetated lands, or other natural fire breaks. Guyette and Cutter (1991) described the fire histories of an oak savanna in Missouri where continuous fine fuels contributed to a consistent mean fire interval, with no population effect evident before Euro-American settlement. Few ignitions are needed in topographically uniform areas (for example, plains or plateaus) for fires to propagate; therefore, fire frequency tends to be independent of human population density. For example, Abrams (1985) found no indication of distinct stages in the fire history of an oak gallery forest in northeastern Kansas. Sufficient topographic inhibition of the spread of fire is necessary for an ignition-dependent stage in an anthropogenic fire regime.

We think that the four stages identified by our research could be used as a temporal model to describe and characterize other ecosystems. For example, Amazonia may typify an area in the ignition-dependent stage because population density is closely linked with fire frequency (Laurance 1998). In Australia, many ecosystems may have attributes of a fuel-limited stage (Pyne 1991). Moreover, tropical savanna and brush lands burn frequently, and these fires often result from human ignitions (Andreae 1991). More rigorous analysis of the dynamic interactions among human population density, fuels, and culture could thus enhance our understanding of change and process in ecosystems.

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REFERENCES

Abrams MD. 1985. Fire history of oak gallery forest in a northeastern Kansas tallgrass prairie. Am Midl Nat 114:188–91.

Agee JK. 1993. Fire ecology of the Pacific Northwest. Washington (DC): Island Press. 493 p.

Alban DH. 1977. Influence on soil properties of prescribed burning under mature red pine. USDA Forest Service Research Paper NC-139. North Central Forest Experiment Station, St. Paul, Minn.

Andreae MO. 1991. Biomass burning: its history, use, and distribution and its impact on environmental quality and global climate. In: Levin JS, editor. Global biomass burning: atmosphere, climate, and biosphere. Cambridge (MA): MIT Press. p 3–21.

Anonymous. 1965. Timber trends in the United States. Forest Resource Report No. 17. Washington (DC): US Government Printing Office. 235 p.

Bailey GA. 1973. Changes in Osage social organization 1673–1906. Anthropological Papers, No. 5. Eugene (OR): University of Oregon.

Baird WD. 1980. The Quapaw Indians: a history of the down-stream people. Norman (OK): University of Oklahoma Press. 290 p.

Baldwin JL. 1973. Climates of the United States. Washington (DC): US Department of Commerce. National Oceanic and Atmospheric Administration, Environment Data Service. 113 p.

Banks A. 1978. Indians of the upper Current River. Eminence (MO): Alan Banks. 87 p.

Batek MJ, Rebertus AJ, Schroeder WA, Haithcoat TL, Compas E, Guyette RP. 1999. Reconstruction of early nineteenth century vegetation and fire regimes in the Missouri Ozarks. J Biogeogr 26:397–412.

Binkley D, Richter D, David MB, Caldwell B. 1992. Soil chemistry in a loblolly/longleaf pine forest with interval burning. Ecol Appl 2:157–64.

Bird MI, Cali JA. 1998. A million-year record of fire in sub-Saharan Africa. Nature 394:767–76.

Cook ER, Meko DM, Stahle DW, Cleaveland MK. 1999. Drought reconstructions for the continental United States. J Clim 12: 1145–62.

Cutter BE, Guyette RP. 1993. Factors affecting species choice for dendrochemistry studies. J Environ Qual 22:611–9.

Cutter BE, Guyette RP. 1994. Fire history of an oak-hickory ridge top in the Missouri Ozarks. Am Midl Nat 132:393–8.

Cwynar LC. 1977. The recent fire history of Barron Township, Algonquin Park. Can J Bot 55:1524–8.

DeBano LF, Dunn PH, Conrad CE. 1977. Fire's effect on physical and chemical properties of chaparral soils. In: Mooney H, Conrad C, Tech. Coord. Proceedings of the symposium on the environmental consequences of fire and fuel management in Mediterranean ecosystems. Forest Service General Technical Report WO-3. Washington, D.C. US Department of Agriculture. p 65–74.

Delcourt HR, Delcourt PA. 1991. Late-quaternary vegetation history of the interior highlands of Missouri, Arkansas, and Oklahoma. In: Henderson D, Hedrick LD, editors. Restoration of old growth forests in the interior highlands of Arkansas and Oklahoma. Proceedings of the Conference Winrock International. Morrilton (AR): Winrock International Institute for Agricultural Development. 15–30.

Delcourt PA, Delcourt HR. 1987. Long-term forest dynamics of the temperate zone. New York: Springer-Verlag. 439 p.

Delcourt HR, Delcourt PA. 1997. Pre-Columbian Native American use of fire on southern Appalachian landscapes. Conserv Biol 11:1010–014.

Dey DC, Guyette RP. 2000. Anthropogenic fire history and red oak forests in south-central Ontario. For Chron 76:339–47.

Dobyns HF. 1983. Their number become thinned. Knoxville (TN): University of Tennessee Press. 378 p.

Foley WE. 1999. A history of Missouri; vol. 1 Columbia (MO): University of Missouri Press. 249 p.

Gerlach RL. 1986. Settlement patterns in Missouri. Columbia (MO): University of Missouri Press. 88 p.

Gilbert J. 1996. The Trail of Tears across Missouri. Columbia (MO): University of Missouri Press. 122 p.

Gregory GR. 1972. Forest resource economics. New York: Wiley. 548 p.

Grissino-Mayer HD. 1995. Fire and climate reconstructions at El Malpais National Monument, New Mexico [dissertation]. Tucson (AZ): University of Arizona. 407 p.

Grissino-Mayer HD, Holmes RL, Fritts HC. 1996. International Tree-Ring Data Bank Program Library user's manual. Version 2.0. Tucson (AZ): Laboratory of Tree-Ring Research. 106 p.

Guyette RP. 1996. Tree-ring data, Ontario and Missouri. International Tree-Ring Data Bank. IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series No. 92-014. Boulder (CO): National Oceanic and Atmospheric Admin./National Geophysical Data Center Paleoclimatology Program.

Guyette RP, Cutter BE. 1994. Barium and manganese trends in tree-rings as monitors of sulfate deposition. J Water Air Soil Poll 73:213–23.

Guyette RP, Cutter BE. 1997. Fire history, population, and calcium cycling in the Current River watershed. In: Pallardy S, Cecich R, Garrett H, Johnson P, editors. Proceedings of the 11th Central Hardwood Forest conference. Forest Service General Technical Report NC-188. St. Paul (MN): US Department of Agriculture. p 355–73.

Guyette RP, Cutter BE. 1991. Tree-ring analysis of fire history of a post oak savanna in the Missouri Ozarks. Nat Areas J 11: 93–9.

Guyette RP, Cutter BE, Henderson GS. 1989. Long-term changes in molybdenum and sulfur concentrations in redcedar tree-rings. J Environ Qual 18:385–9.

Guyette RP, Cutter BE, Henderson GS. 1991. Long-term correlations between mining activity and levels of lead and cadmium in tree-rings of redcedar. J Environ Qual 20:146–50.

Guyette RP, Cutter BE, Henderson GS. 1992. Reconstructing soil pH from manganese concentrations in tree-rings. For Sci 38: 727–37.

Guyette RP, Dey DC. 1995a. A dendrochronological fire history of Opeongo Lookout in Algonquin Park, Ontario. Forest. Research. Report No. 134. Sault Ste. Marie (Ont.): Ontario Forest Research. Institute. 4 p.

Guyette RP, Dey DC. 1997a. A fire history of Huckleberry Hollow. Forest Research. Paper No. 1. Jefferson City (MO): Missouri Department of Conservation. 10 p.

Guyette RP, Dey DC. 1997b. Historic shortleaf pine (*Pinus echinata* Mill.) abundance and fire frequency in a mixed oak–pine forest. In: Brookshire B, Shifley S, editors. Proceedings of the Missouri Ozark Forest ecosystem project symposium. USDA Forest Service General Technical Report NC-193. St. Paul (MN): US Department of Agriculture. p 136–49.

Guyette RP, Dey DC. 2000. Humans, topography, and wildland fire: the ingredients for long-term patterns in ecosystems. In: Yaussy D, editor. Proceedings: workshop on fire, people, and the Central Hardwoods landscape. USDA Forest Service General Technical Report NE-274. US Department of Agriculture. Newton Square (PA): p 28–35.

Guyette RP, Dey DC. 1995b. A presettlement fire history in an oak-pine forest near Basin Lake, Algonquin Park, Ontario. Forest. Research. Report No. 132. Sault Ste. Marie (Ont.): Ontano Forest Research Institute. 11 p.

Guyette RP, McGinnes EA. 1982. Fire history of an Ozark glade. Trans Missouri Acad Sci 16:85–93.

Heinselman ML. 1981. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. In: Mooney and others, Tech. Coord. Proceedings on fire regimes and ecosystem properties, Honolulu, HI. 11–15, December 1978. Forest Service General Technical Report WO-26. Washington (DC): US Department of Agriculture. p 5–57.

Howard JH. 1981. Shawnee: the ceremonialism of a native Indian tribe and its cultural background. Athens (OH): Ohio University Press. 454 p.

Hughes LG, Nigh TA. 2000. Historic vegetation of Missouri, lower Ozarks Pilot Area. Jefferson City (MO): Missouri Department of Conservation.

Jacobson RB, Primm AT. 1997. Historical land-use changes and potential effects on stream disturbance in the Ozark Plateaus, Missouri. Water-Supply Paper 2484. Denver (CO): US Geological Survey. 85 p.

Jenkins SE, Guyette RP, Rebertus AJ. 1997. Vegetation diversity and fire history on Turkey Mountain. In: Pallardy S, Cecich R, Garrett H, Johnson P, editors. Proceedings of the 11th Central Hardwood Forest conference. Forest Service General Technical Report NC-188. St. Paul (MN): US Department of Agriculture. p 184–201.

Kauffman JB, Uhl C. 1990. Interactions of anthropogenic activities, fire, and rain forests in the Amazon basin. Ecol Stud: Anal and Synth 84:117–34.

Kroeber AL. 1934. Native American population. Am Anthropol 36:1–25.

Ladd D. 1991. Reexamination of the role of fire in Missouri oak woodland. In: Burgur G, Ebinger J, Wilhem G, editors. Proceedings of the oak woods management workshop. Charleston (IL): Eastern Illiniois University p 67–80.

Laurance WF. 1998. A crisis in the making: responses of Amazonian forests to land use and climate change. Trends Ecol Evol 13:411–15.

Lynott MJ. 1989. An archeological evaluation of the Gooseneck and Owls Bend sites: Ozark National Scenic Riverways, southeast Missouri. Conducted for the US Department of the Interior, National Park Service, Midwest Archeological Center. Lincoln (NE) Center of Archaeological Research, Southwest Missouri State University

Marriott A. 1974. Osage Indians II. New York: Garland. 270 p.

O'Brien MJ, Wood WR. 1998. The prehistory of Missouri. Columbia (MO): University of Missouri Press. 417 p.

Paullin CO. 1932. Atlas of the historical geography of the United States. Carnegie Institute of Washington and the American Geographical Society of New York. Washington (DC) 166 p.

Pitcaithley DT. 1978. Let the river be: a history of the Ozark's Buffalo River. Santa Fe (NM): Southwest Cultural Resources Center, National Park Service. 133 p.

Porter SR. 1998. Modeling historic woody vegetation in the lower Ozarks of Missouri [thesis]. Columbia (MO): University of Missouri. 134 p.

Price JE, Price CR, Saucier R. 1987. Archeological investigations in the Ozark National Scenic Riverways, 1984–1986. Conducted for the US Department of the Interior, National Park Service, Midwest Archeological Center. Lincoln (NE): Center of Archaeological Research, Southwest Missouri State University, Springfield (MO) 169 p.

Pyne SJ. 1991. Burning bush. New York: Holt. 520 p.

Pyne SJ. 1982. Fire in America. Princeton (NJ): Princeton University Press. 654 p.

Pyne SJ. 1995. World fire: the culture of fire on earth. New York: Holt. 379 p.

Pyne SJ, Andrews PL, Laven RD. 1996. Introduction to wildland fire. New York: Wiley. 769 p.

Rafferty MD. 1982. Historical atlas of Missouri. Norman (OK): University of Oklahoma Press. 113 p.

Ramenofsky AF. 1987. Vectors of death: the archaeology of European contact. Albuquerque (NM): University of New Mexico Press. 300 p.

Record SJ. 1910. Forest conditions of the Ozark region of Missouri. Bulletin No. 89. Columbia (MO): Missouri Agriculture Experiment Station.

Schroeder MJ, Buck CC. 1970. Fire weather. Agricultural Handbook 360. Washington (DC): US Department of Agriculture, Forest Service. 229 p.

Scowcroft PG. 1965. The effects of fire on the hardwood forest of the Missouri Ozarks [thesis]. Columbia (MO): University of Missouri. 126 p.

Shumway DL, Abrams MC, Ruffner CM. 2001. A 400-year history of fire and oak recruitment in an old-growth oak forest in western Maryland, U.S.A. Can J For Res 31:1437–43.

Stevens DL. 1991. A homeland and a hinterland: the Current and Jacks Fork riverways. Historic Resource Study, Ozark National Riverways. Van Buren (MO): National Park Service. 248 p.

Stokes MA, Smiley TL. 1968. Introduction to tree-ring dating. Chicago (IL): University of Chicago Press. 78 p.

Swetnam TW. 1993. Fire history and climate change in Giant Sequoia groves. Science 262:886–9.

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

Turner MG, Romme WH. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecol 9:59–77.

Veblen TT, Kitzberger T, Villalba R, Donnegan J. 1999. Fire history in northern Patagonia: the roles of humans and climatic variation. Ecol Monogr 69:47–67.

Waldman C. 1985. Atlas of the North American Indian. New York: Facts On File. 276 p.

Weslager CA. 1978. The Delaware Indian westward migration. Wallingford (PA): Middle Atlantic Press. 266 p.

Westin S. 1992. Wildfire in Missouri. Jefferson City (MO): Missouri Department of Conservation. 161 p.

Whelan RJ. 1995. The ecology of fire. New York: Cambridge University Press. 346 p.

Wiegers RP. 1985. Osage culture change inferred from contact and trade with the Caddo and the Pawnee [dissertation]. Columbia (MO): University of Missouri. 229 p.

Williams M. 1989. Americans and their forests: a historical geography. New York: Cambridge University Press. 599 p.

Wolferman KC. 1997. The Osage in Missouri. Columbia (MO): University of Missouri Press. 119 p.

Zinke PJ. 1977. Mineral cycling in fire-type ecosystems. In: Proceedings of the symposium on the environmental Consequences of fire and fuel management in Mediterranean ecosystems. Forest Service General Technical Report WO-3. Washington (DC) US Department of Agriculture. 498 p.

Appendix. The Fires of 1780

Dendrochronological evidence suggests the occurrence of extensive, and possibly intensive, fires in at least three areas of eastern North America during 1780, a year of drought and increasing human turmoil. In the Algonquin Highlands of southern Ontario, sites over an area of 2000 km^2 show evidence of fire in 1780 (Cwynar 1977; Dey and Guyette 2000a). At two of these Algonquin sites, 66% and

43% of the trees were scarred, indicating that surface fires must have been intense (Guyette and Dey 1995a, 1995b). In Missouri, 43% of the study sites in the Current River watershed were burned and 28% of the sample trees were scarred along the North Fork of the White River; evidence of fire in the same year was also found near the Gasconade River (Cutter and Guyette 1994). Along the breaks of the Arkansas River in the Boston Mountains, trees at three sites separated by 15 km had scars formed in 1780 (R. P. Guyette and M. Spetich unpublished). In addition, fires occurred circa 1780 in Minnesota (Heinselman 1981) and Maryland (Shumway and others 2001). The extent and severity of these fires was probably the result of a drought in 1780 (Cook and others 1999) coupled with concurrent human activities. Human conflict frequently results in wildland fire. Eastern Native American tribes were forced west and north into areas not yet populated by Euro-Americans circa 1780 and were often in conflict with the indigenous tribes they encountered such as the Osage in the Ozarks (Stevens 1991; Wolferman 1997). Spain declared war on England in 1779. By May 1780, the English, Menominee, and Winnebago were attacking the Spanish colony of St. Louis, Missouri (Foley 1999). There was a considerable struggle among the Americans, French, Osage, Cherokee, Spanish, and English for the control of trade in Missouri. Thus, a combination of human activities and drought probably resulted in one of the worst fire years of the 1700s.