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Compiled by:
Daniel A. Yaussy

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Contains 18 papers and 16 poster abstracts on the history of fire, fire ecology, fire and ecosystem management, and fire and the future presented at the workshop on fire, people, and the central hardwoods landscape.

Keywords: native burning, prescribed fire, prescribed burning, oak, mixed-oak, oak-hickory, barrens, ridgetop-pine, soil microbes, rare plants

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Humans, Topography, and Wildland Fire: The Ingredients for Long-term Patterns in Ecosystems

Richard P. Guyette[1] and Daniel C. Dey[2]

Abstract

Three factors, human population density, topography, and culture interact to create temporal and spatial differences in the frequency of fire at the landscape level. These factors can be quantitatively related to fire frequency. The fire model can be used to reconstruct historic and to predict future frequency of fire in ecosystems, as well as to identify long-term changes in anthropogenic fire regimes. Topographic roughness is positively related by a regression equation to the length of mean fire intervals indicating that fires are less frequent in rough than in flat terrain during periods of low human population density. The strength and direction of this relationship diminishes as the frequency of anthropogenic ignitions increases to the point that the fuel environment is pyro-saturated. Human population density is a master variable in understanding anthropogenic fire regimes and topographic effects. The interactions of these factors through time creates at least two stages in anthropogenic fire regimes: an Ignition Limited Stage in which fire frequency is function of human population density, and a Fuel Limited Stage during which fire frequency is limited by fuel production and is independent of increases in human population density.

Introduction

Human-Landscape Interactions Affect Fire Regimes

Humans are by far the most important factors influencing the frequency of fire ignitions in the Missouri Ozarks and elsewhere throughout much of eastern North America. Most fires occur during the fall, winter, and spring in years of normal precipitation. Dry, warm weather of only a few days is sufficient to cure fine fuels and permit the spread of surface fires, especially in the spring and fall when dead ground vegetation and leaf litter are most abundant and exposed to the sun. Fires during the growing season are rare but do occur during very hot and dry summers. High fuel moisture content and precipitation in summer limit fire ignitions and spread. Despite an abundance of thunderstorms in Missouri (50-70 thunderstorm days per year) (Baldwin 1973), natural ignitions are rare (Schroeder and Buck, 1970). Most thunderstorms occur in the spring and summer and are usually accompanied by heavy rainfall. Fire statistics for Missouri (Westin 1992) indicate that less than 1 percent of fires are caused by lightning, all other causes are human-related.

Topography and the fuel environment also are important variables that determine the fire regime by controlling fire spread, intensity and extent (Whelan 1995, DeBano and others 1998). Human culture and land use directly affect the continuity and nature of the fuel environment. We present a quantitative approach to modeling the interaction of humans with landscapes and their combined effects on fire regimes. Three factors, human population, topographic roughness, and culture, interact to create temporal and spatial differences in the frequency of fire at the landscape level.

Succession in Anthropogenic Fire Regimes

Through time, fire regimes undergo a number of changes based upon population density, topography, and culture. A progression of four stages in anthropogenic fire regimes can be identified in the upper Current River watershed fire record. These include: 1) an Ignition Limited stage, 2) a Fuel Limited stage, 3) a Fuel Fragmentation stage and, 4) a Culturally Limited stage. During Stage 1, fire frequency increases as the human population approaches 0.64 humans/km^2 and the number of potential ignitions increases. Fire frequency is a logarithm function of human population density. In later stages, as human population density increases and the landscape is saturated with ignitions, other factors limit fire frequency such as fuel loading and continuity, cultural attitudes toward fire, and human valuation of natural resources. In the Current River watershed, the second stage, a Fuel Limited Stage, is characterized by limits imposed on the frequency of fire frequency by the primary production of fuels. During this stage, human population density exceeds a threshold of 0.64 humans/km^2 and increases in population density and ignitions do not result in increased fire frequency.

This paper will integrate population density and topographic roughness in an empirically derived model that can be used to reconstruct past or to predict future frequency of fire in ecosystems at specific sites. Here, we focus on the development of an empirically based model of fire frequency from over 2,500 tree-ring dated fire scars at 29 sites in the Current River watershed in southeastern Missouri. This data set is used to develop and verify a regression equation that predicts fire frequency based on topographic and population variables. We also examine the interactions of humans and landscapes with respect to fire regimes, and illustrate, using the fire model, the spatial and temporal variability in the anthropogenic fire regime in the upper Current River landscape.

Rational and Use for Fire Regime Models

Quantitative models of fire regimes can be used in many ways. Past fire regimes can be reconstructed for natural areas that have no on-site fire history information. The equations can be used in conjunction with soil, geology, and species data to reconstruct past and potential flora and

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faunal mosaics. Thus, land managers interested in returning small isolated parcels of land, natural areas, or whole ecosystems to pre-European conditions using prescribed fire can use this model to reconstruct the fire regime. Researchers can also use the equation to create a GIS overlay of a fire regime for use with research plots or to make inferences about future fire regimes based on changes in population and climate, and landscape variables. Perhaps the most important aspect of fire regime models and fire history however, may not be the information provided on fire regimes, but the perspective provided on the long-term interactions between humans and their environment.

The Historical Context of Human Populations, Cultures, and Fire in the Current River Watershed

All of the historic changes in human populations due to war, migration, and disease are probably reflected in the fire scar record. Europeans introduced diseases decimated Native American population. War among peoples caused migration and genocide. Depopulation caused by disease (Dobyns 1983; Ramenofsky 1987), warfare, and migration occurred throughout much of North America (DeVivo 1991) and has been linked with abrupt changes in fire history (Guyette and Dey 1995a; Dey and Guyette in press). Indeed, often the highly variable nature of human populations and culture is reflected in the extreme variability of the fire record within a site (Guyette and Dey 1995b, Cutter and Guyette 1994, Guyette and McGinnes 1982).

Anthropogenic ignitions were probably frequent along the rich fertile bottom lands of large rivers including the Current and Jacks Fork Rivers. About 1000 A.D. (Lynott 1989, Price and others 1983) during the Mississippian Cultural Phase, agricultural communities were located in riparian areas in the Current River watershed, and they would have been a source of many ignitions. With the end of this phase (about 1350 A.D.) began an era of limited use of the watershed by humans from downstream reaches of the river system (Price and others 1976). An early source of anthropogenic ignitions may have been the 6,000 Quapaw (Baird 1980) that lived to the southeast of the Current River in Arkansas near the confluence of the White, Arkansas, and Mississippi Rivers before 1680. Disease came first to large riverine cultures such as the Quapaw because of their location and population density (Dobyns 1983), and reduced the Quapaw population by two thirds in 1698 and again reduced their population in 1747 and 1751 (Baird 1980). There were only about 700 Quapaw by 1763. Coincident with a low percentage of sites burned circa 1750 in the Current River watershed (Guyette and Cutter 1997) were epidemic disease in 1747 and 1751 which reduced the Quapaw population.

The Osage people frequented the study site about the time of first European contact and probably provided many ignitions during the 1700s (Guyette and Cutter 1991). Banks (1978) commented that there were about 6,000 Osage circa 1800 in and around the Ozarks. About 1,200 Great Osage lived on the Osage River 280 km west of the Current River (Marriott 1974). A change in the territorial boundaries of the Osage from the late 1600s to about 1803 (Bailey 1973, Wiegers 1985) is coincident with long-term trends in fire frequency in the Current River watershed (Guyette and Cutter 1997). Territorial expansion by the Osage from 1673 to 1770 probably resulted from many factors, one of which included the acquisition of equestrian technology from aboriginal trade with western tribes. The horse gave the Osage new range and mobility to hunt, exploit, and culture (by fire) areas such as the Current River watershed which were distant from their territorial focus. Wiegers (1985) estimated that the Osage acquired horses as early as 1680 while Waldman (1985) sets the date circa 1719. They hunted in the east for bears (perhaps in the Current River watershed) and in the west for buffalo (Chapman and Chapman 1972). Stevens (1991) reported that the Osage moved south and east toward the Current River on extended spring hunts coincident with Missouri's largest fire season (Westin 1992).

The Cherokee were one of several tribes that migrated into the Ozarks after being displaced from their eastern lands by Euro-Americans (Gilbert 1996). They probably continued the traditional burning practices they had used on their ancestral lands. About 6,000 Cherokee (Gilbert 1996) may have been living in southeast Missouri and northeast Arkansas at the time (1803) of the Louisiana Purchase. In the late 1770s, many of the Cherokee settled to hunt and farm along the St. Francis River, which lies about 60 km east of the Current River. The Osage made war upon the Cherokee (Banks 1978) as the Cherokee infringed upon their hunting grounds. Conflict may have led to wildland burning. A general increase in the percentage of sites burned annually (Guyette and Cutter 1997) in the Current River watershed occurred from 1760 (9 percent) to 1820 (30 percent) coincidently with the migration of the Cherokee (Gilbert 1996) and other eastern tribes.

The Delaware had a tradition of wildland burning before migrating to Missouri from Ohio (Whitney 1994). The Delaware and Shawnee entered Missouri at Cape Girardeau and passed through the Current River watershed on their way west in the late 1700s and early 1800s (Stevens 1991). One estimate of Shawnee and Delaware population west of the Mississippi in 1812 was 400 (Marriott 1974). In 1816, Banks (1978) stated that there were about 840 Delaware and 1,300 Shawnee in all of Missouri. In 1824 there were 1,383 Shawnee in Missouri (Howard 1981). Delaware hunted, lived, and traded in the upper Current River area from about 1815 to 1822. In November 1820, 1,346 Delaware crossed the Mississippi River and made an emergency encampment on the Jacks Fork of the Current River (Weslager 1978). However, they stayed a number of years and this was associated with increased fire frequency (Guyette and Dey 1997). Most of the Delaware and Shawnee had left the Current River watershed by the 1830s and Euro-Americans began to occupy the area.

Old-stock Euro-Americans (Gerlach 1986) from the southeastern U.S., mainly Tennessee, began settling in the area circa 1820 and continued their tradition of wildland burning. Later, circa 1860, Scotch-Irish immigrated into the area. The Current River watershed, like many other forested areas in the eastern United States (Sutherland 1997), experienced an increase in fire frequency with settlement by Euro-Americans. In the Current River watershed the percent of sites burned increased with population density during the 1810 to 1850 period and the average percent of sites burned in a year nearly doubled from 20 percent in 1810 to 39 percent in 1850 (Guyette and Cutter 1997).

Methods

Fire Scars

Fire scars on survivor trees form the data base of this work. In anthropogenic fire regimes, fire scars can be thought of as ecological artifacts. They are objects made or modified by humans. Humans set wildland fires and wounded these woody plants as they attempted to manipulate vegetation with fire for a variety of purposes. As ecological artifacts, they point out the relationships between humans, organisms, and forests. Like artifacts in an archeological context, they can be dated in time and given a location in space. As such, they reflect many human characteristics such as population density and culture that can be used in an anthropological context. The dates and locations of these ecological artifacts are used in this work to examine the relationships between humans, fire, and landscape over a period of extraordinary change and diversity in human history.

The regression equation for reconstructing historic fire frequency is derived from data on fire frequency, topographic roughness, and human population density. The mean fire intervals (MFI) used in the regression equation were derived from fire scar data for three time periods (1700 to 1780, 1781 to 1820,1821 to 1850) at the 29 sites. Much of the fire history information that follows is compiled from more than 2,500 fire scars on shortleaf pine (*Pinus echinata* Mill.) stumps, trees, and remnants in the Current River watershed (Guyette and Cutter 1997, Batek and others 1999). Dendrochronological methods were used to date the fire scars found on over 166 shortleaf pine which are used as the basis for the model and following discussion. The mean fire intervals (MFI) in this study are thought to reflect fire frequency during ecosystem development and a range of human population densities that has occurred over at least the last millennium in the Ozarks. Here, we present the two most significant variables in an equation that characterizes the effects of human population density and topographic roughness on the frequency of wildland fire.

Human Population Estimates

A spatial and a temporal component of human population are combined to reconstruct human population density values for use in the equation. The spatial component reflects the tendency in the watershed for greater population densities and therefore ignitions to occur downstream. We use the distance upstream of a site from Hawes, on the Current River, as a reference variable we call River Mile to model this tendency. Many archeological and historic Native American sites are located in the larger and more fertile bottom lands in the downstream reaches of the Current River (Stevens 1991). For instance, a major Osage trade route to St. Louis intersected the lower Current River. The abundance of these sites decreases significantly (r=-0.53, p=0.03) with their distance upstream. The Mississippian cultural phase (O'Brien and Wood 1998) persisted downstream on the southeast border of the Ozarks until as late as 1700 (Price et al. 1976). Quapaw lived downstream and southeast of the watershed (Rafferty 1981). Later, the density of human built structures in the Current River watershed during the mid 1800s diminishes with their distance upstream (r=-0.69, p=0.002). Even today the population of towns along the Current River and Jacks Fork Rivers decreases as one moves upstream (r=-0.98, p=0.02). Perhaps fertile soils of the lower reaches of the river produces more fuel and forage, which in turn attract more game, hunters, gatherers, and agriculturalist. These are relationships that may persist, to some extent, through time and cultures. Alternatively, fertile soils may be correlated with landscape level fuel and fire dynamics, or land form gradients such as topographic roughness, that may affect the ignition, spread and consequently the frequency of fire.

We derived the temporal component of human population density in the study area from population numbers and trends as described in historical accounts and analyses as reviewed in the introduction. Fire frequency has been found to be strongly associated with human population density (Guyette and Dey 1997, Dey and Guyette in press, Guyette and Cutter 1997). The density of each group in the Current River watershed was calculated by dividing their total population by the area of a circle whose radius was the distance between the population center and the study site. This component of human population density does not take into account the great spatial variation of population density within an area and only reflects changes in population density over time at study sites as a whole.

An Index of Topographic Roughness

The highly dissected topography of the Current River watershed has been shown (Guyette 1995) to affect the spread and frequency of fires during periods of low human population density when anthropogenic ignitions were limited in number. Roughness can slow a low intensity fire by decreasing the rate of spread as fires burn down steep slopes, fuel continuity is broken by creeks, rivers and rocky outcrops, and changes in aspect influence fuel moisture. Topographic roughness is estimated by measuring the surface area of the earth with measuring surfaces of different sizes (Figure 1). Indices of topographic roughness are developed by comparing surface area measurements made with two different sized scales. A circle, 5,000 meters in diameter, is marked on a digital elevation map. The surface area of the earth enclosed by this circle is calculated from pixels that are 30 meters on a side. Their slope and a trigonometric conversion are used to estimate the area of the uneven land surface (Krstansky and Nigh 1999). 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 the circle that is 5,000 meters in diameter. This ratio of the actual

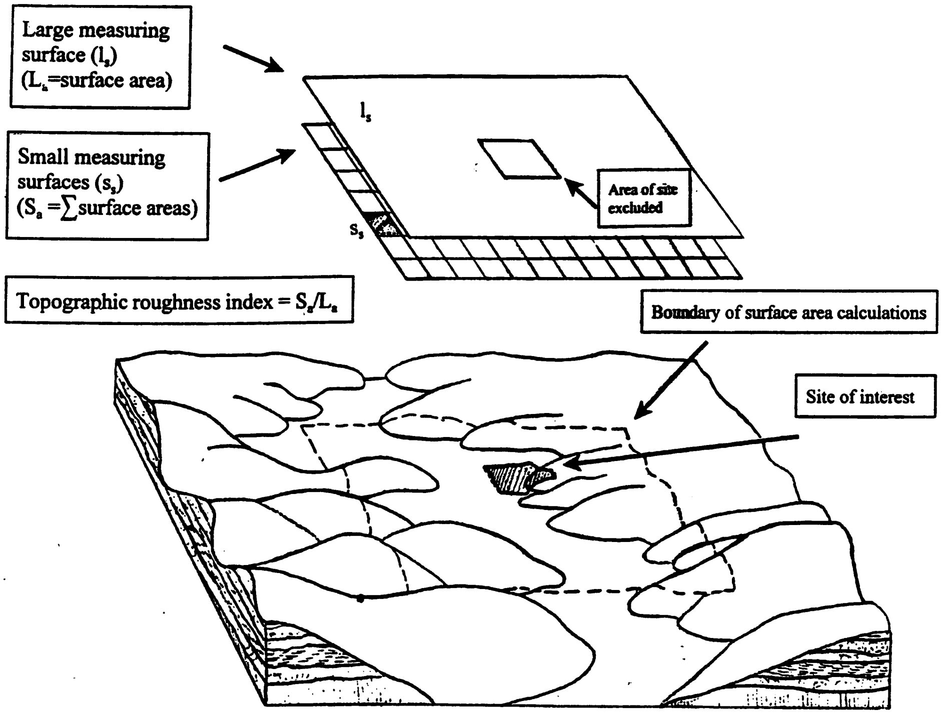

Figure 1.—Topographic roughness is an important variable which interacts with human population density to control the frequency of fire. Topographic roughness can be estimated with an Index of Topographic Roughness. The illustrated example of an Index of Topographic Roughness is calculated by measuring the circumscribed region of the earth of a given dimension and shape with a large measuring surface (l_s) and many small measuring surfaces (s_s). The sum of the areas (S_a) of the small measuring surfaces is then divided by the area (L_a) of the large measuring surface to obtain the Index of Topographic Roughness.

surface area to the planimetric surface area is the Index of Topographic Roughness.

Results and Discussion

Modeling Fire Frequency

We use the Index of Topographic Roughness and estimates of human population density to model the frequency of fire at the landscape level. Central to this model are regression equations derived from and tested with independent fire scar data. The regression used to reconstruct past fire frequency at the study sites for the period 1700 to 1850 is:

$$MFI = -442.1 + (449.9 \times topo) - (0.001 \times pop), \qquad \text{(Equation 1)}$$

where: MFI= mean fire interval
topo = Index of Topographic Roughness for a circle with a 5,000 meter diameter
pop = natural log of human population density times the square of river mile,
n = 78 (three time periods, 29 sites),
$r^2 = 0.51$,
all variables and intercept are significant at $P<0.01$.

This regression explains about half of the variability in fire frequency in time and space. The amount of unexplained variability is not surprising considering the large role chance plays in a complex and highly variable phenomena like wildland fire. In addition, there are methodological problems with the fire scar record such as the number of sample trees at a site, their location, the size of the site, and the hit and miss nature of the scarring process that create errors with respect to the actual spatial and temporal distribution of fire events in the data set. None-the-less, the temporal and spatial depth of the fire scar record allow for the identification of the significant independent variables in this equation. Although the framework of this equation may be applicable in many ecosystems, the calibration of these variables will differ greatly in different ecosystems. Differences in fuels, climate, topographic roughness, and other landscape variables such as the abundance of lakes would require a new calibration.

Human Population Density and Topographic Roughness in Fire Regimes

Anthropogenic fire regimes are the result of complex interactions between human population density and an number of factors, such as culture, fuels, and landscape. Topographic roughness is one of the most important and temporally persistent landscape variables. At low population densities, fire frequency increases as population density does as a result of increasing anthropogenic ignitions (Figure

2) and topographic roughness is an important factor mitigating the frequency of fire (Figure 3). At higher population densities fire frequency may be fuel dependent or diminish as landscape artifacts (i.e., fuel continuity or mosaic that result from human land use), culture, and changes in human economics (ex. real estate, forage, timber) inhibit the ignition and propagation of fire over the landscape. The effects of topographic roughness on fire frequency change with time and human population (Figure 4). Topographic controls on the frequency of fire become less and less important as population density and the frequency of anthropogenic ignitions increases. Just before the era of fire suppression (Figure 4), as population density and agricultural activity become greater, burning increases in topographically rough areas relative to topographically smooth areas as humans attempt to culture vegetation in areas of marginal agricultural productivity. A rule-of-thumb concerning fire history is that at low population densities topographically smooth areas (often prairies and grass lands) burned more often than topographically rough areas (often forested lands). As population density increases, topographically smooth areas burn less often and topographically rough areas burn more often.

Pyro-saturation is a stage in a fire regime when fuels are burned as soon as they accumulate enough to carry a fire. Inorganic decomposition (fire) plays a much greater role than organic decomposition (decay) in controlling the oxidation of biomass. Ecologically, the resistence of an ecosystem to pyro-saturation is a function of human population density and topographic roughness. The resistence of some ecosystems to pyro-saturation from anthropogenic ignitions is very low. For instance, it might take only a handful of humans on horseback or foot to keep a topographically smooth ecosystem, such as a large prairie of tens of thousands of square kilometers, in a state of pyro-saturation. On the other hand, many topographically rough ecosystems, such as the forests of the Central Hardwoods Region, require a relatively high human population density to reach and maintain pyro-saturation. The quantitative relationships expressed in Equation 1 allow us to estimate that in the Current River watershed it takes about 0.64 humans per square kilometer to reach a state of pyro-saturation.

Implications for Landscape Fire Regime Diversity

The fire model (Equation 1) was used to predict the mean fire interval for points throughout the upper Current River watershed (Figure 5). The value to this approach to studying landscape-level fire regimes is that extrapolation of single fire histories of limited spatial and temporal dimensions often underestimate the actual variability within an ecosystem. In contrast, a landscape fire model can represent the diversity of fire regimes as they change across the landscape with variations in topographic roughness and human

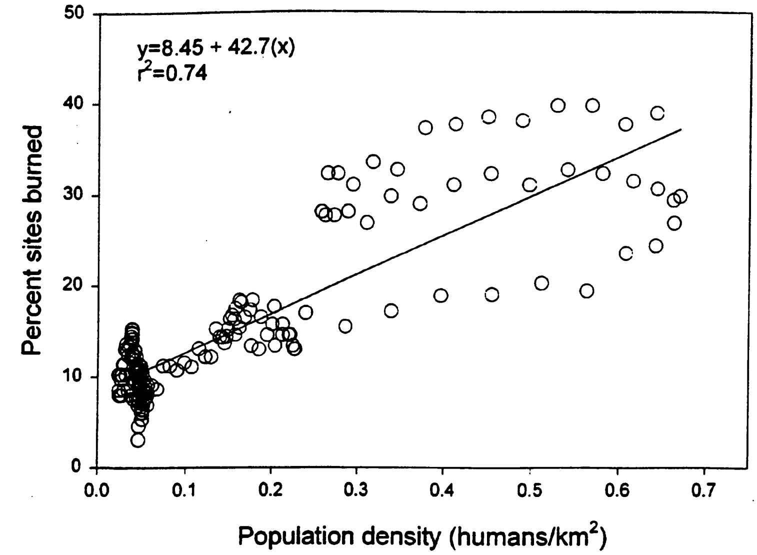

Figure 2.—Human population density is the major factor in the frequency of wildland fire ignitions in many regions. This scatter plot and regression illustrate the change in the percentage of study sites burned each year with human population density. The data is for the period 1620 to 1850 and is from the Current River watershed in Missouri. The percentage of sites burned (y axis) is from annual data that has been smoothed with an 11 year moving average (Guyette and Cutter 1997).

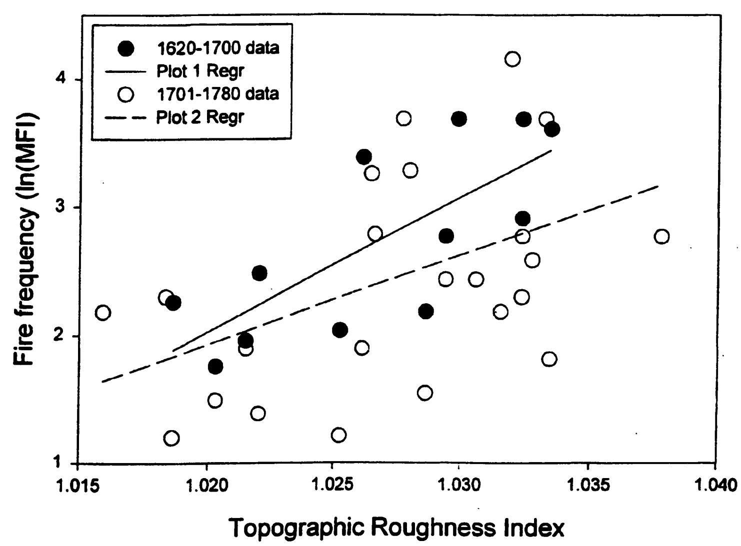

Figure 3.—These two scatter plots and regression lines illustrate the mitigation of fire frequency (MFI) by topographic roughness during two periods of low human population density. Topographic roughness is hypothesized to have reduced the frequency of fire by inhibiting the ignition and spread of anthropogenic fires.

population. The diversity of mean fire intervals present at the landscape level between 1700 and 1780, a period of low population density, may best reflect the fire regime as it was for many centuries before European settlement.

The diversity of fire frequency at specific locations in the Current River watershed is much greater at low population densities than at high population densities as the spread of fires from a limited number of anthropogenic ignitions is mitigated by topographic roughness. The spatial diversity of fire frequency within an ecosystem that results from topographic roughness persists through time and can result in strong species associations. Long-term topographic control of fire regimes can create refugia for fire sensitive species in topographically rough areas as well as creating refugia in topographically smooth areas for fire dependent species. These refugia may provide valuable sources for re-colonization of disturbed landscapes.

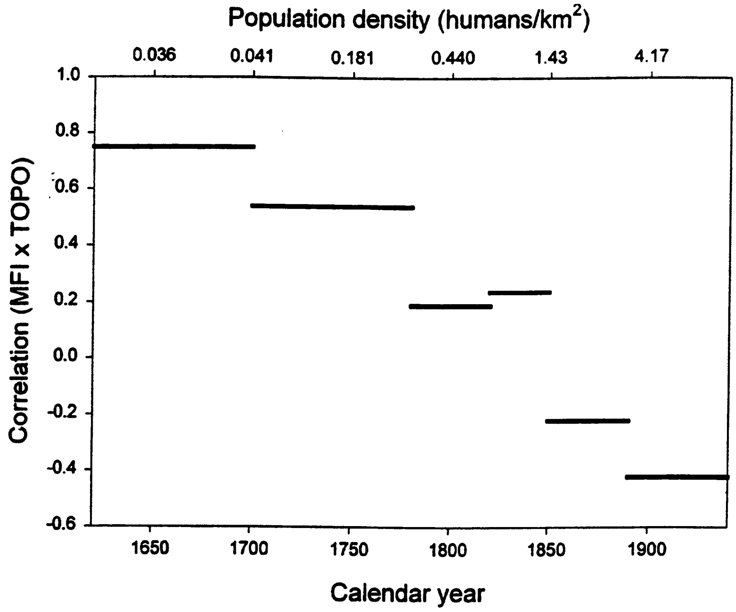

Figure 4.—This graph illustrates how human population density can mitigate the effects of topographic roughness on the frequency of fire. The y axis is the correlation coefficient between fire frequency (MFI) and the Index of Topographic Roughness. The upper x axis shows the mean population density of the period of correlation. The bars indicate the level, sign, and period of the correlation calculation. Correlations for the two earliest and the latest periods are significant ($p<0.05$).

Conclusions

Fire frequency varies spatially and temporally at the landscape-level largely due to changes in topography, human population, and culture. Population density and topographic roughness are master variables in understanding anthropogenic fire regimes that can be quantified and used to model the variability within a fire regime. Although landscape level fire models require a considerable investment in the acquisition of fire scar, site, landscape, and population data, they enable an understanding of long-term fire regimes that can be used in many ways.

Our fire model can be used to estimate the frequency of fire at any or all points in a landscape. Fire frequencies and regimes can be calculated for natural areas, parks, and forests that have no fire scar, historic, or charcoal data base for estimating a fire regime. Future predictions of fire frequency can be made by incorporating changing human population density, values, climate, and fuels into the model. The model enables the mapping of variation within a fire regime in both time and space. Maps of fire regimes and estimates of the long-term frequency of fire can be used in research on flora and fauna, in setting the frequency of fire in prescriptions to restore or maintain fire-dependent ecosystems, and the development of silvicultural prescriptions that mimic “natural” disturbances. Maps of fire regimes and the long-term frequency of fire disturbances can also be used to identify areas in the landscape that are refugia for either fire-dependent or fire-sensitive species.

Anthropogenic fire regimes, composed of complex interactions among fire, humans, fuels, and topography, have altered a continuum of ecosystems in North America for many thousands of years. These fire regimes are dynamic and have a number of identifiable successional stages that change as humans populate and transform their environment by fire and artifact. Human-induced changes in a fire regime are modified by topography and fuels. Stages in anthropogenic fire regimes are marked by changes in factors which limit the frequency of fire such as the frequency of ignitions, the production of fuels, the propagation of fire, and changing cultural values.

Acknowledgments

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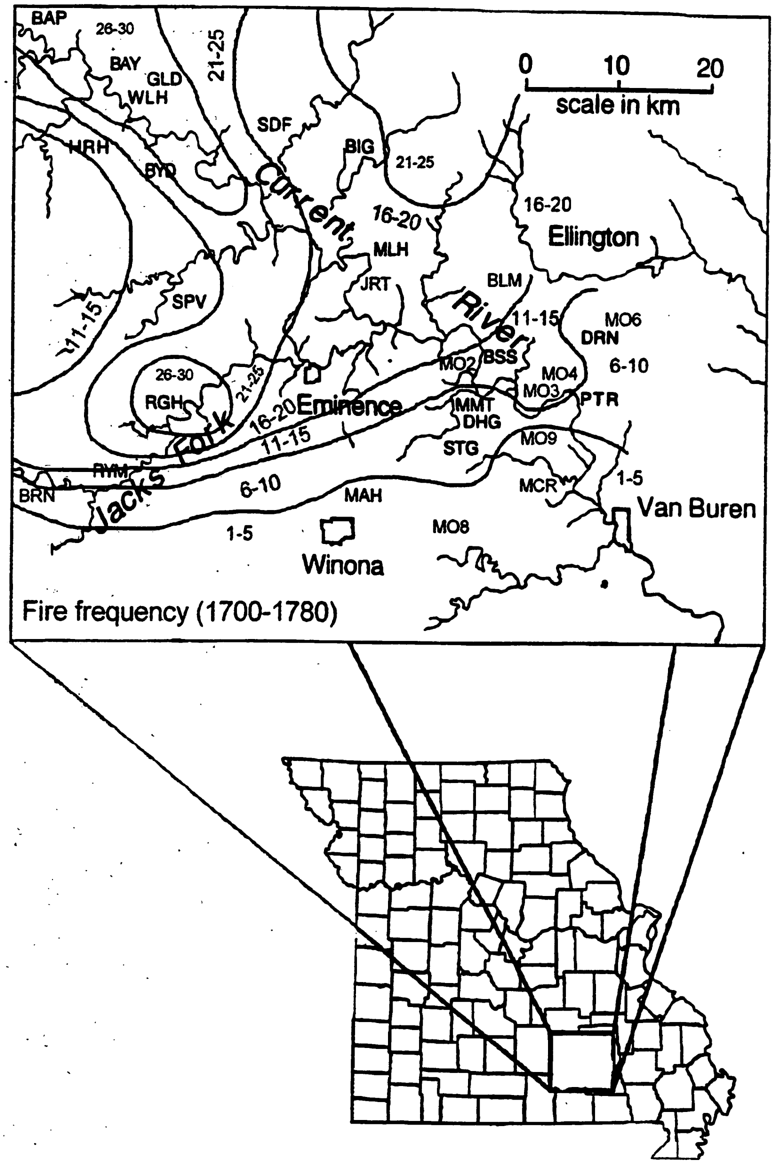

Figure 5.—This map illustrates the diversity of mean fire intervals present at the landscape level during a period (1700 to 1780) of low to moderate population density, which best reflects the fire regime many centuries before European settlement. Fire frequency gradients are represented by the iso-pyro lines. Iso-pyro lines define a gradient of equal fire frequencies. Numbers adjacent to iso-pyro lines give the class of mean fire intervals defined by each line.

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