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Using a spatially explicit ecological model to test scenarios of fire use by Native Americans: An example from the Harlem Plains, New York, NY

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ABSTRACT

It is unclear to what extent Native Americans in the pre-European forests of northeast North America used fire to manipulate their landscape. Conflicting historical and archaeological evidence has led authors to differing conclusions regarding the importance of fire. Ecological models provide a way to test different scenarios of historical landscape change. We applied FARSITE, a spatially explicit fire model, and linked tree mortality and successional models, to predict the landscape structure of the Harlem Plains in pre-European times under different scenarios of Native American fire use. We found that annual burning sufficed to convert the landscape to a fire-maintained grassland ecosystem, burning less often would have produced a mosaic of forest and grasslands, and even less frequent burning (on the order of once every 20 years) would not have had significant landscape level effects. These results suggest that if the Harlem Plains had been grasslands in the 16th century, they must have been intentionally created through Native American use of fire.

1. Introduction

The use of fire by Native Americans in northeast North America has been the subject of much debate shared among a broad group of ecologists, archaeologists and environmental historians. Some like Day (1953), Cronon (1983) and Krech (1999) believe that Native Americans used fire often to manipulate their landscape, and that these manipulations may have taken place over broad extents in the pre-European forests.

Skeptics admit that the rate of forest fires around a village might have been elevated over a background rate because Northeast Indians were using fire for cooking and pottery. However, they find little evidence that fires were widespread or intentionally set (Russell, 1983). Early settlers rarely offer first-hand accounts of fires and fewer still tell of intentional

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burning. These, Russell says, might be attributed to escaped fires.

Intentional burning has many potential benefits for hunting and gathering peoples: frequent fires can clear tangled vegetation, making it easier to travel through and to clear for horticulture (Lewis, 1993); fire can create vegetation mosaics that are attractive to deer and other game species, and make hunting easier (Williams, 1997); sometimes people set fires just for fun (Putz, 2003).

Of course different fire regimes have different effects on the ecology of Northeast forests. A frequent fire regime would favor a grassland with lingering oaks, a fire-tolerant genus (Swan, 1970; Abrams, 1992, 2000). Less frequent fire would lead to regenerating forests (Abrams, 1992). Understanding Native American use of fire is important for understanding the structure and function of pre-European forests.

As part of a larger project to reconstruct the past landscape structure of Manhattan Island (Sanderson, 2003), we examined the use of fire by Native Americans in the Harlem Plains of what is now New York City, NY. Although records are sparse, a few accounts of pre-settlement Harlem exist. De Rasieres describes in 1624 "a large level field, of from 70 to 80 morgens (140–160 acres) of land, through which runs a very fine fresh stream; so that the land can be ploughed without much clearing" (de Rasieres, 1990). Historical maps consistently refer to this area as a plain.

Numerous historical accounts describe grasslands (the most famous of which were the Hempstead Plains of Long Island) (Svenson, 1936; Stalter and Lamont, 1987; Stalter et al., 1991) as well as patchier areas (Wood, 1824) in the New York region. But while the grasslands of the Hempstead Plains appear to be the result of primarily edaphic conditions – specifically dry, sandy soil (Svenson, 1936) – the Harlem Plains seemed to have quite fertile soil, underlain by calcareous bedrock (Baskerville, 1994). Dutch settlers in New Netherlands chose it as one of the first spots to farm on Manhattan (Stokes, 1967). Perhaps the most similar modern-day equivalent to the early Harlem Plains is Floyd Bennett Field in Jamaica Bay, Brooklyn. Recent prescribed burns have maintained the grasslands there, but without constant maintenance, shrublands quickly appear and would soon succeed to forest (Lent et al., 1997).

The Native Americans who lived on Manhattan at the time of European settlement were the Lenni Lenape, or Delaware, people (Cantwell and Wall, 2001). A number of small groups of Lenape Indians lived on Manhattan, from the southern tip to what is now Greenwich Village, Inwood, and the Harlem Plains (Bolton, 1920). The Lenape had a pattern of land rotation, clearing an area and planting maize for a number of years, then letting the fields grow back for approximately 20 years (van der Donck, 1841). Presumably they, as with other Algonquin people, used fire to clear the land for horticulture. What is clear is that within years of removal of the Lenape from the area, much of the land in Harlem became overgrown and reverted to forest (Riker, 1881).

From this history, we hypothesize that if the Harlem Plains could "be ploughed without much clearing" as De Raiseres describes, they likely consisted of grasslands intentionally created by Lenape use of fire. To test this hypothesis, we used a combination of ecological models parameterized under different scenarios of Native American fire use to examine what different landscape configurations would result from different fire regimes. In short, how often would the Lenape have had to burn Harlem to maintain a grassland ecosystem?

2. Methods

2.1. Model overview

To examine the landscape level consequences of Lenape fire use in Harlem, we constructed an interlinked set of spatially explicit models (Fig. 1). First, the fire model FARSITE (Finney, 1998) was used to model the distribution and intensity of fire under different fire frequency scenarios. Second, the results of FARSITE at each time step were fed into a tree-mortality model, yielding vegetation changes as a result of fire in a given year. Third, a successional model was applied to the entire landscape to represent regeneration over time. Our model closely follows Li's (1999) suggested methods for reconstructing historic fire regimes, however we do not make the assumption that forest cover types remain the same before and after the fire and succession.

The model was run at annual time steps for 200 years and with spatial resolution of 10 m^2. 200 years was assumed to be long enough to clarify the emergent patterns of the burning regimes—that, whatever the initial conditions, the resultant landscape would emerge over a long enough time frame. Fires were assumed to be associated with agricultural clearance and therefore all to have occurred in early April. Fire frequency

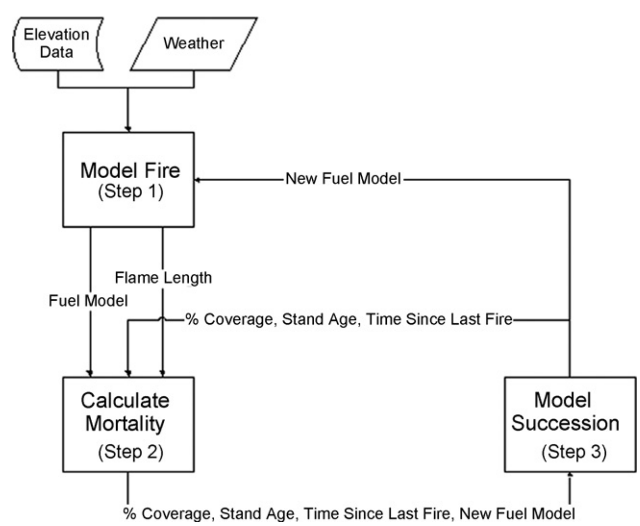

Fig. 1 – Overview of the models. The computer model cycle consists of three steps: FARSITE, using fixed elevation data and changing weather data, models a fire over the Harlem landscape. Next, a Perl script combines information from FARSITE with information about individual raster cells to calculate mortality of the vegetation. Finally, these changes in vegetation are given to the succession script. Step 3 allows the grasses, shrubs and trees in the fuel model to grow for a given length of time, after which the new vegetation map is sent to FARSITE to model a new fire. The process is repeated over 200 years.

scenarios were tested with ignitions every year, every 10 and 20 years. Four different input vegetation maps were used: forest, old savanna, young savanna and grasslands. Originally, we had intended to start each scenario as old growth forest (the assumed climax vegetation for Manhattan). In the process of running the models, it became clear that the Lenape may have been forced to initiate a number of fires in quick succession to clear the forest, but that after the first clearance, a longer interval between fires would have sufficed. Our question was not how the Lenape created an open grassland or savanna, but whether they would have been required to maintain it.

Initially, each scenario was to be run 10 times to allow for stochasticity in the models. After one test run, however, extreme scenarios showed clear results and were run fewer times. For fires set every 10 years in grassland and savanna, the 200-year cycle was run 10 times; other scenarios were run once because of their deterministic nature.

It is possible the Lenape burned in the late fall, after the harvest; some have suggested they burned twice a year, once in the fall and once in the spring (Day, 1953). We conducted sample tests using October weather to determine if the time of year had an effect on the outcome. Fires were set every 10 years in October with a starting condition of old savanna. We also ran the model by burning, every 20 years, with initial vegetation of old savanna and forest.

2.2. Fire model

FARSITE requires five Geographic Information System (GIS) inputs and a number of climatic inputs (Finney, 1998). The spatially explicit, GIS inputs include elevation, aspect, and slope, based on a digital elevation model (DEM), and a fuel model and crown cover map based on a vegetation map. The climatic inputs are maximum and minimum ambient temperature; maximum and minimum relative humidity; cloud cover; wind velocity and direction; and precipitation type, amount and duration. Finally, FARSITE requires information on the moisture of dead and live fuels (vegetation).

The historical DEM of the Harlem Plains was developed from historical map sources, survey notes, and modern elevation measurements on extant landscape features (e.g. Mt. Morris in Marcus Garvey Park). The main map source was the British Headquarters Map, circa 1782 that shows much of the historical topography before 19th and 20th century development (Stevens, 1900; Cohen and Augustyn, 1997). The survey notes were drawn from the surveys of John Randel Jr. for the street grid of Manhattan constructed from 1812 to 1821 (Randel, 1812–1822). Randel provides elevations approximately every 50 ft. (15 m) for several of the avenues and streets of Harlem. Modern measurements were made on extant rock outcrops using a global positioning system and an altimeter (Bean, 2004). A contour map of Central Park (Viele, 1855) also provided some information for the southern part of the landscape prior to extensive development. These data were used to drive a systematic interpolation of elevations at 10 m intervals across the landscapes. After manual adjustment over areas of high slope change, these were used to derive the DEM, and from that DEM slope and aspect were derived using standard techniques (McCoy and Johnston, 2002).

A simple initial vegetation map was developed with three classes: forest (defined as more than 50% tree cover), oak savanna (defined as 5–50% tree cover) and grassland (less than 5% tree cover) (Brewer and Grigore, 1993). Fuel models for each of these vegetation types were based on those described by Anderson (1982): Fuel Model (FM) 1 is designated for grassland ecosystems, FM 2 for oak savannas, and FM 9 for oak-hickory stands and other northeastern hardwoods (Anderson, 1982). A recent study showed that FM 2 was the best at predicting fires in oak savannas in Wisconsin (Grabner et al., 2001). After the first fire, two other fuel models were necessary: FM 5 for shrublands (tree cover <5%) and FM 8 for recently burned, regenerating forest.

The vegetation map was a simplification of the varied landscape in the Harlem Plains. However, because we were interested in the general results of different burning patterns, we felt a generalized landscape would suffice. Whether burning every 10 years could have created a grassland south of 125th street seemed less important than whether it could have created an open landscape in Harlem at all. As stated, we believed 200 years to be a long enough period of time to essentially negate our initial vegetation conditions.

Fuel models are conditioned by fuel moisture, usually reported for 100-h, 10-h, 1-h and live fuels. Review of the US Forest Service fuel moisture maps for southeastern New York in April 2002 and 2003 consistently indicated 100-h fuel moistures of 15–20 or >20% (United States Forest Service, 2004)—we set 100 h fuel moisture to 20%. 10-hour fuel moistures in a similar forest near Marienville PA were also 20%. 1-h fuel moistures were set to 18%. A recent measurement of live fuel moistures (Moritz and Morais, 2003) set live herbaceous moisture at 85% and live woody at 105%—these percentages can go as high as 130%. We increased these live fuel moistures by 10% to account for wetter spring conditions in early April, so 95% for live herbaceous fuels and 115% for live woody fuels. Because the fuel moistures in the Moritz and Morais study were measured in a much drier landscape, we conducted sensitivity analyses on the fuel moistures, increasing and decreasing them by 50%.

Detailed weather records for Manhattan begin in 1869 (National Climatic Data Center, 2003). Studies of pollen counts and tree rings indicate that the climate in New York 400–600 years ago was relatively similar to that of the past 150 years (Kleinstein, 2003), so that extrapolating weather from the past 135 years to the 15th and 16th century is possible. We used the Central Park weather records to calculate mean and standard deviations for temperature and precipitation. Mean and standard deviation for maximum and minimum relative humidity were based on data from a fire weather observatory in Marienville, PA (National Wildfire Coordinating Group, 2004)—the closest fire observatory to Harlem. Data on wind distribution were not available, so winds were set to vary stochastically both in direction and velocity, between 0 and 5 miles (0–8 km) per hour. We presumed that if a day were too windy, the Lenape would not ignite a fire (Table 1).

2.3. Tree-mortality model

Tree mortality due to fire was calculated using the “First Order Fire Effects Model” described by (Reinhardt et al., 1997),

Table 1 – Weather inputs for FARSITE

	Max temperature	Min temperature	Max humidity	Min humidity	Amount	Probability (%)
Rain						
Mean	54	41	95	48	0.33	35
S.D.	9	6	3	20	0.14	
Data points	693	693	399	399	693	
No rain						
Mean	57	40	85	35		
S.D.	10	7	12	13		
Data points	1188	1188	423	423		

Temperature and precipitation data were taken from Central Park records for the past 135 years. Humidity data comes from the Marienville, PA fire observatory records. Separate data were used depending on if the day was chosen as rainy or not.

that is:

$$P_m = \frac{1.0}{1.0 + \exp(-1.941 + 6.316(1.0 - \exp(-BT)) - 0.000535\,CK^2)} \quad (1)$$

where P_m is the probability of mortality, BT is bark thickness and CK is the percent of crown killed. The probability of tree mortality was used to record the percentage of trees killed in each 10 m^2 cell. Each 10 m^2 cell was assumed to be even-aged. Calculations of mortality were performed for the entire stand based on the age of the oldest trees in each stand.

Bark thickness can be calculated based on the diameter at breast height (DBH). For a generic oak species (Reinhardt et al., 1997):

$$BT = 0.045\,DBH \quad (2)$$

DBH in turn is modeled as function of tree age, based on an equation provided by Loewenstein et al. (2000) for oaks in Missouri:

$$DBH = 25.706\,(\ln(\text{age})) - 85.383 \quad (3)$$

Finally, we estimated the percentage of crown killed (CK) based on an analysis of scorch height, crown ratio and tree height. Scorch height is a function of flame length (Van Wagner, 1973), such that

$$SH = 3.1817(FL \wedge 1.4503) \quad (4)$$

Flame length is an output of FARSITE. When the scorch height does not reach the bottom of the crown (calculated as (1 − crown ratio) tree height), the percent of crown killed is 0. Once the scorch height reaches the crown, however, CK is not a simple relation between crown ratio and scorch height. By varying tree height, crown ratio and flame length in (Reinhardt et al., 1997) our fire effects model, we estimated their equation for CK as

$$CK = 41.961\left(100\left(\ln\left(\frac{SH - CH}{CL}\right)\right)\right) - 89.721 \quad (5)$$

Because of the empirical basis of the tree growth and mortality equations, we conducted sensitivity analyses on the model by modifying the coefficients ±50% in Eqs. (1) and (3). Model outputs were examined for each and compared to the base model using the parameters as shown.

2.4. *Successional model*

A simple state-transition succession model (e.g. Allen Diaz and Bartolome, 1997; Shlisky and Hann, 2003) was built for vegetation recovery after fire, as shown in Fig. 2. This model was based on old-field studies of forest recovery in the Northeast (e.g. Pickett, 1982; Keever, 1983; Myster, 1993). Succession was based simply on time since the raster cell last burned. Grasslands succeed to shrublands if left unburned for 8 years. Based on analysis of oak growth curves, we estimated that after 18 years as a shrubland, the vegetation would change to regenerating forest (fuel model FM 8). After 80 years without a fire, the vegetation type succeeded to mature oak-hickory forest (fuel model FM 9).

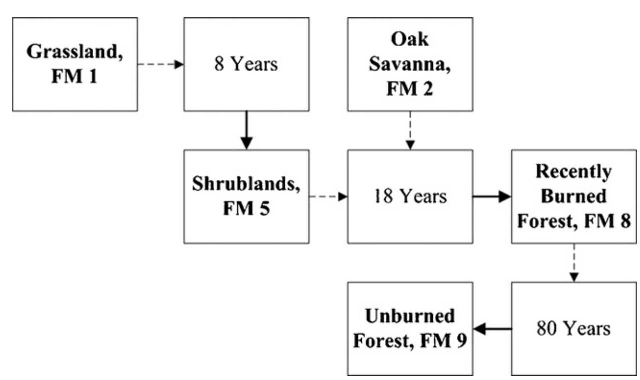

Fig. 2 – Fuel model changes due to succession (years since last fire). It takes about 8 years for a grassland to grow into shrublands. If a raster cell of FM 1 had not been burned for 8 years, it switched for FM 5. It typically takes oaks about 18 years to grow large enough to dominate a landscape. If a cell that started as grassland had not been burned for 18 years, it switched to forest (after a cell switched from grasses to shrubs, only 10 additional years were needed to grow into forest). The savanna also switched to forest if unburned for 18 years. Finally, if a forest had not been burned for 80 years, enough litter gathered to be considered a different fuel model, FM 9.

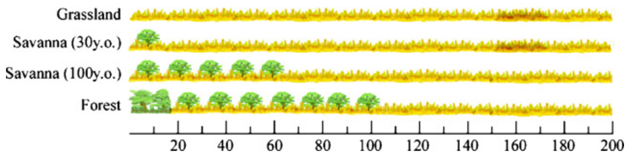

Fig. 3 – Results of burning every year. Time scale along the bottom axis is in years. By burning the landscape every year, the Lenape would have created a single, dominant ecosystem: grasslands. The switch from savanna (30 years old) occurred after 3 years. The older savanna took 66 years to be converted mainly to grasslands. The forest shifted to savanna after 18 years, then again to grassland after 105 years.

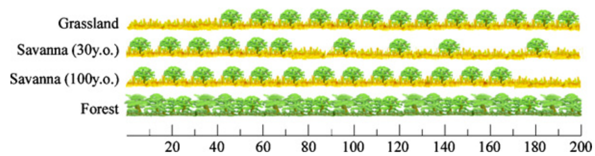

Fig. 4 – Results of burning every 10 years. After the fourth fire (40 years), some of the grasslands switched to savanna; the landscape then consisted of grasslands, savanna, and forest throughout the rest of the run. In young savanna, major grasslands were created after 7 fires (70 years); again, the landscape then contained savanna, grassland, and forest. The older savanna took longer to create grasslands (170 years), and the grasslands created never covered much of the landscape. The forest never changed.

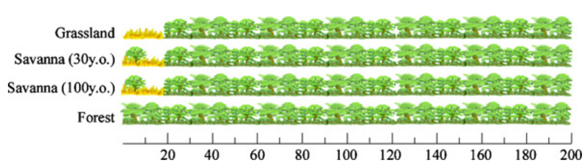

Fig. 5 – Results of burning every 20 years. After the first fire, the landscape grew into a young forest for all four starting input types (this should be clear based on the successional model: after 18 years of not burning, all cells switch to FM 8). The forest gained hold, and further burning never produced any other type of ecosystem. 20 years was not frequent enough to maintain a grassland or savanna.

3. Results

The model results are summarized graphically in Figs. 3–5. Fig. 6 gives an example of time steps for one scenario showing the process of landscape change.

3.1. *Scenario 1: Burning every year*

The combined models indicate that burning every year converts the entire landscape to grassland, no matter the initial vegetation type. The time to grassland conversion does depend on the initial vegetation, with the outer limits being forest ecosystems which take approximately 17 years to convert to a savanna, which then holds out for another approximately 80 years before giving way to grassland ecosystem type. The results of burning every year negated any need to test whether burning twice a year would create and maintain a grassland.

3.2. *Scenario 2: Burning every 10 years*

The combined models indicate that burning once every 10 years yields different landscape structures, depending on the initial conditions. Initial grassland ecosystems convert to a savanna after approximately 40 years and that condition is maintained dynamically through the rest of the model run. Initial savanna ecosystems eventually convert to grasslands, but differ by the average tree age: savannas with younger trees convert in approximately 70 years, with average tree cover varying around 5% through the rest of the simulation. Savannas with older trees are maintained as savanna ecosystems through most of the model run, but around 170 years eventually drop below the 5% tree cover threshold to become grasslands.

3.3. *Scenario 3: Burning every 20 years*

Burning once every 20 years is insufficient to hold back the forest succession process, regardless of the initial conditions. Typical succession rates in Northeast forests return trees resistant to fire in less than 20 years.

3.4. *Sensitivity analysis and model validation*

All modifications resulted in approximately the same landscape structure, indicating that the overall combined model is relatively insensitive to changes in the tree-mortality equations and other inputs used. Results are summarized in Table 2.

Validating our model is a difficult task; long-term studies of varying fire regimes have not been conducted in northeastern hardwood forests. In one sense, the grasslands in Floyd Bennett Field confirm that, if the Lenape needed open space, they would have had to have burned the area frequently. The key question posed by the model, however, is whether a fire after 20 years of succession in an oak woodland would be sufficient to kill the young trees. Using our parameters – and conducting sensitivity analyses on those parameters – suggest the answer is no.

4. Discussion

Our model results indicate that by controlling fire frequency in the pre-settlement Harlem Plains, the Lenape people could control the structure of the landscape. Van der Donck's claim that they cleared the land every 20 years does not appear to be supported by our model results. For the land to be a "plain" or "grassland" the landscape would have had to been burned at least once every 10 years and, depending on initial condition, would have yielded a mosaic of vegetation types. Burning every year overwhelms succession through disturbance and keeps the landscape in a grassland steady state.

Thinking back to the putative reasons for Native American fire use, it seems that if the main goal was to create open

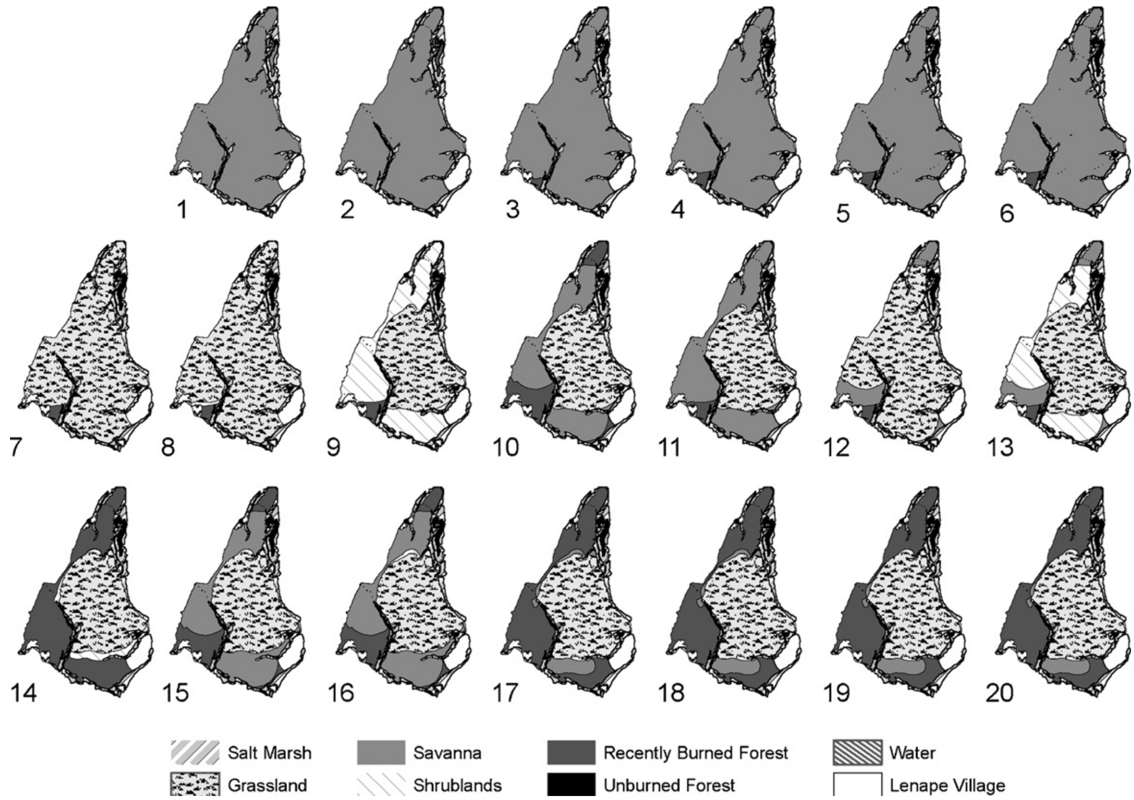

Fig. 6 – A sample run. These 20 landsacapes are the result of a fire every 10 years, started on an initial landscape of young savanna (30-year-old trees). The landscapes are shown immediately after a fire has occurred and vegetation mortality was calculated, but before succession takes place. Note that after 10 years of succession, the grasslands shown would turn to shrublands; any subsequent fire in that area then returns it to grassland.

views, then an annual fire frequency would be most appropriate. If the purpose was to create a mosaic of wildlife habitat and facilitate hunting with cover and open spaces, then burning once every 10 years would suffice. Burning every 20 years is not sufficient to change the landscape structure, though it still might be fun!

Our results suggest that the hardwood forests of the northeast required significant maintenance in order to keep them clear and open—escaped fires and lightning strikes would not suffice to maintain a savanna or grassland. We believe this adds to the consensus that, while individual historical accounts may be suspect, the evidence continues to suggest

Table 2 – Sensitivity analysis results

Equation	Grassland	Savanna	Forest
$P_m = 1.0/(1.0 + \exp(-\mathbf{0.9705} + 6.316(1.0 - \exp(-BT)) - 0.000535\,CK^2))$	0	61.39	38.61
$P_m = 1.0/(1.0 + \exp(-\mathbf{2.9115} + 6.316(1.0 - \exp(-BT)) - 0.000535\,CK^2))$	0	69.17	30.83
$P_m = 1.0/(1.0 + \exp(-1.941 + \mathbf{3.1568}(1.0 - \exp(-BT)) - 0.000535\,CK^2))$	96.67	0	3.33
$P_m = 1.0/(1.0 + \exp(-1.941 + \mathbf{9.4704}(1.0 - \exp(-BT)) - 0.000535\,CK^2))$	0	69.44	30.56
$DBH = \mathbf{38.559}(\ln(age)) - 85.383$	0	78.06	21.94
$DBH = 25.706(\ln(age)) - \mathbf{42.692}$	0	78.75	21.25
$DBH = 25.706(\ln(age)) - \mathbf{128.075}$	58.61	0	41.39
Fuel moistures increased 50%	0	72.42	27.58
Fuel moistures decreased 50%	0	84.32	15.68
October weather, 10-year cycle	0	58.61	41.39
October weather, 20-year cycle, old savanna	0	0	100
October weather, 20-year cycle, forest	0	0	100

Results of the sensitivity analyses, percentage of each landcover type at the end of a 200-year run: key constants (bold values) were increased and decreased, then the model was run on a 10-year fire cycle, with initial conditions old savanna. The final two scenarios were run with weather data from October on a 20-year fire cycle with starting conditions of old savanna and forest. While the amount of grassland and savanna changes, it is clear that a 10-year cycle would be enough to maintain an open landscape, whereas a 20-year cycle would not.

that Native Americans were using fire to control their landscape, not only in the western and plains states, but also in the northeast.

In a larger context, our results indicate the utility of ecological models to address historical questions of human–nature interactions. Though models are formulated largely for modern purposes, like FARSITE (used mainly to predict wildlife spread in the western US), there is no reason they cannot be applied in historical scenarios, given that the model inputs can be reconstructed for a past time. Addressing historical and archaeological questions through ecological reconstructions provides a new way to gain insights about our past. While others have created fire succession models – as reviewed in Keane et al. (2004) – and used them to explore historical fire regimes – Scheller et al. (2005) – this is the first study undertaken to model pre-colonial anthropogenic fire disturbance in northeastern North America.

Our models could be improved in a number of different ways. First, our models for tree mortality are based on a number of empirical relationships borrowed from other sites and systems. Although our sensitivity analysis indicated that the model results are relatively robust to changes in these model parameters, additional validation of these parameters is required. Second, we do not explicitly account for additions of dead tree biomass to the fuel models. The recently burned fire model used (FM 8) does not only account for the boles of trees, but only the removal of small detritus on the ground. Including these dead trees in the model would cause the fires to burn more intensely, creating additional tree mortality than predicted here, and increasing the rate of progression toward savanna and grassland ecosystem types. Third, we could increase detail with which the vegetation types are described, including variable age–structure and species composition, to include a more realistic model of forest change. With an individual based model of tree growth, the older stands of forest would have included some much younger trees and may have resulted in a more open canopy faster. However, our model showed that even young oaks were not killed by the fires, which tended to be low intensity.

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