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Research article

Characterizing historical and modern fire regimes in Michigan (USA): A landscape ecosystem approach

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Abstract

We studied the relationships of landscape ecosystems to historical and contemporary fire regimes across 4.3 million hectares in northern lower Michigan (USA). Changes in fire regimes were documented by comparing historical fire rotations in different landscape ecosystems to those occurring between 1985 and 2000. Previously published data and a synthesis of the literature were used to identify six forest-replacement fire regime categories with fire rotations ranging from very short (<100 years) to very long ($>1{,}000$ years). We derived spatially-explicit estimates of the susceptibility of landscape ecosystems to fire disturbance using Landtype Association maps as initial units of investigation. Each Landtype Association polygon was assigned to a fire regime category based on associations of ecological factors known to influence fire regimes. Spatial statistics were used to interpolate fire points recorded by the General Land Office. Historical fire rotations were determined by calculating the area burned for each category of fire regime and dividing this area by fifteen (years) to estimate area burned per annum. Modern fire rotations were estimated using data on fire location and size obtained from federal and state agencies. Landtype Associations networked into fire regime categories exhibited differences in both historical and modern fire rotations. Historical rotations varied by 23-fold across all fire rotation categories, and modern forest fire rotations by 13-fold. Modern fire rotations were an order of magnitude longer than historical rotations. The magnitude of these changes has important implications for forest health and understanding of ecological processes in most of the fire rotation categories that we identified.

Introduction

The emulation of natural disturbances is increasingly being used as a basis for managing natural resources (Hunter 1993; Attiwill 1994; Kimball et al. 1995; Nowacki and Kramer 1998; Bergeron et al. 1999; Cissel et al. 1999; Engstrom et al. 1999). Comparison of current disturbance regimes to the historical range of variability in natural disturbances provides one means of evaluating effects of disturbances imposed through management, and of addressing many issues including fire risk, forest health, fragmentation, and provision of habitats for the full array of native species (Landres et al. 1999; Schmidt et al. 2002; Swetnam et al. 1999). Obviously, this approach requires knowledge about disturbance regimes prior to mod-

ern human intervention. Most often, however, this knowledge is limited.

As part of the Great Lakes Ecological Assessment, we are characterizing historical and contemporary fire regimes across 24.3 million hectares in northern Michigan, Minnesota, and Wisconsin; this research reports results for northern lower Michigan. A number of approaches have been used to characterize historical fire regimes. These include use of dendrochonological techniques to date fire scars (Clements 1910; Heinselman 1973; Arno and Sneck 1977; Simard and Blank 1982; Loope 1991; Brown et al. 2001), use of current age class data fit to a negative exponential curve to calculate fire rotations (Van Wagner 1978), and use of stratigraphic charcoal analysis on petrographic thin sections (Clark 1988a; 1988b). Each of these methods has advantages and disadvantages related to adequately assessing fire regimes at relevant spatial and temporal scales (Agee 1993). The many challenges associated with characterizing fire regimes include area effects on estimates of fire return intervals or fire rotations (Arno and Petersen 1983; Johnson and Gutsell 1994), assumptions regarding flammability of fuels and fire behavior across heterogeneous landscapes (Turner et al. 1989; Gosz 1992; Turner and Romme 1994; Brown et al. 2001), and adequacy of approaches for understanding long term patterns (Clark 1988a; Clark 1988b).

An important initial facet of our research was to map categories of landscape ecosystems based on associations of ecological factors known to affect fire regimes. Area effects on estimates of fire occurrence were addressed by studying fire regimes across a very large study area totaling 4,262,160 ha. Landscape heterogeneity was reduced by networking landscape ecosystems into fire regime categories and determining fire rotations within relatively homogeneous units. Long-term patterns were partially addressed by studying fires occurring in the early 1800s as well as modern fires. Specifically, we addressed the following objectives with this paper: 1) to develop an initial map of fire regime categories within Michigan; 2) to derive quantitative estimates of both historical and modern fire rotations within these categories; and 3) to consider the ecological and social reasons for differences between modern and historical fire activity across fire regime categories. We expect this information to support current policy initiatives, which attempt to incorporate the temporal and spatial scale of historical disturbance into management guidelines. Use of a landscape ecosystem approach provides an ecological basis for development and use of this information across scales, and extrapolation of the technique to other geographic regions.

Methods

Study area

The study area encompasses 4,262,160 hectares in northern lower Michigan, USA (Figure 1). Landforms of this region resulted from four deglaciation episodes occurring between 14,500 and 11,500 years before present. Landforms include well-sorted sandy outwash plains deposited by high-energy glacial meltwaters, sandy ice-contact topography, loamy ground, terminal, and end moraines, and sandy to loamy glacial lake beds. Due to variations in mode of deposition, sediment loads, and time of deposition, some landform classes may be predominately sandy in texture while others may be of a loamy texture.

The climate of northern lower Michigan is moderated by its proximity to Lake Michigan and Lake Huron. Precipitation and growing season decrease along a south to north and a west to east gradient due to latitudinal and orographic effects. Mean annual precipitation ranges from 98 to 81 cm, and growing seasons from 158 to 94 days based on a 0 degree centigrade reference temperature.

The historical forests of northern lower Michigan were diverse due to the wide variety of landforms and soils occurring in this area, and interactions of landforms, disturbance regimes, and tree species reproductive strategies. The dominant forest communities were mixed northern hardwoods and hemlock (*Tsuga canadensis*)-hardwoods of the moraines, white pine (*Pinus strobus*)-hemlock of the finer textured glacial lakebeds, mixed white-red pine (*P. resinosa*) of the ice contact and outwash plains, jack pine (*P. banksiana*) within the coarse sandy xeric outwash and glacial lakebed systems, and both wetland coniferous and deciduous within poorly and very poorly drained landforms (Comer et al. 1995).

Landscape ecosystem fire regime (FR) categories

We used previously published data and a synthesis of the literature to identify six forest-replacement fire rotation (FR) categories ranging from very short ($<$ 100 years) to very long ($>$ 1,000 years; see Ap-

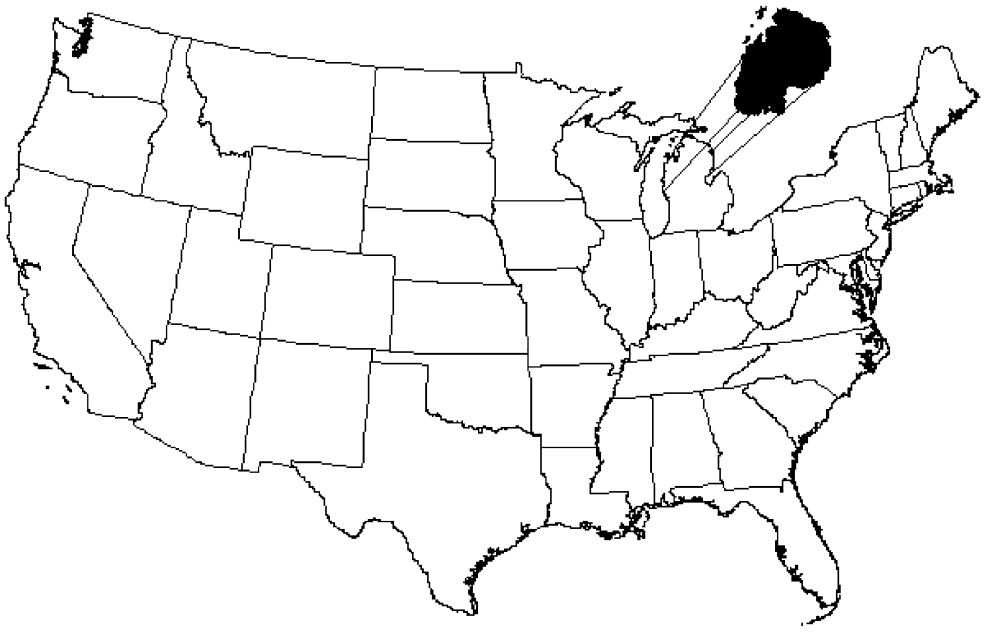

Figure 1. Study area in northern lower Michigan, USA.

pendix 1). Within northern Michigan, landscape ecosystem fire regime categories are:

FR1 – landscape ecosystems historically experiencing frequent, large, catastrophic stand-replacing fires. Average fire return intervals reported in the literature ranged from 26 to 69 years, fire rotations from 50 to 170 years. These ecosystems typically occur within very dry, flat outwash plains underlain by coarse-textured sandy soils. The dominant forest types were short-lived jack pine (*P. banksiana*) and mixed pine forests.

FR2 – landscape ecosystems historically experiencing large, catastrophic stand-replacing fires at lower frequencies, hence longer fire rotations, than the FR1 category. Average fire return intervals reported in the literature ranged from 83 to 250 years, fire rotations from 150 to 350 years. These ecosystems typically occur within dry outwash plains and ice-contact landforms underlain by sandy and loamy sand soils. The dominant forest types were mixed red-white-jack pine forests.

FR3W – landscape ecosystems historically experiencing relatively infrequent stand-replacing fires. Average fire rotations reported in the literature ranged from 100 to 190 years. These wetland ecosystems typically occur within or adjacent to fire-prone landscapes, with fires often intruding from adjacent landscapes. The dominant forest types were wetland conifers including cedar (*Thuja occidentalis*), tamarack (*Larix laricina*), white pine, and hemlock. Fire regimes and fuel formation were likely caused by interactions of insect and disease, blow-downs, and periods of drought.

FR3 – landscape ecosystems historically experiencing infrequent stand-replacing fires at much longer fire rotations than the FR1 or FR2 categories. Average fire return interval reported in the literature for white pine-hemlock forests was 250 years. These ecosystems typically occur within dry-mesic to mesic ice-contact, glacial lakebed, and morainal landforms underlain by loamy sand to sandy or silt loam soils. The dominant forest type was long-lived mixed hemlock-white pine forests with minor elements of northern hardwood forests.

FR4 – landscape ecosystems historically experiencing very infrequent stand-replacing or community maintenance (surface) fires. Average fire return intervals reported in the literature ranged from 400 to 700 years, fire rotations from 550 to 2800 years. These ecosystems typically occur within mesic to moist-mesic moraines and glacial lakebeds underlain by fine-textured sandy loam to heavy clay and silt loams soils. The dominant forest types were long-lived, fire-intolerant northern hardwood forests including sugar maple (*Acer saccharum*), beech (*Fagus grandifolia*), and hemlock.

FR4W – landscape ecosystems historically experiencing very infrequent stand-replacing or community maintenance (surface) fires. Average fire return intervals reported in the literature ranged from 400 to 1,700 years, fire rotations from 890 to 6,000 years. These ecosystems typically occur within wetlands embedded within or adjacent to fire-resistant, hence fire protected landscape ecosystems (FR4). The dominant forest types were wetland conifer-hardwood forests including cedar, hemlock, tamarack, sugar maple, white pine, spruce (*Picea* spp.), and black ash (*Fraxinus nigra*).

The location of landscape ecosystems of varying susceptibility to fire disturbance was estimated using Landtype Association (LTA) maps as initial units of investigation. The use of the landscape ecosystem approach (Rowe 1980; Rowe 1984; Rowe 1992; Spies and Barnes 1985; Cleland et al. 1997) in assessing fire regimes is premised upon the assumption that fire behavior following ignition is related to the conditions, processes, and spatial dimensions of particular categories of landscape ecosystems defined by integrating multiple biotic and abiotic factors.

Landscape ecosystems (Landtype Associations) of northern lower Michigan were mapped by the Michigan Natural Features Inventory by integrating information on landform, lake densities, soil drainage, and soil texture (Albert et al. 1996; Corner et al. 1999), i.e., factors affecting the distribution of fire-prone versus fire-resistant ecosystems, and aspects of landscape heterogeneity affecting fire spread. The LTA concept in Lower Michigan is somewhat different than other areas of the Lake States in that delineation criteria emphasized these four abiotic factors, without consideration of historical or potential vegetation. In other parts of the region, these biotic factors were incorporated into LTA concepts and maps.

Albert et al. (1996) and Corner et al. (1999) identified 107 categories of LTAs based on these criteria, including seven categories of lakes, which were used in mapping more than 850 polygons within the study area. More than half these polygons were less than 2,023 ha, whereas the two largest polygons (categorized as broad, flat outwash plains, few or no kettle lakes, excessively to somewhat excessively well drained, sand or loamy sand) were 148,812 ha and 116,224 ha.

We evaluated each LTA polygon using a number of GIS data sets, including Natural Resource Conservation Service (NRCS) digital soil surveys, GLO notes on tree species and diameter, a 30-meter DEM and maps derived from this topographic information, hydrography, surficial geology, and current vegetation (using FIA and USGS GAP land cover data). NRCS soil mapping units were qualitatively assigned to one of five moisture-nutrient categories based upon soil texture and drainage, and historical forest composition. These classes were xeric, dry-mesic, mesic, moist-mesic, and hydric. Interpretations based on associations of these ecological factors were made using simple overlays, and each polygon was assigned to one of six fire-regime categories. When necessary, polygons were subdivided or revised based on soil or historical vegetation criteria.

Historical and modern fire rotations

To document changes in fire regimes since European settlement, we compared historical fire rotations in different landscapes to those occurring between 1985 and 2000. Historical fire rotations were estimated from information recorded by the General Land Office (GLO) between 1836 and 1858. GLO surveyors marked township and section boundaries, and noted a number of ecological conditions every half-mile and along transects of section lines, providing a grid of ecological data at a relatively fine scale (Manies et al. 2001). Observations included areas that were burned or blown down, and other indications of recent disturbance such as "pine thickets," pine and oak barrens, prairies, and so forth.

Microfilmed GLO notes were converted to ArcInfo point coverages. Historical fire boundaries were determined using ordinary kriging for the interpolation of the fire occurrence data points, with output in the form of a probability map (Maclean and Cleland 2003). This approach was chosen over simple kriging since it requires neither knowledge nor stationarity of the mean over the entire study area. Use of probability of occurrence not only provided predictions of the spatial extent of the fires, but also provided a level of confidence for the prediction.

We obtained a modern fire database for the 1985-1995 period from previously published research (Cardille et al. 2001) and updated this data to include fires through 2000. Two fire databases were created; one containing all reported fires, the second only fires occurring within dominantly forested survey sections. These records were compiled and standardized and locations of fires were determined to the center of the nearest survey section.

Table 1. Historic fire rotations, based on General Land Office survey data, for landscape ecosystem fire regime (FR) categories.

Historic Fire Regime	Northern Lower Michigan LTA Fire-rotation Category	Unit size (ha)	Area burned (ha)	Percent burned/year	Rotation (years)
FR1	Extremely xeric LTAs dominated by jack pine	338,402	85,420	1.683	59
FR2	Xeric LTAs dominated by white-red pine	416,486	58,619	0.938	107
FR3W	Wetland LTAs adjacent to fire-prone LTAs	200,177	24,936	0.830	120
FR3	Dry-mesic LTAs dominated by white pine-hemlock	668,721	21,204	0.211	47
FR4	Mesic LTAs dominated by northern hardwoods	1,526,404	16,536	0.072	1,385
FR4W	Wetland LTAs adjacent to mesic hardwood LTAs	387,791	8,503	0.146	684
Total	Study Area Total	3,537,982	215,221	0.406	247

Fire rotations usually are determined by calculating the average stand age of a forest whose age distribution fits a negative exponential or a Weibull function (Van Wagner 1978). For our study, historical fire rotations were determined by calculating the area burned for each fire rotation category, dividing the area burned by the area represented by each unit, and dividing this area by 15 (number of years of data) to estimate area burned per annum while assuming this to be a conservative burned area recognition window (Canham and Loucks 1984). Fire rotations for the modern period (1985-2000) were determined by dividing the area burned for each fire rotation category by the number of years of records ($N = 16$) to estimate area burned per annum.

Distribution of tree species and land cover communities

We developed summary information on tree species found in the region historically, and modern communities found on the landscape. These data were used to investigate changes in distribution of ecological communities (i.e., fuel type) as one of the potential factors influencing differences in fire regimes between historical and modern periods. Information on historical tree species was derived from GLO line tree data. Surveyors recorded the species of each tree encountered when walking a township survey line and these data are thought to provide a less biased indication of forest communities that existed than are trees recorded at the corners or quarter-corners of townships (K. Brosofske, manuscript in preparation). We calculated the percentage of GLO line trees ($N = 92{,}034$) by species for each FR category (Table 4). We also determined the percentage of each FR category that currently exists in modern land cover communities, as defined by the Michigan Department of Natural Resources classification (Table 5).

Table 2. Modern fire rotations for all land within landscape ecosystem fire regime (FR) categories. See Table 1 and Appendix 1 for descriptions of FR categories.

Historic Fire Regime	Area burned (ha)	Percent burned/year	Rotation (years)
FR1	6,296	0.127	787
FR2	5,711	0.088	1,136
FR3W	869	0.017	5,882
FR3	4,033	0.032	3,125
FR4	3,041	0.012	8,333
FR4W	1,074	0.013	7,692
Total	21,708	0.034	2,941

Results

Networked landscape ecosystems exhibited differences in historical and modern fire occurrence and extent (Figure 2). Modern fire rotations were an order of magnitude longer than historical rotations (compare Table 1, Table 2, and 3). Historical rotations varied by a 23.5-fold range across all categories, and modern forest fire rotations by a 13.5-fold range, reflecting changes in land cover and perhaps focused fire suppression activities within the most fire-prone areas. The most fire-prone landscape ecosystem category, FR1, had a historical fire rotation of 59 years, occupied 9.6% of the study area, and accounted for 39.7% of the total historical fire acreage. In contrast, the least fire-prone category, FR4, had a historical fire rotation of 1,385 years, occupied 43.1% of the study area, and accounted for 7.7% of the historical fire acreage. Most fires in this northern hardwood dominated landscape ecosystem category were associated with blowdowns observed by GLO surveyors. The wetland LTAs (FR4W) had a shorter historical rotation period (684 years) than did mesic LTAs in FR4, likely due to the inclusion of a conifer component and thus an increased probability of crown, rather than ground fires, in the latter.

Table 3. Modern forest fire rotations for forested land within landscape ecosystem fire regime (FR) categories. See Table 1 and Appendix 1 for descriptions of FR categories.

Historic Fire Regime	Area burned (ha)	Percent burned/year	Rotation (years)
FR1	6,296	0.129	775
FR2	5,573	0.095	1,057
FR3W	714	0.032	3,126
FR3	2,923	0.024	4,242
FR4	1,377	0.009	11,260
FR4W	851	0.013	7,582
Total	17,735	0.037	2,671

Table 4. Percentage of line trees reported in General Land Office survey notes by tree species and category of fire regime.

		Category of Fire Regime					
Species	*Scientific Name*	FR1	FR2	FR3	FR3W	FR4	FR4W
Jack Pine	*Pinus banksiana*	53.4	17.7	1.4	2.8	0.1	0.5
Red Pine	*P. resinosa*	13.5	27.7	11.3	5.4	0.9	1.8
Pine	*Pinus spp.*	17.1	12.9	18.4	3.9	3.0	2.0
White Pine	*P. strobes*	6.4	16.6	15.7	10.4	3.1	5.5
White Oak	*Quercus alba*	0.9	4.2	2.9	0.3	0.3	0.2
Red Oak	*Q. rubra*	0.5	2.2	2.2	0.2	0.5	0.1
Maple	*Acer spp.*	0.2	1.2	4.1	2.6	1.8	2.5
Aspen	*Populus spp.*	1.7	3.8	2.1	6.3	0.9	2.5
Beech	*Fagus gradifolia*	0.4	1.4	9.7	2.0	24.3	5.6
Elm	*Ulmus Americana*	0.1	0.2	0.7	0.9	3.2	1.7
Basswood	*Tilia Americana*	0.1	0.1	0.5	0.3	2.2	0.7
Hemlock	*Tsuga Canadensis*	0.9	2.7	16.6	10.3	21.6	17.7
Sugar Maple	*Acer saccharum*	0.2	0.7	3.1	1.1	27.9	5.7
White Birch	*Betula papyrifera*	0.6	1.4	1.8	4.3	1.7	3.3
Black Ash	*Fraxinus nigra*	0.1	0.3	0.9	3.3	1.1	3.9
Balsalm Fir	*Abies balsamea*	0.1	0.5	0.6	3.0	0.5	2.9
Spruce	*Picea spp.*	0.6	1.0	0.5	4.1	0.3	4.2
Tamarack	*Larix laricina*	1.2	2.0	1.7	15.5	0.9	11.2
Cedar	*Thuja occidentalis*	1.1	2.7	4.1	20.2	3.5	26.1
Total		99.0	99.2	98.4	97.0	97.6	97.8

While there were twelve times as many hectares burned in the 1800s as there are today (compare Table 1, Table 2), the proportion of area burned within LTA categories to total area burned is comparable for the FR1, FR2, FR4, and FR4W landscape ecosystem categories (Figure 3). This antecedent similarity suggests that landscape ecosystems that were most prone to burning historically are most prone to burning currently.

An indication of similarities between historical and modern forest fire rotations is the relative proportion of the percent of total area burned within each fire rotation category to the percent of the study area occupied by each category (Figure 4A, Figure 4B). These ratios show that the most fire-prone landscape ecosystem historically had 22 times the proportion of total area burned than the least fire-prone system. In modern times, the most fire-prone landscape ecosystem has 11 times the proportion of total area burned than the least fire-prone system for all fires, and 14 times the proportion of forest fires occurring only in dominantly forested survey sections of this area. Ratios for forest fires are similar for five of six LTA categories. Fire regimes for the wetland category that historically burned with relatively short rotations (FR3W) now exhibit rotations similar to the wetland category than historically burned at long fire rotations (FR4W). This is probably partly due to the suppression of fires in adjacent upland landscapes.

Historical forest composition and proportions of fire-prone and fire-resistant species are an indication of differences in fire regimes among landscape ecosystem categories. Historically, the most fire-prone landscape ecosystem category (FR1) was dominated

Table 5. Percentage of current land cover, by communities of the Michigan Department of Natural Resources land cover classification, in categories of fire regime.

	Category of Fire Regime					
Community	FR1	FR2	FR3	FR3W	FR4	FR4W
Jack Pine	36.8	13.5	3.4	5.0	1.9	2.0
Red/White Pine	8.8	7.8	5.3	3.2	3.6	2.1
Mixed Conifer	6.5	1.4	0.9	0.9	0.5	1.6
Mixed Hardwood-Conifer	2.3	3.2	2.2	3.9	1.3	2.3
Aspen-Birch	9.6	24.1	18.9	10.5	9.2	8.4
Oak	7.6	12.8	8.2	2.1	1.1	0.6
Northern Hardwoods	4.5	10.6	21.6	6.5	27.5	10.2
Lowland Conifer	0.6	0.5	0.3	1.4	0.3	1.3
Lowland Hardwood-Conifer	3.1	5.2	4.7	28.5	3.5	26.5
Lowland Hardwood	0.3	0.5	1.7	3.3	1.0	4.2
Shrubland	1.6	1.9	2.1	1.1	1.9	1.1
Non-forested Wetland	1.0	2.4	3.9	13.3	2.1	12.4
Non-forested	16.5	14.7	24.9	16.5	45.2	24.9
Water	0.9	1.5	2.0	3.7	0.7	2.5
Total	100.0	100.0	100.0	100.0	100.0	100.0

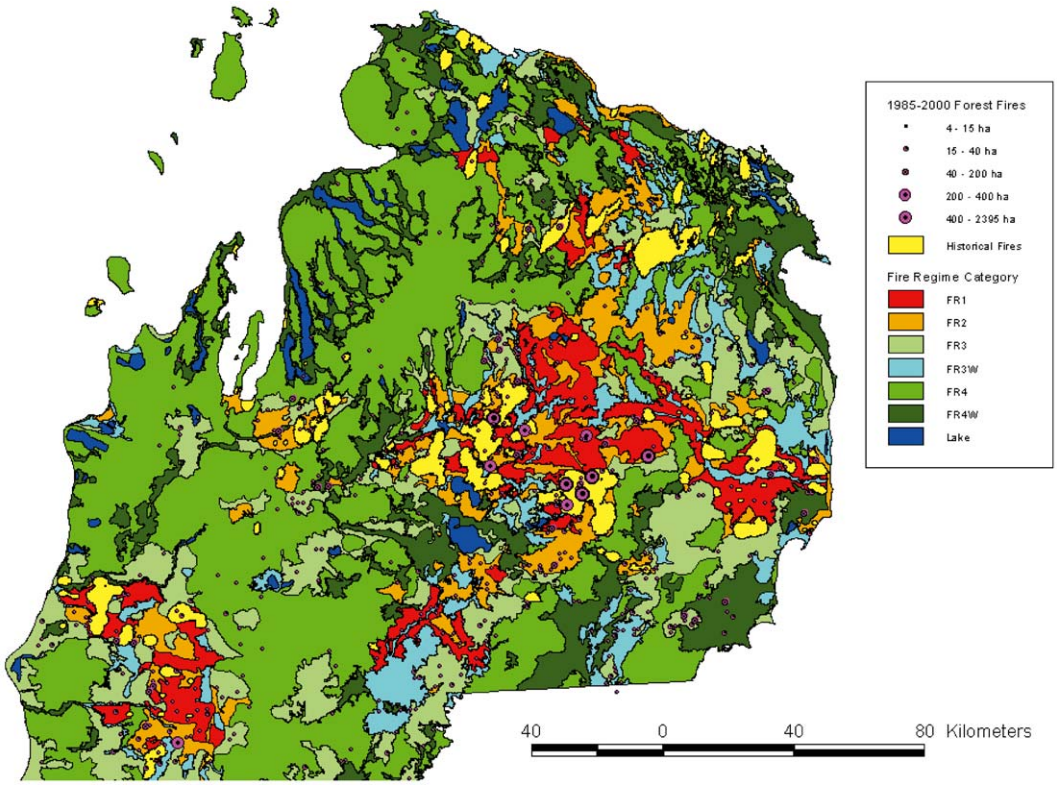

Figure 2. Historical fire boundaries and fire regime categories of northern lower Michigan.

by pine species, with jack pine comprising 53.4% of all line trees observed (Table 4). Jack pine is able to produce viable seed within a decade or so after germination, bears predominantly serotinous cones over much of its natural range, and thus is well adapted to very short fire rotations. The next most fire-prone category (FR2) was more diverse and was dominated by longer-lived pines, particularly red pine and white

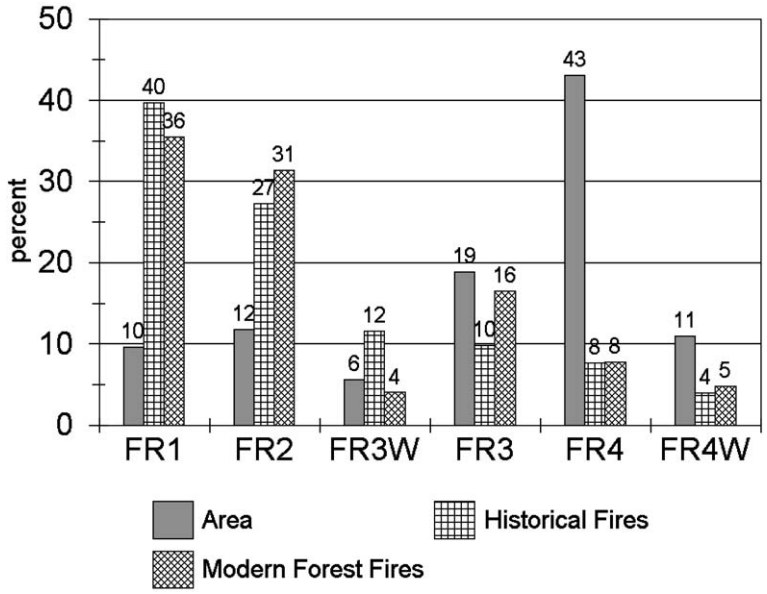

Figure 3. Percent of land area and percent of total historical and modern forest fire area by fire regime category.

pine. Red and white pines require several decades to produce viable seed, and are therefore less adapted to shorter fire-rotations than jack pine. Early-successional deciduous species (aspen (*Populus* spp.), oak (*Quercus* spp.), white birch (*Betula papyrifera*)) represented 11.6% of line trees in FR2, as compared to only 3.7% of the more xeric FR1 category. Very long-lived conifers including white pine and hemlock dominated the FR3 category. Hemlock is sensitive to injury and mortality following fire, and hemlock and white pine have very long life expectancies, thus these species would be well adapted to the nearly 500-year fire rotation of the FR3 category than species favored by shorter fire rotations. Both of the wetland landscape ecosystem categories (FR3W and FR4W) were dominated by, tamarack, hemlock, spruce, and balsam fir (*Abies balsamea*). However the fire-prone FR3W category had very low proportions of fire-intolerant hardwood species (sugar maple, beech, elm (*Ulmus americana*) and basswood (*Tilia americana*)), had twice the proportion of fire-dependent species (pine, white birch, aspen, and oak) and had only 58% of the proportion of fire-sensitive hemlock as the FR4W category. The FR4 category was dominated by fire-intolerant species (sugar maple, beech, hemlock, elm, basswood), with minor inclusions of white pine and "pine" that probably regenerated through gap-phase disturbance regimes associated with fine-scale blowdown. The FR4 category had low proportions of early-successional deciduous species (3.4% of all line trees), indicating very infrequent catastrophic disturbance.

Discussion

Fire regimes depend upon frequency and seasonality of ignition, and factors influencing fire spread such as flammability of living and dead plant material, vegetative structure including fuel ladders and tree spacing, landscape patterns and spatial heterogeneity, and local weather conditions at the time of the fire (Sousa 1984). Since the inception of the discipline, fire researchers have recognized the relationship of climate, soils, topography, vegetation, and land ownership patterns to fire occurrence (Plummer 1912; Mitchell and Sayre 1929; Mitchell and LeMay 1952). Geologic and topographic variations, and subsequent soil patterns, strongly influence fire movement and the distribution of fire-prone or fire-resistant communities (Brubaker 1975; Heinselman 1981; Loope 1991; Motzkin et al. 1999). These factors may thus account substantially for the scale and pattern of fire-controlled vegetation mosaics (Grimm 1984), and mapping systems accounting for the spatial variability of these ecological factors should be useful in assessing fire regimes. Most LTAs in the Lake States were mapped based upon naturally occurring associa-

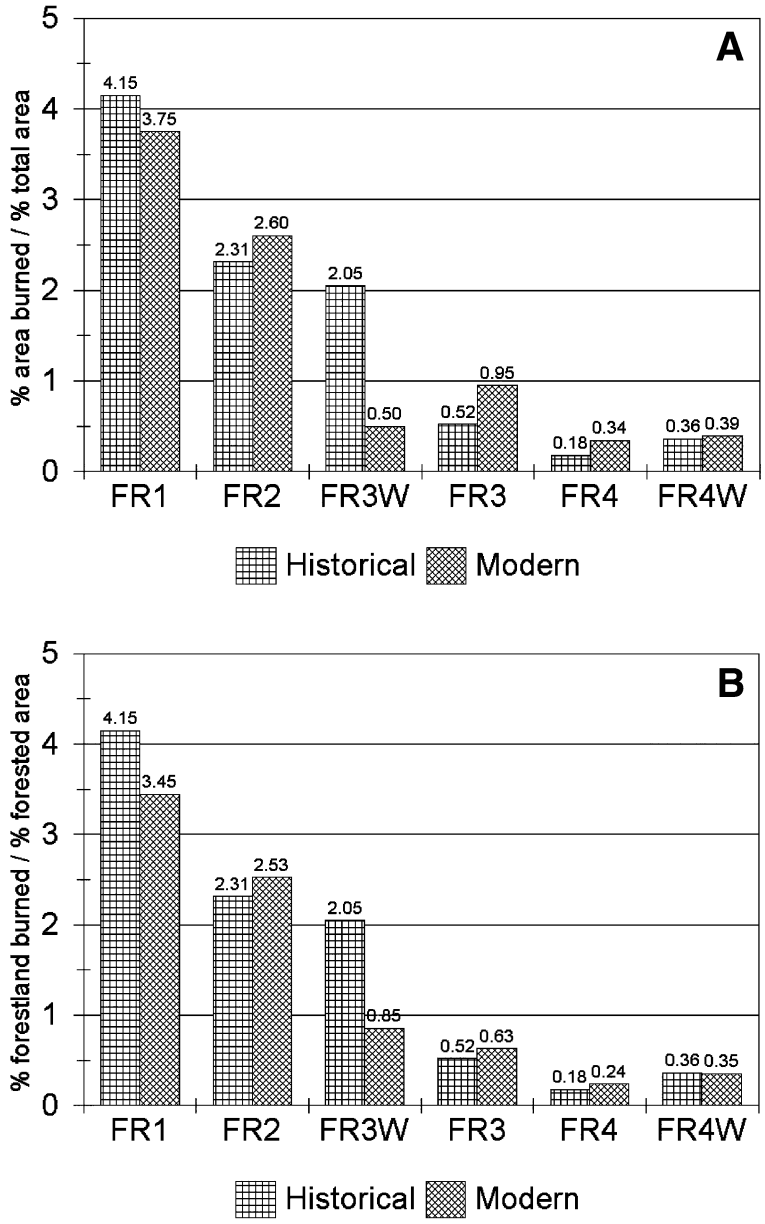

Figure 4. A. Percent of total area burned divided by percent of area occupied by fire rotation category. B. Percent of forested area burned divident by percent of forested area occupied by fire rotation category.

tions among landforms, soil, hydrography, and vegetation (Jordan et al. 2002), and provide a practical framework for addressing the spatial distribution of ecological factors known to influence fire regimes at a landscape scale.

The size of the area under investigation and for which fire-return intervals or cycles are calculated is an important factor in interpreting fire regimes. Generally, the larger the study area, the more frequently fire will occur somewhere within it. In his classic study, Heinselman (1973) estimated the fire-return interval from 1542 to 1971 for the entire 214,892 ha Boundary Waters Canoe Area (BWCA) in northern Minnesota to be six years. In contrast, Swain's (1980) estimate of the 1580 to 1970 fire-return interval for the birch-aspen area around Hug Lake in the eastern BWCA was 65 years. Obviously, these estimates are not comparable. Large areas experience more fires,

and inevitably contain many plant communities, so fire frequency or rotation data for such an area represents an amalgamation of several fire regimes, diluting its relevance. Moreover, the two principal measures of fire regimes, fire frequencies and fire rotations, require clearly specifying the location and size of the area of interest. Therefore, identifying ecologically homogenous areas within which fire regimes can be analyzed and reported is an essential step in the assessment of natural disturbance regimes.

Johnson and Gutsell (1994) concluded the size of study areas used in estimating fire frequencies is often too small for time-since-fire maps or samples to have much meaning. In a study based on a 187-year pre-European settlement fire history record in the BWCA, fire-interval distributions varied from positively to negatively skewed, but for most units the Weibull distribution fit significantly (Baker 1989). However the distributions varied spatially, and cluster analysis suggested that three fire regions, each containing a relatively homogeneous fire regime, could be identified. Baker concluded that reconstruction of fire-interval distributions requires historical data; landscape age-class distributions at an instant in time are insufficient. To address these issues, we studied fire regimes across a very large study area, and determined fire locations and extents during the pre-suppression era (1800s).

Historical fire rotations determined in this research are supported by previous research findings. Fire regimes within the FR3W fire-prone wetland category have changed most dramatically; rotations have been extended from 120 years to 5,882 years for all fires and 3,126 for forest fires. These systems now experience fire at very long rotations, analogous to the wetland category than historically burned at long fire rotations (FR4W). This is most likely due to effective fire suppression preventing large fires from spreading into these wetlands from nearby fire-prone uplands, as well as increased proportions of fire-resistant deciduous species in today's landscape. In concert with activities that increase the number of fire ignitions, human presence has typically tended to increase regional fire frequency (number of fires per area), diminish fire size, and lengthen the fire rotation at any location (Christensen 1993).

The landscape ecosystems formerly supporting white-pine hemlock forests (FR3) and the mixed red-white pine forests (FR2) are now dominated by early successional deciduous forest types, principally oak, red maple, and aspen, based on the Michigan Department of Natural Resources land cover classification (Table 5). These coppicing and light-seeded species were favored by the wholesale clearcutting and burning that took place during the turn-of-the-century logging era. The potential for catastrophic crown fires has thus been reduced substantially within these landscapes. Nonetheless, the proportion of total acres burned when compared to other landscape ecosystem categories is higher today in these systems than in the 1800s, although actual forested acres burned have been reduced by more than ten-fold in the FR2 category and seven-fold in the FR3 category. This increased proportion may be due to the high density of ignitions associated with modern human populations causing surface fires that spread due to oak litter, conifer seedlings, and perhaps woody shrubs commonly occurring beneath today's oak, oak-red maple, and aspen forests (Host et al. 1987).

It should be noted that historical fires observed by GLO surveyors were likely crown-fires, whereas many hectares of modern fires, particularly within deciduous forest communities or non-forested areas, were surface fires. The potential for catastrophic crown fires still exists within upland coniferous forest types that occur across more than half of the forestlands within most fire-prone landscape ecosystem (FR1) and one-quarter of the next most fire-prone category (FR2).

Our conclusions that landscape ecosystems formerly most prone to burning continue to be the most fire-prone may be due to interactions of cultural and ecological factors. Following the turn-of-the-century logging era, landscapes formerly dominated by pine species were left non-forested. Adult trees capable of surviving fires had been harvested, the seed source removed, and young progeny destroyed. The Civilian Conservation Corp often replanted these deforested lands to conifer species in the 1930s, thus restoring the original pyrophilic forest over much of its former range. The extensive sandy outwash plain and ice-contact landforms that comprise the FR1 and FR2 landscape ecosystem categories, associated droughty soils, and lack of natural fuel-breaks (lakes, rivers, wetlands) typifying these landforms promote large fires. In addition, the volatile fuels in overstory and understory conifers, accumulation of recalcitrant oak and pine litter along the forest floor, and the vertical structure of fuels leading to "fuel ladders" may also be causally related to fire occurrence within these pyrophilic ecosystems. In contrast, mesic northern hardwood ecosystems are usually underlain by loamy

soils that have high moisture holding capacity, seldom accumulate litter along the forest floor due to readily decomposable, labile carbon in fallen leaves, support ground flora principally composed of succulent herbs and forbs, and are composed of deciduous tree species that seldom if ever experience catastrophic crown fires.

Conclusions

Due to fire suppression and human-created changes in the composition and structure of the landscape, modern fire rotations are many times longer compared to the historical record for all the landscape ecosystems that we studied. When averaged among all landscape ecosystems, fire rotation increased from ~ 250 years in the past to ~ 3,000 years in the present. The magnitude of these changes has important implications for forest health and ecological processes in most of the fire rotation categories that we identified.

Despite differences in absolute area burned between the past and present, similarities were found in the range of fire rotations among the FR categories and the relative proportions of area burned to the area occupied for each FR category. Historically, the most fire-prone ecosystem had 22 times the proportion of total area burned than the least fire-prone ecosystem, this proportion has been reduced but remains at 14-fold in the modern record. Those landscape ecosystems that were fire-prone historically remain so due to interactions of their physical environment (soil, landform) with the vegetation these environments support.

Our results demonstrate the importance of landscape context in characterizing and understanding fire regimes. One of the fire rotation categories, the wetland complex embedded in a fire-prone landscape matrix (FR3W) that historically burned frequently now has a long fire rotation approaching that characteristic of the category FR4W. The resulting changes in the composition, structure, and function of the wetland ecosystems in the FR3W category have received little attention from managers and researchers. The six forest-replacement fire rotation categories identified for northern lower Michigan are useful tools for developing strategies for emulating natural disturbance for managing forests within our study area. When combined with information on existing fuels and ignition sources, these categories may also provide a means of assessing fire risk.

In the past, fire and wind disturbance interacted with biological and physical components of ecosystems to regulate patterns in the composition, structure, and age of forested landscapes, and the habitat these conditions provided for dependent species. Today humans are also disturbing forests through resource extraction, fire suppression, recreational use, and rural development. Understanding the beneficial or adverse effects of disturbance, such as fire risk, is essential for conflict resolution and sustainable forest management.

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Appendix 1

Table A1. Historic fire regime categories with associated return intervals for the northern Great Lakes Region.

Regime	Community Type	Fire Return Interval (Yrs)	Location	Reference	Notes
FR 1	Jack pine/red pine	26 (range 12-60)	N. Lower Michigan (Mack Lake)	Simard and Blank 1982	Based on 6 fire years + 2000 fire
	Jack pine/red pine/white pine	35 (range 9-89)	N. Minnesota (Itasca)	Spurr 1954	Based on 6 cohort-producing fires (1714-1886)
	Jack pine/ birch/spruce	27 (range 4-47)	S of Lake Abitibi, Quebec	Dansereau and Bergeron 1993	Based on 10 cohort-producing fires (1760-1923)
	Jack pine/black spruce	34	N. Alberta (Wood Buffalo NP)	Larsen and MacDonald 1998b	Based on 16 fires (1429-1934); charcoal & pollen analysis
	White spruce	69 (range 30-130)	N. Alberta (Wood Buffalo NP)	Larsen and MacDonald 1998a	Based on 12 fires (1185-1940); charcoal & pollen analysis
	Mixed boreal conifer/hdwd	26 (range 1-74)	Lake Duparquet, Quebec	Bergeron 1991	Based on 8 fires along lakeshore (1760-1944))
	Mixed boreal conifer/hdwd	23 (range 3-46)	Lake Abitibi, Quebec	Bergeron and Dansereau 1993	Based on 10 fires (1760-1964)
	Mixed pine/boreal conifer/hdwd	9 (range 1-38)	N. Minnesota (entire BWCA)	Heinselman 1973	Based on dates of stand origin (1595-1971)
	Mixed boreal conifer/hdwd	65 (range 20-100)	N. Minnesota (Lake of the Clouds)	Swain 1973	Based on charcoal & pollen analysis past 1,000 years
	Paper birch/aspen	65	N. Minnesota (BWCA-Hug Lake)	Swain 1980	Based on 6 fires (1580-1970); charcoal & pollen analysis
FR 2-FR 3	White pine/ hemlock/ hardwoods	250+	New Hampshire (Harvard Tract)	Henry and Swan 1974	Based on fire origin of 1 stand but maybe blown down first
	White pine/mixed conifer hdwd	83	Ontario, Algonquin Park	Cwynar 1978	Based on sediment core analysis (850-1249 AD)
	Birch/white pine/hemlock	120 (range 40-230)	N. Wisconsin (Hell's Kitchen Lake)	Swain 1978	Based on 14 fires (350-1840 BP); charcoal & pollen analysis
FR 4	N.hdwds/hemlock/white pine	400+	N. Wisconsin (Forest Co.)	Stearns 1949	Virgin stands studied may have originated from fire in 1500s
	N. hdwds/hemlock/white pine	1700	Michigan UP (Sylvania Tract)	Davis et al. 1993	Based on 2 fires since 3500 yrs BP; charcoal & pollen analysis

Table A2. Historic fire regime categories with associated fire rotation periods for the northern Great Lakes Region.

Regime	Community Type	Fire Rotation Period (Yrs)	Location	Reference	Notes
FR 1	Jack pine	80-170	N. Lower Michigan	Whitney 1986	Based on GLO records of fires
	Jack pine	130	Michigan UP (Luce District)	Zhang et al. 1999	Based on GLO records of fires
	Jack pine/black spruce	50	N. Minnesota (BWCA)	Heinselman 1981	Revised estimate based on Van Wagner 1978
	Jack pine/black spruce	100	Quebec	Chandler et al. 1983	Source unknown (from Table 6.1)
	Jack pine/black spruce	60	Ontario	Chandler et al. 1983	Source unknown (from Table 6.1)
	Aspen/birch/fir	80	N. Minnesota (BWCA)	Heinselman 1981	Revised estimate based on Van Wagner 1978
FR 2-	Red/jack//white pine	130-260	N. Lower Michigan	Whitney 1986	Based on GLO records of fires
FR 3	Red/jack/white pine	160	Michigan UP (Luce District)	Zhang et al. 1999	Based on GLO records of fires
	Pine/oak	170-350	N. Lower Michigan	Whitney 1986	Based on GLO records of fires
	Red pine/white pine	180	N. Minnesota (BWCA)	Heinselman 1981	Revised estimate based on Van Wagner 1978
	Red pine/white pine	150	N. Minnesota (Itasca)	Frissel 1973	
	Red pine/white pine	320	Michigan UP (Luce District)	Zhang et al. 1999	Based on GLO records of fires
	Aspen/birch	210	Michigan UP (Luce District)	Zhang et al. 1999	Based on GLO records of fires
FR3W	Tamarack	190	Michigan UP (Luce District)	Zhang et al. 1999	Based on GLO records of fires
	Black spruce peatland	150	N. Minnesota (Lake Agassiz)	Heinselman 1981	Estimated
	Black spruce	100	Ontario	Chandler et al. 1983	Source unknown (from Table 6.1)
FR 4	Sugar maple/hemlock	900	Michigan UP (Porcupine Mtns)	Frelich & Lorimer 1991	Surface & stand replacing fires 1870-1980
	Sugar maple/hemlock	550	Michigan UP (Huron Mtns)	Frelich & Lorimer 1991	Surface & stand replacing fires 1870-1980
	Northern hardwoods/ pine/hemlock	1400-2800	N. Lower Michigan	Whitney 1986	Based on GLO records of fires
	Northern hardwoods	2600	Michigan UP (Luce District)	Zhang et al. 1999	Based on GLO records of fires
	Northern hardwoods	1000+	New Hampshire	Bormann and Likens 1979	Estimated
	Sugar maple/hemlock	1700—	Michigan UP (Sylvania Tract)	Frelich and Lorimer 1991	Based on surface & stand replacing fires 1870-1980
FR4W	Swamp conifers	3000-6000	N. Lower Michigan	Whitney 1986	Based on GLO records of fires
	White cedar	1700	Michigan UP (Luce District)	Zhang et al. 1999	Based on GLO records of fires
	Lowland hardwood/conifer	1100	Michigan UP (Luce District)	Zhang et al. 1999	Based on GLO records of fires
	Mixed lowland conifer/hardwoods	580	Michigan UP (Luce District)	Zhang et al. 1999	Based on GLO records of fires
	Black spruce	890	Michigan UP (Luce District)	Zhang et al. 1999	Based on GLO records of fires

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