Determining the Spatial Extent of Historical Fires With Geostatistics in Northern Lower Michigan

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Abstract—*Interpolated General Land Office fire occurrence notes were used to determine the spatial extent of pre-European settlement fires for 26 counties in northern lower Michigan using ordinary kriging with probability output. Best fit of a surface was achieved using a spherical model with a lag distance of 860 meters, an angular tolerance of 45 degrees, and consideration of anistropy. The interpolated data were associated with Land Type Associations to determine fire rotation and occurrence intervals for pre-European and modern day fires. The results show that modern day fire suppression efforts have curbed the size and frequency of fires.*

Introduction

Many natural resource conservation and production issues stem from concerns regarding the effects of natural and human-caused disturbance both at the landscape and local level. These issues are international in scope and range from loss of species diversity to threats to human safety and property from wildfire. The need to improve our understanding of natural disturbance and apply that knowledge to forest resource management practices is well documented (Watt 1947; Heinselman 1963, 1973, 1981; Wright and Heinselman 1973; Borman and Likens 1979; Canham and Loucks 1984; Sousa 1984; Botkin 1990; Forman and Godron 1991; Christensen 1993; and Tillman 1996). In the past, fire and wind disturbance have interacted with biological and physical components of the ecosystem to regulate patterns in the composition, structure, and age of forested landscapes in Michigan (Whitney 1986, 1987). 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 to conflict resolution and ultimately sustainable forest management.

Large modern day fires in the Lake States are rare due to effective fire suppression, though they do occur with devastating results. In the late summer of 1976, a fire near Seney in Michigan's upper peninsula burned approximately 74,000 acres. The fire, started by lightning, resulted in fire suppression and damage costs of more than $8,000,000. The Mack Lake fire, which occurred in northern lower Michigan in May, 1980, burned more than 20,000 acres in 6 hours. It eventually burned 24,000 acres, destroyed 44 homes and buildings, and caused one fatality. Simard and Blank (1982) reported that there have been 5 other fires in excess of 10,000 acres since 1820 within the area burned by the 1980 Mack Lake fire. The average return interval for these fires is 28 years. Simard et al. (1983) noted, "Given that fires will continue to

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occur, and that critical weather conditions will occasionally prevail, there is every reason to believe that some future jack pine fires will escape initial attack." There have been 215 fires in Oscoda County in the Mack Lake area within the past 16 years. Five were larger than 100 acres with 1 fire larger than 5,000 acres. The potential for a major conflagration exists within this area and in many other Michigan counties due to the extensive acreages of xeric outwash plains supporting pyrophilic jack and red pine ecosystems.

Simard et al. (1983) also stated, "Each fire is only a single observation of a complex process, and many observations are needed before patterns are observed." Clark (1987) noted that fire regimes are inherently difficult to assess because "the high variance associated with any low-probability event requires large sample sizes to determine expected values." While there are large numbers of modern fire records available for developing predictive models of fire ignition, modeling the potential of fires of varying size may be difficult due to the low number of observations of larger fires due to effective fire suppression. For example, of the 65,535 fires reported by state and federal agencies in the Lake States between 1985 and 2000, only 1,104 were larger than 100 acres and 122 larger than 1,000 acres. Thus, fires larger than 100 acres represent only 1.6 percent, or 1,104 of the 65,535 fires reported during this period. Therefore determining fire locations and extents during the pre-suppression era may provide information essential to estimating where large fires could occur today if undetected, or under circumstances where several fires occur concurrently, exceeding fire fighting capacity.

A number of approaches have been taken to estimate historical fire regimes in terms of frequency and extent or rotation. Clements (1910), Heinselman (1973), Arno and Sneck (1977), Simard and Blank (1982), Loope (1991), and Brown et al. (2001) used dendrochronological methods to examine fire scars for dating fire events at particular points. They then extrapolated the point data to represent the area under investigation. Van Wagner (1977) introduced the use of current age-class data fitted to a negative exponential curve to calculate fire rotations such that reconstructions of past fire events was not needed. Clark (1988a, 1988b) used stratigraphic charcoal analysis on petrographic thin sections to reconstruct a 750 year fire history in Itasca State Park, Minnesota. Each of these methods has advantages and disadvantages (Agee 1993) related to adequately assessing fire regimes at appropriate or relevant spatial and temporal scales. Area effects on estimates of fire return intervals or fire rotations (Arno and Petersen 1983), assumptions regarding flammability of fuels and fire behavior across heterogeneous landscapes (Gosz 1992, Brown et al. 2001), and adequacy of approaches for understanding long-term burn patterns (Clark 1987, 1988, 1990) are among the many challenges associated with meaningfully assessing fire regimes in space and time.

For this research, the approach to estimating fire locations and extent and subsequent interpretations involves the use of spatial statistics, specifically kriging, to interpolate fire observations made by General Land Office (GLO) surveyors. The original land survey by the GLO was initiated in Michigan in 1826, providing the earliest systematically recorded information on forest conditions in the Lake States. GLO surveyors noted fire locations along section lines and at section and quarter section corners. This provides a grid of observations along transects approximately one mile apart (Almendinger 1997). GLO records have been used to provide information on tree species composition, diameter size distribution, and disturbance patches in the pre-European settlement forests of the Lake States (Cottam 1949; Stearns 1949; Bourdo 1956, 1983; Cottam and Curtis 1956; Curtis 1959; Loucks 1983; Whitney 1986, 1987; Frelich 1995; and Owens 2001). Our use of GLO fire observations enables us to develop spatially explicit estimates of fire frequency and rotation intervals over an extensive geographic area.

Methodology

GLO Data Set

Microfilmed GLO notes for the section and quarter-section corners of 26 counties in Michigan's Northern Lower Peninsula (figure 1) were converted to ArcInfo point coverages. The coverages were rectified and georeferenced to a Modified Albers Conical Equal Area projection. Projection parameters on the modified projection are as follows: false easting and false northing 0 degrees, central meridian -89.50 degrees, first standard parallel 42.33 degrees, second standard parallel 47.66 degrees, latitude of origin 41.00 degrees, datum NAD 27, and spheroid Clark 1866. Attribute information associated

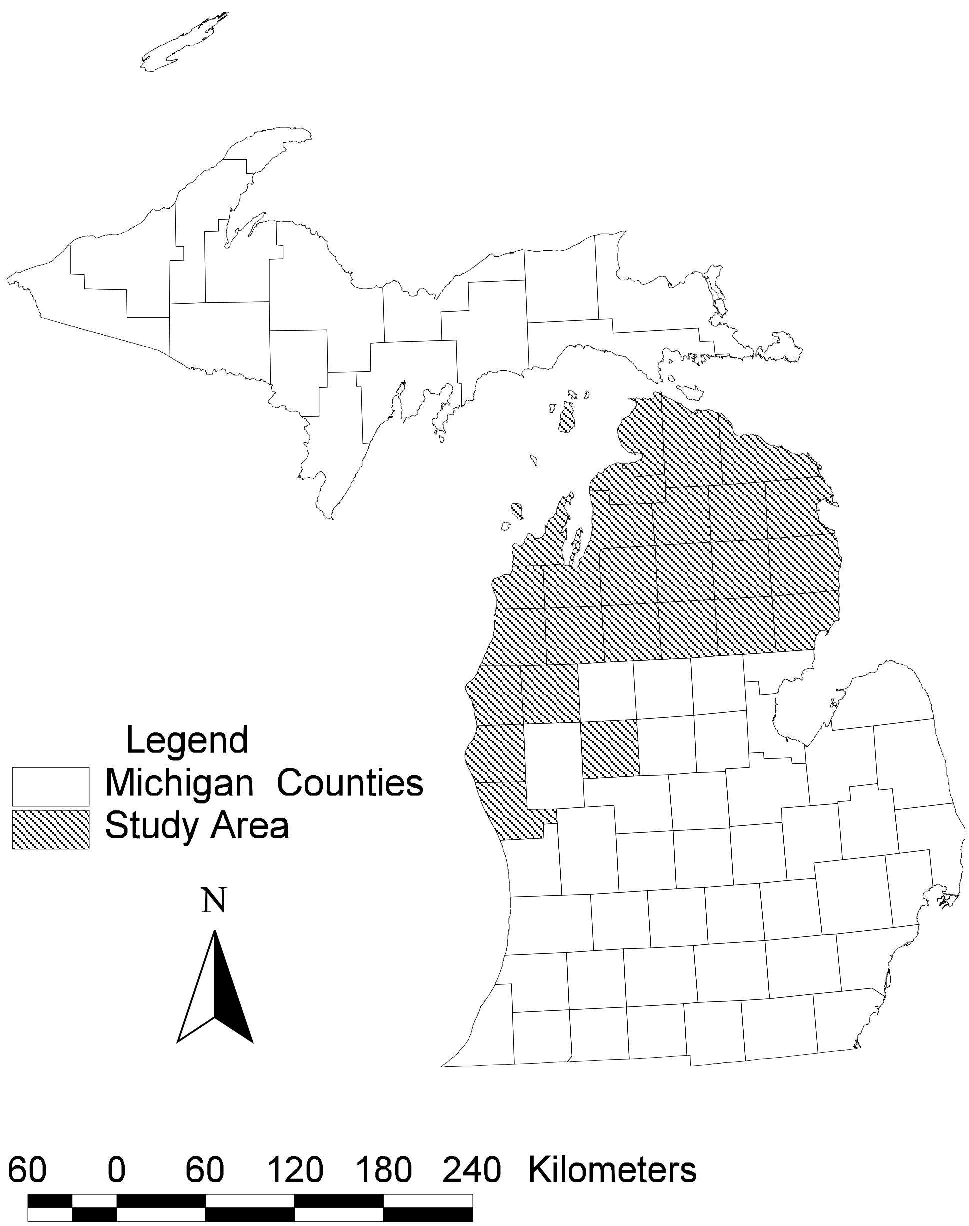

Figure 1—Michigan counties (shaded) included in fire occurrence study.

with the point coverages includes: corner record number; X and Y geographic coordinates of the corner; corner number; county of location, witness tree species, diameters, azimuths and directions; noted landscape disturbances; ecosystem classification; timber composition; other observations; surveyor's name and year of survey.

Noted fire occurrences were utilized to determine fire point locations. Designations of visible burn area (VB), entering burned area (EB), leaving burned areas (LB),visible burn area and fallen timber (VU), entering burn area and fallen timber (EU), and leaving burn area and fallen timber (LU) were included in the analysis. An addition field was created in the attribute table and labeled fire_code. A fire_code of 1 indicates a point of noted fire occurrence, and a value of 0 indicates no notation of fire damage.

Analysis Procedures

The ESRI ArcGIS (Version 8) Geostatistical Analyst extension was used to perform the analysis. This extension provides advanced surface modeling using deterministic and geostatistical methods. It also bridges the gap between geostatistics and GIS through integration of interpolation procedures into the ArcGIS software. The software provides the capability for analyzing data sets using different kriging approaches (simple, ordinary, probability, co-kriging, indicator and disjunctive), evaluating variogram or covariance plots utilizing different surface models, and calculation and evaluation of the effects of anistrophy.

A preliminary assessment of the data showed that the fire locations were naturally grouped into neighborhoods across the region (figure 2). This grouping can be explained in part by the fact that certain vegetation types, such as jack pine, are more susceptible to fire. The data were subset into these neighborhoods, and each neighborhood independently interpolated. The subsetting also facilitated the evaluation of directional autocorrelation within each neighborhood.

Ordinary kriging was used for the interpolation of the fire occurrence data points with output in the form of a probability map. It was chosen over simple kriging since it requires neither knowledge nor stationarity of the mean over the entire study area. Goovaerts (1997) noted that ordinary kriging with local search neighborhoods amounts to estimating the local mean at each location with data specific to the neighborhood, then applying the simple kriging estimator using that estimate of the mean rather than the stationary mean. 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.

Omni-directional variograms were generated to explore the structure of each neighborhood. Best fit of a surface for all of the neighborhoods was achieved using a spherical model. It is recommended by Isaaks and Srivastava (1989) that if the sample points are located on a grid, that the grid spacing is usually a good lag spacing. The distance between the points on a perfectly surveyed GLO grid would be 804.67 meters. However the greatest distance was found to be 858 meters, and distance of 860 meters was chosen to provide distance tolerance.

Glacial landforms strongly influence the location of the various vegetation types. The direction of the landform is influenced by the direction of advancement and retreat of the glaciers. Hence the data is expected to exhibit directional autocorrelation. Direction of anistrophy was calculated for each data set and used in the interpolation. A directional angular tolerance of 45 degrees was specified to account for directional variation in the north-south and east-west section lines. This information was then used to define the shape of the search neighborhood. The search neighborhood was divided into 4 sectors with the

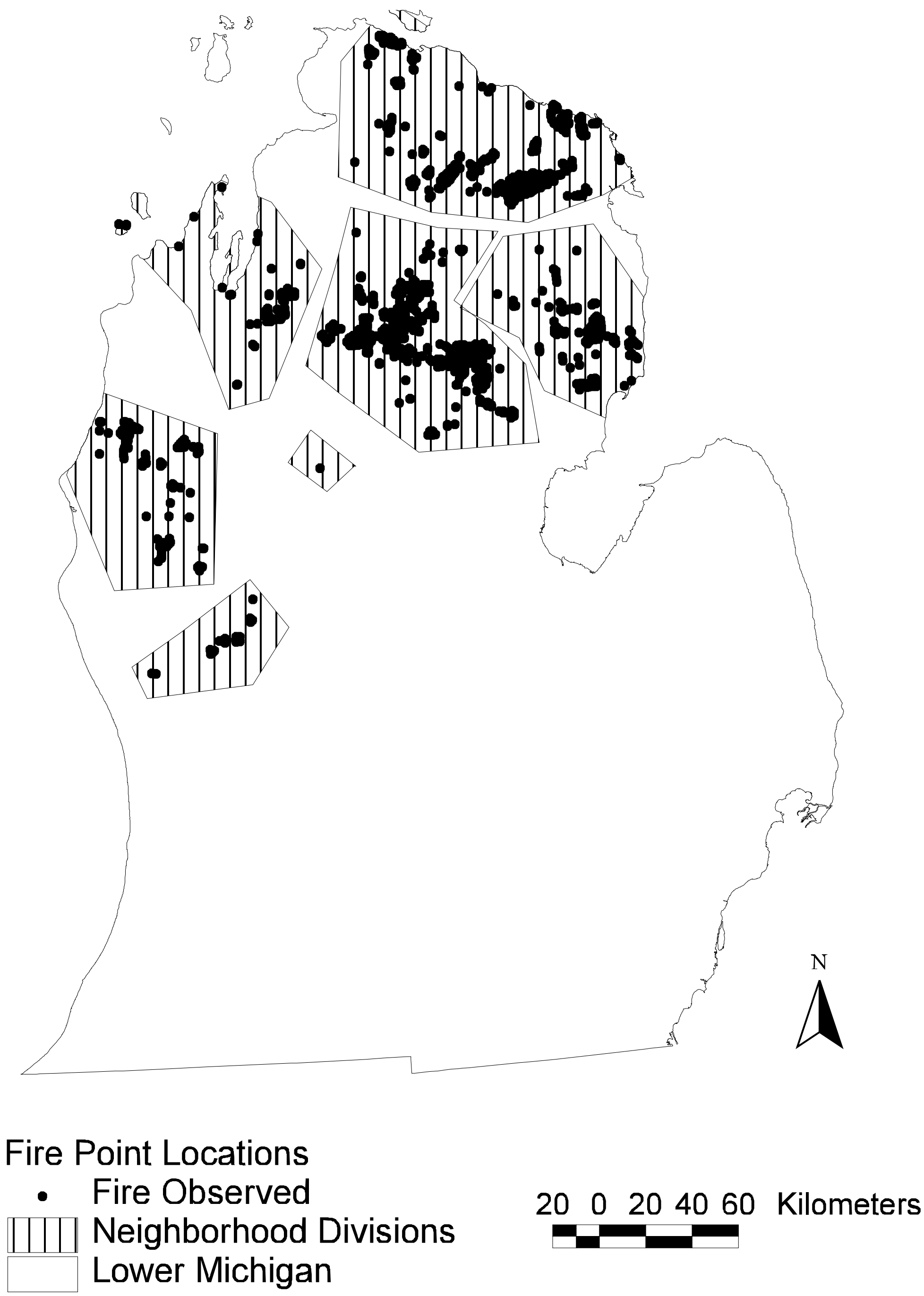

Figure 2—Locations of GLO fire points and neighborhood groupings.

sector axes running NW-SE and NE-SW. This reduced the directional influence of the GLO grid on the interpolation.

The probability of occurrence interpolations was converted from ArcGIS layer (.lyr) files to ARC grid files with a 100 meter spatial resolution. This spatial resolution provided the same scale as the original GLO point files.

Discussion

Results of Kriging

Probabilities of fire occurrence ranged from 30 to 100%. Low probabilities tend to be found in those ecosystems supporting long-lived, fire resistant northern hardwood and hardwood-hemlock forests including sugar maple, basswood, and white ash, or wetland hardwoods and mixed hardwood-conifer forests including black and green ash, silver maple, elm, and cedar. As we were interested in looking at probability of fire occurrence greater than 70%, the continuous probability classes were reclassified into three discrete classes with probability ranges of 70-79%, 80-89%, and 90-100%. Probabilities < 70% were not utilized in our analysis. The division into discrete classes facilitated acreage calculations and further analysis of the data set. However, it is important to note that forest managers could treat the output as a continuous data set and utilize the full range of output across the entire study area.

Applications for Research, Management, and Fire Risk

The interpolated probabilities of fire occurrence thematic layers are being used in several research and management applications in Michigan. Through a Joint Fire Science Program funded research project, the Great Lakes Ecological Assessment (Cleland et al. 2000; is characterizing historical and modern fire disturbance regimes of the Lake States. This research is conducting a comprehensive literature review and documenting how fire regimes have changed since European settlement. Spatially explicit estimates of historical and modern fire frequencies and rotations are being developed for landscape ecosystems mapped by interagency teams. Maps are being revised where necessary based on associations of ecological factors known to influence fire regimes. The assessment of changes in fire regimes since European settlement involves the comparison of historical fire frequencies and rotation intervals to those occurring between 1985 and 2000. We are using a hierarchical approach to assess interactions and spatial relationships among fire-dependent and fire-sensitive forest ecosystems and their associated disturbance regimes at three spatial scales. Results of these analyses are being incorporated into planning and management activities on the Hiawatha, Huron-Manistee, and Ottawa National Forests.

Use of the landscape ecosystem approach (Rowe 1980, 1984, 1992; Spies and Barnes 1985) is premised upon the assumption that fire behavior and risk are related to the conditions, processes, and spatial dimensions of particular ecosystems defined by integrating important physical and biological factors (Cleland et al. 1997). We are testing the hypothesis that historical and modern fire frequencies and rotation intervals are significantly different among multi-scaled ecological units *a posteriori*. Two principal measures of fire regimes, fire frequencies and fire rotations, provide critical information on fire risk (Agee 1993). Fire frequency is simply the number of fires per unit time and area. Fire rotation is the length of time necessary for an area equal to the entire area of interest to burn (fire cycle). This definition does not imply that the entire area will burn during a cycle; some sites may burn several times and others not at all. Meaningful estimates of these measures require clearly specifying the size of the area of interest. Thus identifying ecologically homogenous areas within which fire regimes can be analyzed is an essential step in the assessment of this process. Furthermore, mapping the location of modern and historical fires over large areas accommodates the random distribution of fires within smaller areas, improving estimates of fire regimes within ecologically similar spatial units.

Figure 3 displays a preliminary natural disturbance regime map based on aggregations or subdivisions of Land Type Associations (LTAS) for northern lower Michigan (Albert et al. 1996, Corner et al. 1999). Each polygon was evaluated using a number of GIS data sets, including Natural Resource

Conservation Service digital soil surveys, GLO notes on tree species and diameter, a 30-meter digital elevation model, hydrography, and current vegetation. Interpretations based on associations of ecological factors known to influence fire regimes were made, and each polygon was assigned to one of six fire rotation categories. The definitions for each category were based on a synthesis of the literature.

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 this research, fire rotations were determined by calculating the area burned for each fire rotation category, and dividing this area by 15 to estimate area burned per annum while assuming this to be a conservative burned area recognition window (Canham and Loucks 1984). Table 1 displays the historical and modern fire rotations calculated for the draft natural disturbance regime categories in northern lower Michigan. These results are an example of the application of interpolated GLO fire points in landscape ecosystem analyses. The following briefly describes the landscape ecosystem fire regime based on fire rotation forest rotation (FR) classes.

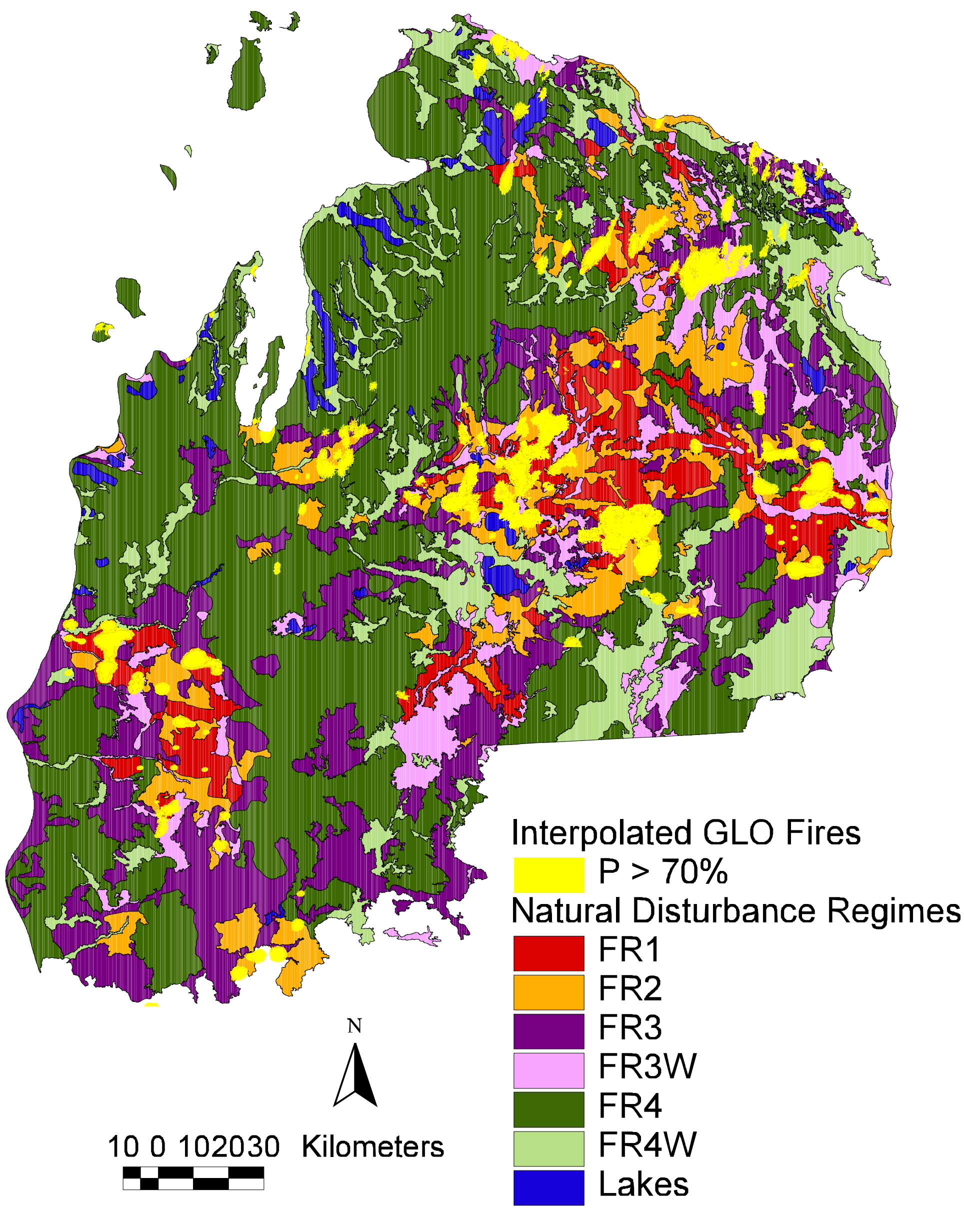

Figure 3—Natural disturbance regimes overlaid with interpolated historical fire locations with a probability of occurrence > 70%. FR1 sites experience frequent large catastrophic, stand-replacing fires. FR2 experiences less frequent large catastrophic, stand-replacing fires. FR3 and FR3W (wetlands) experience relatively infrequent stand-replacing fires. FR4 and FR4W (wetlands) experience very infrequent stand-replacing fires.

Table 1—Historic and modern fire rotations in Northern Lower Michigan.

Historical (1800s) fires **LTA grouping**	**Fire regime**	**Unit size**	**P>70% Acres burned**	**% burn/yr**	**Fire rotation**
Xeric LTAs dominated by jack pine and barrens	FR1	836,192	211,075	1.683	60
Less xeric LTAs dominated by white-red pine	FR2	1,029,138	144,850	0.938	107
Dry-mesic LTAs dominated by hemlock-white pine	FR3	1,652,410	52,396	0.211	473
Wetland LTAs adjacent to fire-prone LTAs	FR3W	494,638	61,618	0.830	120
Mesic LTAs dominated by northern hardwoods	FR4	3,771,745	40,862	0.072	1,385
Wetland LTAs adjacent to mesic hardwood LTAs	FR4W	958,232	21,012	0.146	684
Average fire rotation- 247 years	Total	8,742,355	531,813	0.406	

Modern (1985-2000) fires **LTA grouping**	**Fire regime**	**Unit size**	**Acres burned**	**% burn/yr**	**Fire rotation**
Xeric LTAs dominated by jack pine and barrens	FR1	902,052	15,552	0.115	870
Less xeric LTAs dominated by white-red pine	FR2	1,066,009	13,766	0.086	1,162
Dry-mesic LTAs dominated by hemlock-white pine	FR3	2,052,353	7,219	0.023	4,264
Wetland LTAs adjacent to fire-prone LTAs	FR3W	845,278	1,763	0.014	7,192
Mesic LTAs dominated by northern hardwoods	FR4	4,340,305	3,402	0.005	19,137
Wetland LTAs adjacent to mesic hardwood LTAs	FR4W	1,325,801	2,103	0.011	9,456
	Total	10,531,798	43,805	0.042	
Average fire rotation- 2,381 years					

FR1 represents landscape ecosystems historically experiencing frequent, large catastrophic stand-replacing fires. These ecosystems typically occur within very dry, flat outwash plains underlain by coarse-textured sandy soils. The pre-European settlement dominant forest types were short-lived jack pine forests and pine barrens.

FR2 represents landscape ecosystems historically experiencing large, catastrophic stand-replacing fires at lower frequencies, hence longer fire rotations, than the FR1 category. These ecosystems typically occur within dry outwash plains and ice-contact landforms underlain by sandy and loamy sand soils. The dominant pre-European forest types were white-red pine and mixed red-white-jack pine forests.

FR3 represents landscape ecosystems historically experiencing relatively infrequent stand-replacing fires at much longer fire rotations than the FR1 or FR2 categories. These ecosystems typically occur within dry-mesic ice-contact, glacial lakebed, and morainal landforms underlain by loamy sand to sandy loam soils, and commonly occur within close proximity to fire-prone ecosystems. The dominant pre-European forest type was long-lived mixed hemlock-white pine forests with minor elements of northern hardwood forests. Frequent ground-fires prevented succession to fire-sensitive hardwoods.

FR3W represents landscape ecosystems historically experiencing relatively infrequent stand-replacing fires. These ecosystems typically occur within wetlands embedded within or adjacent to fire-prone landscapes. The dominant pre-European forest types were wetland conifers including spruce, fir, and tamarack. Fire regimes and fuel formation were likely caused by interactions of insect and disease and large-scale blow-downs, as well as periods of drought.

FR4 represents landscape ecosystems historically experiencing very infrequent stand-replacing or community maintenance (ground) fires. These ecosystems typically occur within mesic (moist) moraines and glacial lakebeds underlain by fine-textured sandy loam to heavy clay and silt loams soils. The dominant pre-European forest types were long-lived, fire-sensitive northern hardwood and hardwood-hemlock forests including sugar maple, basswood, and white ash.

FR4W represents landscape ecosystems historically experiencing very infrequent stand-replacing or community maintenance (ground) fires. These ecosystems typically occur within wetlands embedded within or adjacent to fire-sensitive, hence fire protected landscape ecosystems (FR4). The dominant pre-European forest types were wetland hardwoods and mixed hardwood-conifer forests including black and green ash, silver maple, elm, and cedar.

Results of this research are also being applied by the North Central Research Station and cooperating universities as part of a fire risk assessment of the Lake States. This effort is assessing both historical and modern fire frequencies and rotation intervals, current vegetative conditions, and human population densities. We are investigating historical fire regimes in addition to modern regimes because preliminary analyses of a 1985-2000 modern fire database suggest that areas with the potential for large fires may not be adequately identified through regression due to the low number of large fires and the overwhelming influence of humans on fire ignition and spread. For example, Cardille and Ventura (2001) reported more than 97% of all fires occurring in the Lake States are due to human ignition, and 58% of all fires larger than 100 acres are due to arson. All fires reported were suppressed by fire fighting crews. These anthropogenic influences may obscure the elucidation of ecological factors associated with fires of different sizes. We believe the use of data on both historical and modern fire regimes will improve estimates of where the risk of large fires is greatest. Results will also provide insight into the effectiveness of fire suppression activities by allowing comparisons of pre-suppression fire regimes to those occurring today.

In summary, integrating information on historical disturbance regimes with other information such as ecological units, potential natural vegetation, and current vegetation will aid in understanding natural disturbance regimes and fire risk. This knowledge will also be useful in addressing a larger goal of improving our understanding of the characteristic rate of change, technically termed the dynamics of homeorhetic stability (Reice 1994, O'Neill et al. 1986), that formerly distinguished and maintained landscape and local ecosystems of the Lake States.

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