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Occurrence of wildfire in the northern Great Lakes Region: Effects of land cover and land ownership assessed at multiple scales

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Abstract. Risk of wildfire has become a major concern for forest managers, particularly where humans live in close proximity to forests. To date, there has been no comprehensive analysis of contemporary wildfire patterns or the influence of landscape-level factors in the northern, largely forested parts of Minnesota, Wisconsin and Michigan, USA.

Using electronic archives from the USDA Forest Service and from the Departments of Natural Resources of Minnesota, Wisconsin, and Michigan, we created and analysed a new, spatially explicit data set: the Lake States Fire Database. Most of the 18 514 fires during 1985–1995 were smaller than 4 ha, although there were 746 fires larger than 41 ha. Most fires were caused by debris burning and incendiary activity. There was considerable interannual variability in fire counts; over 80% of fires occurred in March, April, or May.

We analysed the relationship of land cover and ownership to fires at two different fire size thresholds across four gridded spatial scales. Fires were more likely on non-forest than within forests; this was also true if considering only fires larger than 41 ha. An area of National or State Forest was less likely to have experienced a fire during the study period than was a forest of equal size outside National or State Forest boundaries. Large fires were less likely in State Forests, although they were neither more nor less likely to have occurred on National Forests. Fire frequency also varied significantly by forest type. All results were extremely consistent across analysis resolutions, indicating robust relationships.

Keywords: fire, wildfire, Forest, Great Lakes, Minnesota, Wisconsin, Michigan, land cover, ownership, USDA Forest Service, DNR.

Introduction

Humans play an integral role in ecological dynamics at broad spatial scales (Turner *et al*. 1995 ; Vitousek *et al*. 1997), and it is imperative to assess human influence on ecosystem processes. This is especially true for fire ecology, in which humans currently affect both the origin and the suppression of fires (Frissell 1973; Harrington and Donnelly 1978; Haines 1983; Harrington *et al*. 1983; Frelich and Lorimer 1991; Stocks *et al*. 1996).

Fire was widespread throughout the forests of Minnesota, Wisconsin and Michigan prior to European settlement. Early work by Heinselman (1973) and Frissell (1973) concluded that, in the northern, forested part of Minnesota, the composition of biotic communities was highly influenced by fire frequency and severity. Vogl (1971) in Wisconsin, Loope (1991) in the Upper Peninsula of Michigan, and Whitney (1986) in the Northern Lower Peninsula of Michigan all found a relationship between fire frequency and forest type.

Studies of the period since European settlement show that the frequency of fires in the northern Great Lakes region has changed under human influence (Frissell, 1973; Heinselman 1981*b*; Frelich and Lorimer 1991). This has affected the composition of some forests in the region (Curtis 1959; Swain 1980; Whitney 1987; Loope 1991). The pervasive nature of these human-caused changes was summarized well by Heinselman (1981*b*), saying 'fire control, logging, land clearing and ... development ... have so greatly lengthened and modified natural fire cycles that they are no longer relevant except to understand the natural ecosystem and in the management of large nature reserves'.

Although we would like to better understand the spatial and temporal patterns of fire across northern Great Lakes

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forests, ecologists and fire managers lack comprehensive information about the modern forest fire regimes of the region. Contemporary fire information is compiled only on a state-by-state basis, or for widely separated National Forests. Maps and analyses of recent fire patterns for the entire forested northern Great Lakes region are a critical prerequisite for answering fundamental questions about modern fire regimes.

In this study, we analyse the occurrence of modern-day wildfire in the northern Great Lakes region. We present the Lake States Fire Database, a new data set that unifies extensive fire information from one federal and three state agencies in the region. Since large fires pose different management challenges from smaller fires, we conduct analyses using fires of two fire size thresholds. To assess the impact of forest management on fire frequency, we compare fire and ownership patterns. To determine whether, as in the pre-settlement period, fire frequency still varies with forest community type, we also compare fire patterns with land cover. Since results can vary by the scale of analysis (Meentemeyer 1989; Turner 1989; Turner *et al*. 1989), we perform each analysis at four different spatial scales.

We use the Lake States Fire Database with ownership and land cover factors to answer the following questions:

- What are the recent annual, seasonal, and spatial patterns of fire occurrence in the northern Great Lakes region?
- What are the causes of fires?
- Are fires more likely on State or National Forests?
- Is a fire more likely to occur in non-forested areas of the region than in Great Lakes forests?
- Does the occurrence of fire vary by forested land cover type?
- Are the results consistent across analyses at multiple scales?
- When only large fires are considered, how do these results change?

The answers to these questions will provide a first look at the northern Great Lakes region's modern fire regime.

Methods

Study area

The study area for this analysis centered on the northern forested part of Minnesota, Wisconsin, and Michigan (Fig. 1). It included counties or parts of counties within the Laurentian Mixed Forest Province (Bailey 1995) where the appropriate Department of Natural Resources or the USDA Forest Service had primary attack responsibility for wildfires. This produced a study area of approximately 2.8×10^5 km^2.

Nearly all forests of the Laurentian Mixed Forest Province have been logged at least once (Pyne 1982). Current vegetation includes upland conifer forests, peatlands and conifer swamps in northern and eastern Minnesota; aspen parkland and prairie in north-western Minnesota; and northern hardwood forests, white pine / red pine forests and jack pine barrens in northern Wisconsin, the Upper Peninsula of Michigan, and the northern Lower Peninsula of Michigan (Albert 1995).

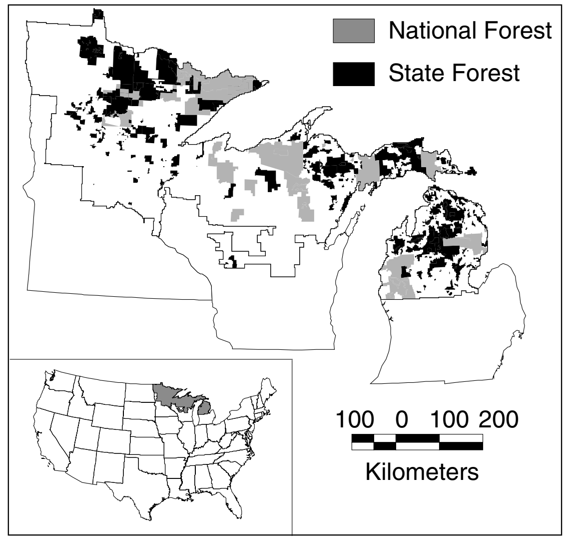

Fig. 1. Study area location and land management status, northern Great Lakes region.

Lake States Fire Database

As part of the Great Lakes Assessment at the USDA Forest Service and the University of Wisconsin-Madison, the Lake States Fire Database was constructed containing fire records from 1985 to 1995. This data set, the first that allows for GIS-based statistical analysis of fires across the region, was produced by combining the electronic fire database of the USDA Forest Service with those from the Departments of Natural Resources of Minnesota, Wisconsin, and Michigan.

Data sources

Minnesota DNR: for this study, the Minnesota Department of Natural Resources (DNR) provided all fire records held at the state level for wildland fires from 1985 through 1995. Included in the Minnesota database were those fires of any size to which the Minnesota DNR responds, and those fire reports from Volunteer Fire Departments (VFDs) throughout the state that forwarded their data to the state level (Abbott, pers. comm.).

Wisconsin DNR: for this study, the Wisconsin DNR provided all state-level fire records from 1982 through 1995. Unlike the Minnesota records, which covered the entire northern part of the state, computerized Wisconsin information is primarily confined to the 'intensive' and 'extensive' fire control areas, those areas outside of incorporated villages and cities in which burning permits are generally required (Steffen, pers. comm.). These fires, fought or managed primarily by the DNR, include reports from VFDs (Holdsambeck, pers. comm.). Fires in areas of 'cooperative' fire control, however, were only sporadically recorded during the study period and thus were not considered for this analysis.

Michigan DNR: for this study, the Michigan DNR provided all state-level fire records from 1982 through 1995. Although this data set did not include any information about Volunteer Fire Departments (Johnson, pers. comm. 1996), the state had 'primary initial attack responsibility' for DNR-controlled lands in Michigan's Upper Peninsula and in the northern two-thirds of its Lower Peninsula (Johnson, pers. comm. 1997). Since this area of primary responsibility generally coincides with the forested part of Michigan, differences in

VFD reporting among databases did not have a significant effect on the usefulness of the combined data.

USDA Forest Service: for this study, the USDA Forest Service's Region 9 office provided computerized location data for fires from 1970 through 1995. Records were compiled and checked at each National Forest and united at the regional level. These records included fires within the boundaries of the study area's seven National Forests, and in some areas also included information about fires in 'inholdings': private lands surrounded by a National Forest (Hancock, pers. comm.; Johnson, pers. comm. 1996; Miller, pers. comm.). Since wildfire management in Minnesota, Wisconsin, and Michigan is organized to minimize overlaps in area of responsibility, managers believe that duplicate fire reporting between local, state, and federal agencies is possible but unlikely (Hancock, pers. comm.; Miller, pers. comm.).

Spatial resolution

For nearly all fires in the database, origin information was received as a Public Land Survey System (PLSS) description. For each fire the township, range, and section value were specified. Section-level values allowed a fire's origin to be located within a 1 square mile (2.59 km^2) area.

State-specific translation tables were used to convert the PLSS description of the thousands of fire origins to the appropriate Universal Transverse Mercator Zone 15 coordinates (in the case of Minnesota), Wisconsin Transverse Mercator coordinates (for fires in Wisconsin), or Michigan State Plane coordinates (in Michigan). Fire points in each of these systems were then projected to an Albers Equal-Area Conic projection centered on the region.

USDA Forest Service spatial data were mixed between fire origins specified in latitude–longitude format (from GPS positioning or map-based assessment) and PLSS format. PLSS data were translated using the state-specific tables, while the geographic data were projected directly to the study's special projection.

Study period and temporal resolution

Although each source provided data from slightly different time periods, the intersection among all sources was 1985 through 1995. Accordingly, this was the time period used for construction of the fire database. Temporal information included the month, day, and year of the origin of each fire.

Fire size stratification

The fire database contained fires of vastly different sizes: most reports concerned small fires, but some fires were extremely large. Since factors influencing the smallest fires might be different than factors influencing the occurrence of larger fires, two levels of fire size were separately considered: 'all' fires, which included all fires with a total area larger than or equal to 1 acre (0.4 ha); and 'large' fires, which included only those fires larger than or equal to 100 acres (41 ha). This distinction is consistent with fire size classifications for each of the three states and the USDA Forest Service, and provided enough large fires to contrast with the set of all fires. This size stratification for fires between 1985 and 1995 created an 'all fires' set containing 18 514 fires; the 'large fires' set contained 746 fires (Fig. 2).

Land cover and ownership data

To answer fundamental questions relating fire patterns to land cover and forest ownership, we collected the following information across the entire study region:

Current Land Cover: the USDA Forest Service 1-km land cover data set (Powell *et al.* 1992) was used to represent the current land cover throughout the study area. Derived from NOAA Advanced Very High Resolution Radiometer (AVHRR) images and ancillary data, this data set consisted of a classification oriented around the forest cover of the study area. It classified each 1 km pixel into one of the following categories: white–red–jack pine; spruce–fir; oak–hickory; elm–ash–cottonwood; maple–beech–birch; aspen–birch; non-forest; and water.

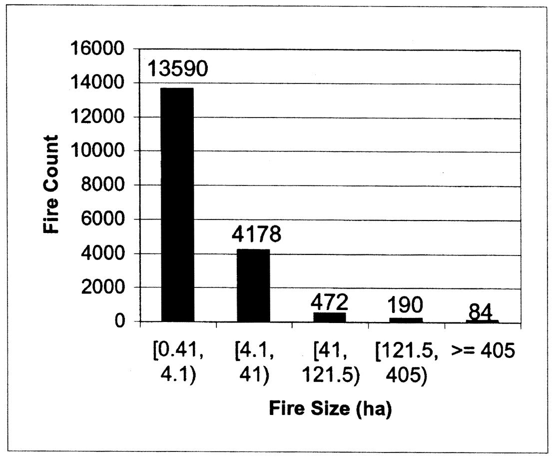

Fig. 2. Total fire count by size in the northern Great Lakes region, 1985–1991.

Ownership: using the data set provided by McGhie *et al.* (1996), a set of ownership layers of different types was produced for the study area. Compiled at 1:2 000 000 scale with a minimum mapping unit of 100 ha, it provided information on the responsibility for managed areas throughout the entire study area. The National Forest data set was created from those polygons in McGhie *et al.* (1996) that were classified as USDA Forest Service land or USDA Forest Service Wilderness Units. The State Forest data set was created from polygons classified as State Forest belonging to Minnesota, Wisconsin, or Michigan. National Forest land comprised 14% of the study area, while State Forest land comprised 19% of the study area (Fig. 1).

Grid representation

To facilitate statistical analysis of fire occurrence and layers of land cover and ownership, a grid-based spatial framework was chosen. The study area was partitioned into equal-sized square cells, with each fire occurrence and potentially related factors measured within each cell. Creation of a single, co-registered reference system greatly simplified analysis—it partitioned the study area into equivalently sized units of analysis, allowing comparisons between cells; it allowed point-based features such as fire occurrence to be viewed not just as tens of thousands of individual points but as a spatially varying density throughout the study area; it allowed polygon data, like that of State Forest boundaries, to be represented as a binary (0,1) variable; and it allowed gridded data, such as the grid representing Current Land Cover, to be seamlessly co-registered with the other layers.

Spatial scaling

Because processes potentially influencing fire occurrence could appear to behave differently at different scales, the Lake States Fire Database and the land cover and ownership layers were gridded at four different resolutions. Since the single-dimension spatial precision of the fire database was 1 mile (1.6 km), the finest analysis resolution was chosen to be 2 km. In addition, the databases were interpreted using grids with spatial resolutions of 3 km, 5 km, and 10 km. This system was chosen to allow comparison of analyses at wholly nested scales (2 km and

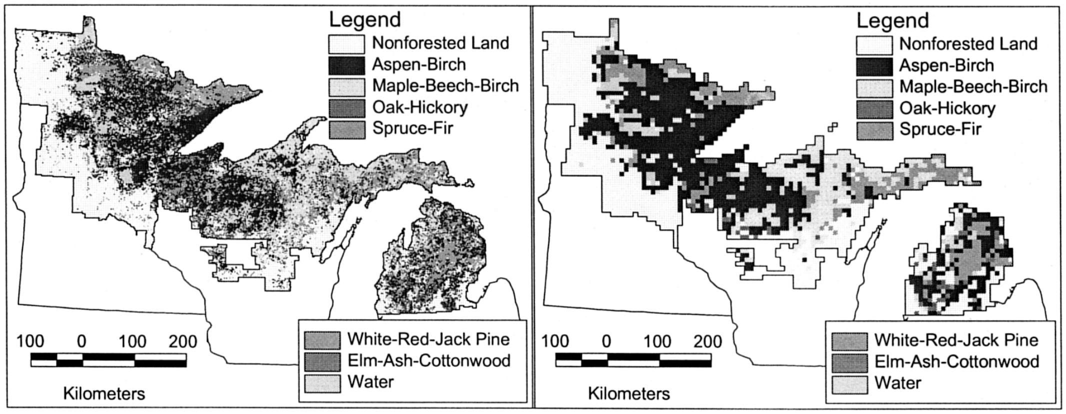

Fig. 3. Northern Great Lakes region land cover. (*a*) 2 km resolution. (*b*) 10 km resolution.

10 km, and 5 km and 10 km), and at similar scales having phase-shifted edges (2 km and 3 km).

When coarsening Current Land Cover from its original 1-km scale, the majority cover type was chosen wherever a majority existed. Where there were equal amounts of two or more cover types, the cover type of the 1-km cell nearest to the center of the coarser cell was chosen. This method effectively selected a land cover at random from those contained within the larger cell. Although the coarsening algorithm diminished somewhat the presence of rarer land cover types at the coarsest spatial resolutions (Table 1), this scaling strategy produced a consistent map across spatial scales for the Current Land Cover layer (Fig. 3). Scaled images for National and State Forest ownership showed minimal change across scales.

Statistical analysis

To determine whether patterns of fire differed by ownership and by land cover, we used a series of two-sided Z tests for proportion differences (Ott 1988; Wonnacott and Wonnacott 1990). These tests used maps of fire occurrence to investigate whether the proportion of cells that contained a fire of a given size threshold and had a particular factor attribute was significantly different than that same proportion of fire cells calculated over areas not having that factor attribute. For example, to investigate whether large fires were more likely on State Forests, we compared the proportion of cells within State Forests that contained a large fire against the proportion of forest cells outside State Forests that contained a large fire. This test was repeated both for large fires and for all fires, for ownership and land cover, at each of four scales.

Table 1. Proportions of land cover in the northern Great Lakes region

Land cover	As proportion of all study area cells		As proportion of forest cells	
	2 km	10 km	2 km	10 km
Non-forest	0.31	0.32	—	—
Aspen–birch	0.30	0.37	0.45	0.56
Maple–beech–birch	0.16	0.14	0.25	0.22
White–red–jack pine	0.11	0.09	0.16	0.13
Oak–hickory	0.05	0.02	0.07	0.03
Spruce–fir	0.05	0.04	0.07	0.06
Elm–ash–cottonwood	0.0005	0.0004	0.001	0.001
Water	0.02	0.02	—	—

Spatial autocorrelation

Spatial autocorrelation was not considered an issue in this study for several reasons. First, since the origin of each fire was recorded as a dimensionless point, no single fire could be recorded in adjacent cells. Second, at even the finest spatial resolution (2 km), all but the largest fires had a vanishingly small likelihood of actually having had a fire perimeter that lay across the border of two adjacent cells. Third, because fires themselves were typically so much smaller than even the finest spatial resolution, the occurrence of a fire in a given cell would not have significantly raised or lowered the probability that a fire would occur in an adjacent cell. Finally, although the PLSS system means that fires tend to appear 1 mile (1.6 km) apart, the spatial resolution of 2 km, 3 km, 5 km, and 10 km ensures that the effective sampling distance is greater than this likely lag distance.

Results

Lake States Fire Database

Annual and monthly distributions

During 1985–1995 in the northern Great Lakes region, annual fire frequency varied greatly (Fig. 4). Years with drier springs and summers (e.g. 1987, 1988) had many more fires than years with wetter springs and summers (e.g. 1986). During the study period, the average annual number of fires was 1683.1, with standard deviation 653.8.

Monthly frequency data for the study period (Fig. 5) show that April and May were, by far, the most significant months for fire in the northern Great Lakes region. Over 70% of all fires between 1985 and 1995 began during one of these two months, during which the winter's snow had melted but new vegetation had not yet fully grown. A second, smaller peak in fire frequency occurred in October, during which the summer's vegetation had senesced but winter snows had not begun.

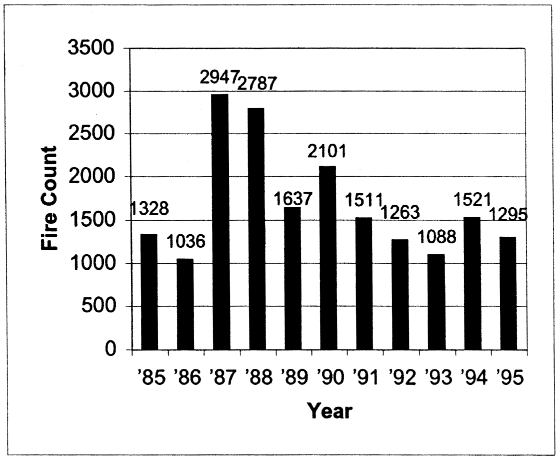

Fig. 4. Total fire count by year in the northern Great Lakes region, 1985–1995.

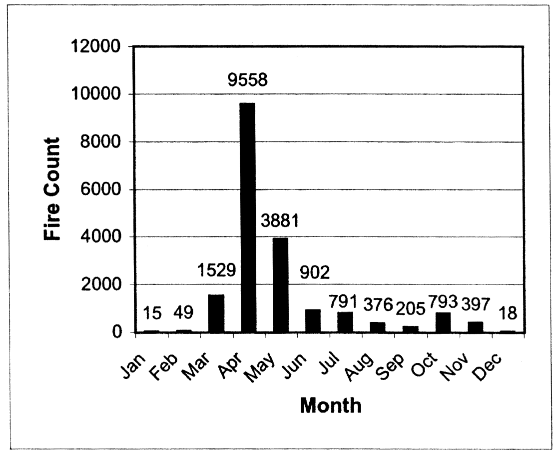

Fig. 5. Total fire count by month in the northern Great Lakes region, 1985–1995.

Fire cause

During the study period in the northern Great Lakes region, the vast majority of fires were of human origin (Fig. 6). More than a third originated because of debris burning, a category referring to the burning of material from land clearing, dumps, and trash. Lack of more detailed fire cause data from Minnesota prevented a more detailed classification of this important fire cause. Nearly 30% of fires were attributed to incendiary activity, which included grudge fires, pyromania, and habitat improvement for game.

Large fires during the study period were also predominantly of human origin (Fig. 7). In the case of large fires, however, incendiary activity played a much greater role suggesting that, whereas a person responsible for a debris fire was generally willing to report a problem immediately, fires involving incendiary activity often went unreported until they had reached a greater size, resulting in greater probability that they would become large fires.

Fire patterns

When the presence or absence of a fire of any size was considered for the entire 1985–1995 period, the proportion and pattern of wildfire cells varied by spatial scale (Fig. 8). When fires from all years were grouped at the 10-km scale, the pattern shows that only a few cells contained fire in the western-most part of the study area, where agricultural fields in north-western Minnesota are common. Fires were also rare in areas dominated by Lake of the Woods and the Red

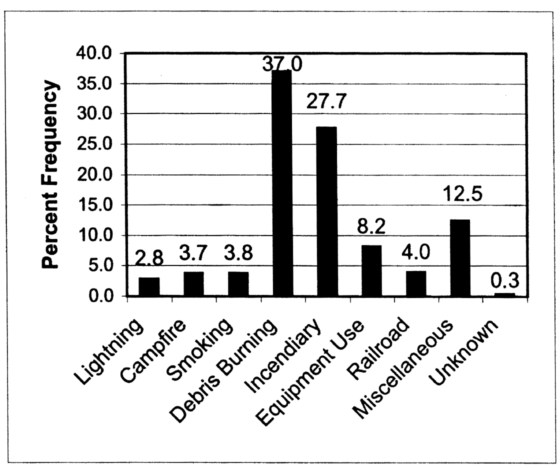

Fig. 6. Percentage frequency of all fires by fire cause in the northern Great Lakes region, 1985–1991 (n = 18 514).

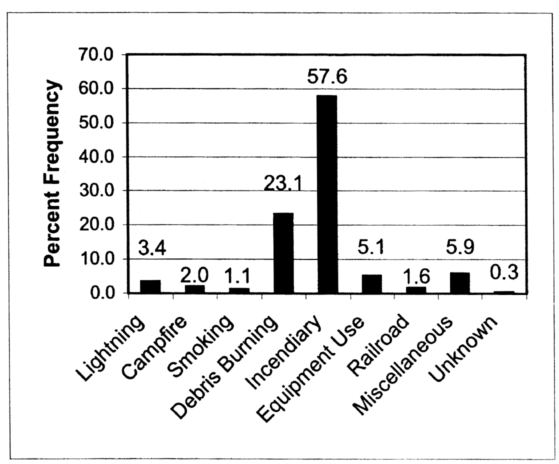

Fig. 7. Percentage frequency of large fires by fire cause in the northern Great Lakes region, 1985–1991 (n = 746).

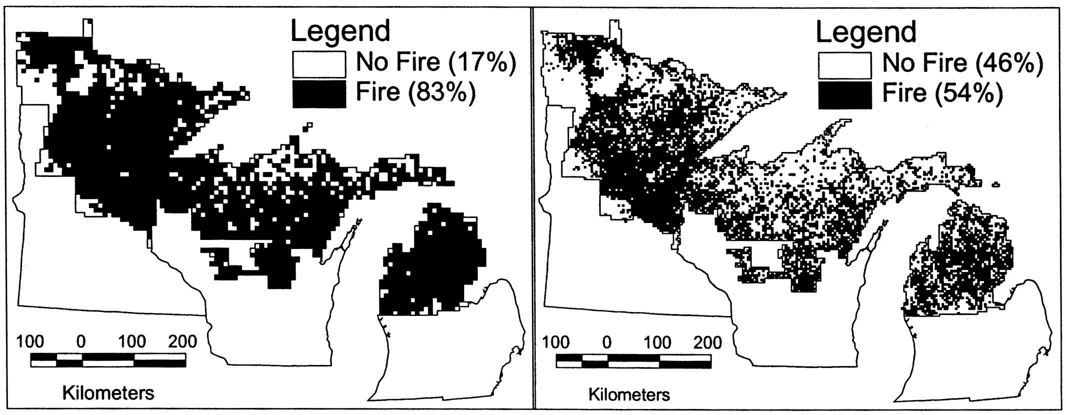

Fig. 8. Northern Great Lakes region fire occurrence. (*a*) 10 km resolution. (*b*) 5 km resolution.

Lakes. In northern Wisconsin and the Upper Peninsula of Michigan, a relatively low proportion of cells contained at least one fire. At the 5-km scale, north-eastern Minnesota, northern Wisconsin and the Upper Peninsula of Michigan are seen to have been largely devoid of fires: central Minnesota and the interior of Michigan's Lower Peninsula had extensive areas where nearly all cells contained a fire.

In comparison with images of all fires, images of large-fire occurrence were more consistent across scales (Fig. 9). Since large fires were much rarer than fires of any size, only a small percentage of the study area contained a large fire. Because these large fires were not overwhelmingly clustered into a small area, overall patterns at multiple resolutions appear similar. In particular, there was a cluster of large fires to the north-west of the Red Lakes in Minnesota and another to the south-west and to the north of Mille Lacs Lake. Most other large fires were scattered throughout the study area, except for a cluster in the north central part of Michigan's Lower Peninsula.

Fire occurrence on Non-forest

At three of the four analysis scales, areas of Non-forest had higher probability of fire than did forested areas (Table 2, part *a*). For example, at the 2 km resolution, where Non-forest constituted 31% of the study area (Table 1), fire occurred on 21.9% of the Non-forest cells (Table 2); that proportion was significantly greater than the 14.7% of forested cells that had one or more fires.

Areas of Non-forest were also more prone to large fires than were forested areas during the study period (Table 2, part *b*). For example, at the 10 km resolution, where Non-forest constituted 32% of the study area (Table 1), at least one large fire occurred on 22.2% of the Non-forest cells; that proportion was significantly greater than the 10.0% of

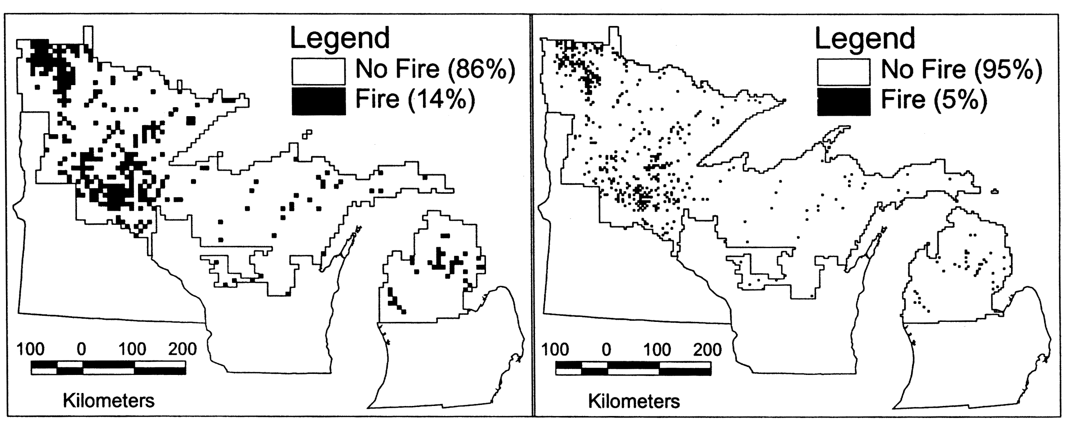

Fig. 9. Northern Great Lakes region large-fire occurrence. (*a*) 10 km resolution. (*b*) 5 km resolution.

Table 2. Comparison of fire probability for the northern Great Lakes region during 1985–1995, by management designation and land cover

Bold formatting indicates a significant difference at the 95% level for a two-sided *Z*-test between proportions. Comparison was between proportion of fire cells for specified land cover / management and proportion of fire cells in remainder of study area

	Analysis resolution			
	10 km	5 km	3 km	2 km
		(a) All fires		
Study area	0.831	0.541	0.306	0.170
Non-forest	ns	**0.605**	**0.375**	**0.219**
		(b) Large fires		
Study area	0.140	0.047	0.019	0.009
Non-forest	**0.222**	**0.084**	**0.035**	**0.017**
		(c) All fires		
Forested study area	0.838	0.510	0.273	0.147
National Forests	**0.753**	**0.374**	**0.181**	**0.092**
State Forests	ns	**0.460**	**0.227**	**0.115**
		(d) Large fires		
Forested study area	0.100	0.029	0.011	0.005
National Forests	ns	ns	ns	ns
State Forests	ns	**0.021**	**0.007**	**0.003**

Table 3. Comparison of fire probability for northern Great Lakes region forests during 1985–1995, by forest type

Bold formatting indicates a significant difference at the 95% level between proportions. Comparison was between proportion of fire cells for specified forest type and proportion of fire cells in remainder of forested study area. Where n was sufficiently large to warrant a Normal approximation t the Binomial, a two-sided *Z*-test was used. [b] indicates tests which used the Binomial. ns, differences which were not significant. All tests excluded water cells from consideration

	Analysis resolution			
	10 km	5 km	3 km	2 km
		(a) All fires		
Forested study area	0.84	0.51	0.27	0.15
Aspen–birch	**0.88**	**0.56**	**0.30**	**0.16**
Maple–beech–birch	**0.77**	**0.40**	**0.21**	**0.11**
White–red–jack pine	ns	**0.57**	**0.31**	**0.18**
Oak–hickory	**0.94**[b]	**0.70**	**0.36**	**0.20**
Spruce–fir	**0.58**	**0.27**	**0.14**	**0.08**
Elm–ash–cottonwood	**1.00**[b]	**1.00**[a]	ns[b]	**0.31**[b]
		(b) Large fires		
Forested study area	0.100	0.029	0.011	0.0055
Aspen–birch	**0.122**	**0.035**	**0.013**	**0.0068**
Maple–beech–birch	**0.051**	**0.017**	**0.008**	**0.0033**
White–red–jack pine	**0.126**	**0.038**	**0.014**	**0.0059**
Oak–hickory	**0.019**[b]	**0.003**[b]	**0.006**	**0.0046**
Spruce–fir	**0.065**	ns	**0.009**	**0.0052**
Elm–ash–cottonwood	ns[b]	ns[b]	ns[b]	ns[b]

forested cells that had one or more large fires. Though the proportion of cells having large fires differed considerably at each analysis resolution, the significance of the difference between Non-forest and forested cells was consistent across all four analysis scales.

Fire occurrence on National Forests

Between 1985 and 1995, cells within National Forests were significantly less likely than forest cells outside National Forests to have had at least one fire (Table 2, part *c*). At the 2 km resolution, for example, 9.2% of National Forest cells had a fire during the study period. This was a significantly smaller proportion than the 16.2% of forest cells outside National Forests that had a fire. However, National Forests were no more or less likely to have experienced a large fire than forest cells outside National Forests (Table 2, part *d*).

Fire occurrence on State Forests

At three scales of analysis, cells within State Forests were significantly less likely to have had a fire during the study period than were forest cells outside State Forests (Table 2, part *c*). It is interesting to note that the proportion of State Forest cells that had experienced a fire was somewhat higher, at each resolution, than the proportion of National Forest cells that had one or more fires during the study period. At all but the 10 km resolution, however, this proportion of State Forest fire cells was still low enough to be significantly different than the proportion of forest fire cells outside State Forests.

With respect to large fires on State Forests, however, a different picture emerged from that of large fires on National Forests. At the three finest scales, the proportion of State Forest cells that experienced a large fire was significantly smaller than the proportion of forest fire cells outside State Forests.

Fire occurrence by forest cover type

Across all scales of analysis, probability of fire varied significantly by forest type (Table 3). When specific forest types were isolated and compared to the rest of the forested study area, it became clear that there is no ‘typical’ forest with respect to fire probability. These results were generally also significant for large fires (Table 3). Results for specific forest types are discussed below:

- Cells of the aspen–birch category, the dominant forested land cover (Table 1), were more likely to have had a fire than forest cells outside this category. This tendency toward fires in aspen–birch was also seen for large fires: at all scales, aspen–birch was more likely than other forest categories to have had a large fire during the study period.
- Cells of the maple–beech–birch category, which constituted between 22% and 25% of the forested study area (Table 1), were less likely to have had a fire than other forested areas. Furthermore, when only large fires were considered, the difference in fire proportion between

maple–beech–birch and other forests was even more extreme.

- At three analysis scales white–red–jack pine forests, which covered around 15% of the forested study area (Table 1), were more likely than other types of forests to have had at least one fire during the study period. Large fires were also more likely on white–red–jack pine forests than on other forests during the study period.
- Oak–hickory forests, which constituted only 3% to 7% of the study area (Table 1), were more likely than other forests to have had a fire during the study period. However, these forests were significantly less prone to large fires than other forests in the study area. This tendency away from large-fire occurrence on oak–hickory forests was quite consistent across scales even though low large-fire cell counts prohibited a Normal approximation to the Binomial at coarser scales.
- Cells of the spruce–fir category were significantly less likely than other forests to have had a fire or a large fire.
- Elm–ash–cottonwood forests were extremely rare in the study area (Table 1). Although those few cells were more likely to have witnessed some fire, large-fire probability there was no different than on other forests. Due to their extreme rarity they did not contribute heavily to fire patterns in the region.

Discussion

Analyses of fire patterns in the northern Great Lakes region, made possible here for the first time, indicate significant variation in size, annual frequency, and monthly frequency. Several major conclusions about fire patterns in the region emerge from this work:

Fires were less likely to have occurred in a forested area than on Non-forest

At all but the coarsest scale of analysis, a Non-forest cell was more likely than a forest cell to contain a fire during the study period. This may be due to the relative ease with which a fire can start in grassy or agricultural areas, but may also be due to differences in accessibility to humans. That is, areas must be quite heavily forested to be classified as forest at these spatial resolutions. When compared to more open areas, areas classified as forest would be less likely to be regularly accessed by humans. Large fires were also much more likely on Non-forest than in forested areas. This may be due to ease of burning Non-forest fuels, but may also be related to the propensity of fires of any size to occur on Non-forest. That is, with more fires of all sizes occurring in Non-forest, some suppression agencies may be busy fighting a fire in one part of the non-forested study area while another fire grows larger than it might were it quickly suppressed. Finally, it is possible that the lack of large fires on National and State Forests tends to also affect this forest–Non-forest comparison.

Fires were more likely to occur outside of State and National Forest boundaries than within them

This tendency was seen at nearly all scales and was seen both when all fires were considered and when only large fires were analysed. With respect to fires of all sizes, unequal ignition probabilities on and off these forests seem likely to result in a greater likelihood of fires outside National and State Forests. Most fires are human-caused (Haines *et al*. 1983; USDA 1987) and caused in particular by local permanent residents (Main and Haines 1974). Because there is a much lower population on National and State Forest land than on forested land outside their boundaries, we would expect fewer fires there. However, whereas differences in all-fire probability is likely due to access, the decreased likelihood of large fires on National and State Forests is probably an expression of fire suppression effort outside Wilderness areas. Because these government-managed forests typically have significant economic value, fire suppression programs are designed to prevent widespread burning of timber in State and National Forests and likely result in decreased large-fire occurrence.

Fire probability varied significantly by land cover

We contrasted each forested land cover type against the rest of the forest cells of the study area, and found that land cover was significantly related to fire probability.

Constituting about half of the forested land cover, Aspen–birch forests were more likely than the rest of the forest cells to have witnessed at least one fire during the study period. There was a similar increased probability of large fires on these forests. This tendency may indicate a lingering effect of the fire regime as it would be without human influence: Heinselman (1978) described the significant role of fire in aspen communities; Albert (1995) echoed the role of frequent fire in aspen parkland communities. Aspen-Birch also may be occurring in these areas due to fire in recent decades.

Maple–beech–birch forests were less likely than other forest types to have had at least one fire during the study period; these forests were also particularly less likely to have experienced a large fire. This is consistent with Frelich and Lorimer (1991), who characterized the major natural disturbance regime in Northern Hardwoods forests not as fire, but as windthrow. Although this relative lack of fire in maple–beech–birch forests may be due to purely ecological reasons like landscape position and soils, it is noteworthy that the areas classified as maple–beech–birch occur mainly in north-eastern Wisconsin and the Upper Peninsula of Michigan. These areas have high amounts of National and State Forest lands, so the decrease in large fires on that cover type may be partly due to an interactive effect of cover type and ownership.

Less common cover types generally showed a significant tendency with respect to the probability of any fire and of large fires, though their rarity weakened their influence on overall fire patterns in the study area. White–red–jack pine was more likely than other forest types to have experienced a fire: this is consistent with Frissell (1973) and Heinselman (1981*a*), who noted short fire-return intervals for this type. Oak–hickory, which commonly experienced fire in the region prior to European settlement (Albert 1995), was more likely than expected to have witnessed a fire during the study period. Spruce–fir, which constituted only a small part of the forested study area, was much less likely than the remainder of the forest cells to have had a fire. The relative lack of fire in spruce–fir forests may be related to its location in the region: most spruce–fir occurs in and near the Superior National Forest in Minnesota, where fire probability is lower.

Conclusion

The development of the Lake States Fire Database had made it possible, for the first time, to describe and analyse modern fire occurrence in Minnesota, Wisconsin, and Michigan. Maps of fire occurrence for all fires and for large fires constitute the first regional look at fire data for the area.

This study has performed several analyses new to the northern Great Lakes region. By demonstrating that fire probability is different on State and National Forests than outside them, we have shown that modern fire patterns vary by ownership. By contrasting fires in forested areas with fires in Non-forest, we have shown that fire patterns vary by land cover type. By analysing the occurrence of fires by forested land cover type, we have demonstrated that fire patterns follow expected ecological behavior and may suggest long-term positive feedbacks between fire frequency and forest cover type. The success of this approach suggests that it may well be useful to incorporate additional environmental and social factors into statistical analyses of fire patterns in the region.

Given that binary maps of fire occurrence were so different at the four analysis resolutions, results across scales were remarkably consistent. In almost all tests, results at one scale matched well with results at all other scales: although a few analyses were non-significant at the 95% level for one of four resolutions, these typically occurred at the coarsest scale with its expected loss of detail. On the whole, the multi-scale approach lent strong confidence that these results are not merely an artifact of the sampling scheme or spatial resolution, but are instead related to the modern fire regimes of the northern Great Lakes region.

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