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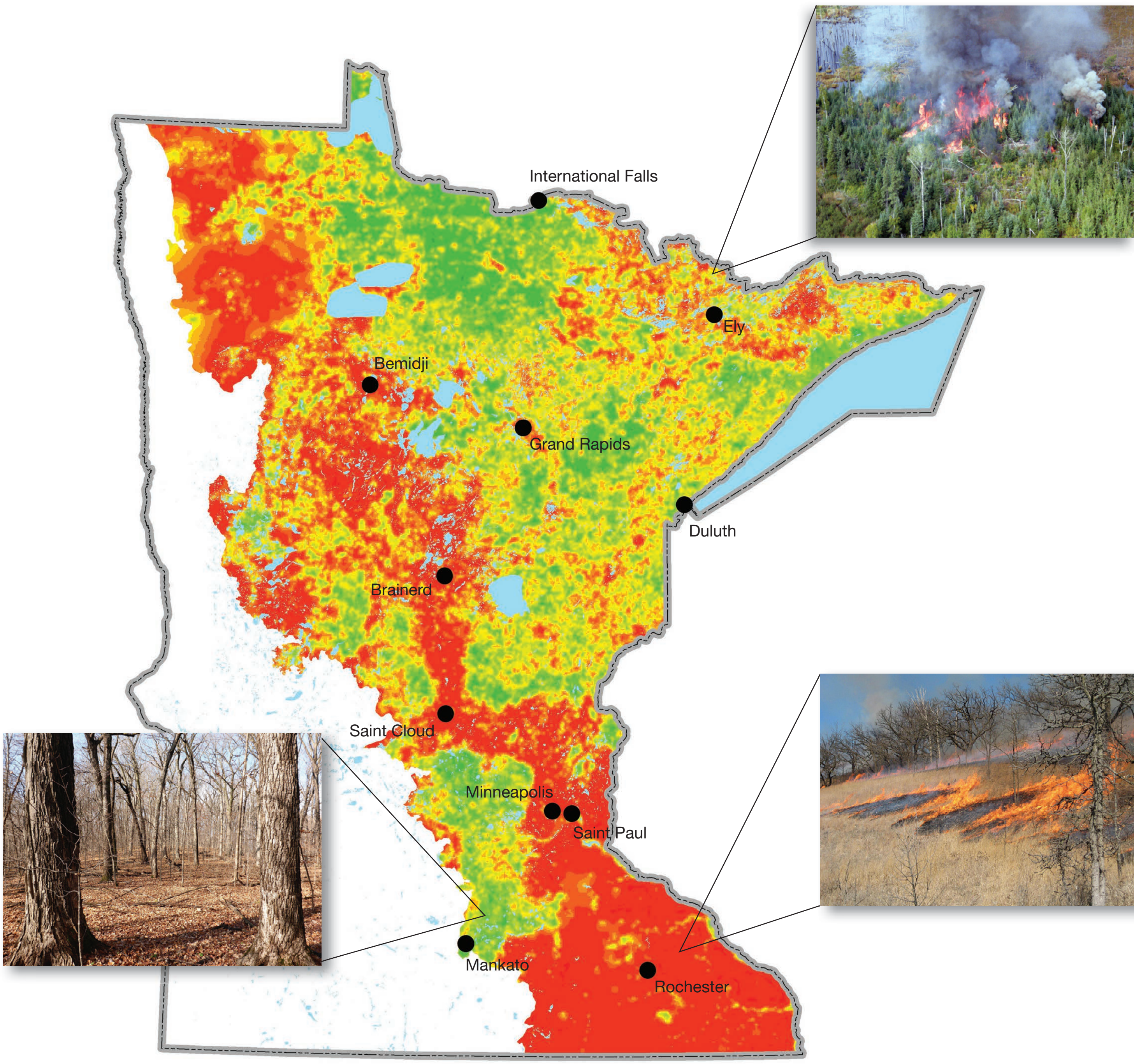
Landscape-Fire Relationships Inferred from Bearing Trees in Minnesota

Melissa A. Thomas-Van Gundy and Gregory J. Nowacki



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Abstract

We display the influence of pre-European settlement fire on vegetation across Minnesota by harnessing the power of bearing trees as indicators of past fires on the landscape. Species and genera of trees used as bearing trees in Public Land Surveys were categorized as either pyrophilic (fire-adapted) or pyrophobic (fire-sensitive) and the percentage of pyrophilic trees was calculated and interpolated to create a map showing the inferred importance of fire. Ecological units at four spatial scales (province, section, subsection, and landtype association) were examined against our pyrophilic percentage maps, irregularities noted, and line improvements suggested based on the prevailing fire setting (the set of vegetation and topographic conditions under which fires occur or are inhibited) before European settlement. Our maps and analyses for Minnesota, the Chippewa National Forest, and the Superior National Forest provide a strong ecological basis for locating areas where long-term burning left an indelible mark on plant composition, structure, and biodiversity and thus where prescribed burning for ecosystem restoration is most appropriate today.

The Authors

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Cover

Map of pyrophilic percentage across Minnesota, ranging from areas with a large proportion of fire-adapted trees (such as the oaks in the lower right photo; red areas on map) through intermediate areas of mixed composition (such as the sub-boreal forest of fire-sensitive firs and spruces and fire-adapted pines in the upper photo; yellow areas on map) to areas with a high proportion of fire-sensitive trees (such as the maples in the lower left photo; green areas on map). Photo at top by Travis Durkin, U.S. Forest Service; lower left photo by Kyle Steele, Natural Resources Conservation Service; lower right photo by Tom Brock, Pleasant Valley Conservancy, used with permission; map by U.S. Forest Service.

Quality Assurance

This publication conforms to the Northern Research Station's Quality Assurance Implementation Plan which requires technical and policy review for all scientific publications produced or funded by the Station. The process included a blind technical review by at least two reviewers, who were selected by the Assistant Director for Research and unknown to the author. This review policy promotes the Forest Service guiding principles of using the best scientific knowledge, striving for quality and excellence, maintaining high ethical and professional standards, and being responsible and accountable for what we do.

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INTRODUCTION

Three major ecosystems converge in Minnesota: grasslands from the west, central (oak) hardwoods from the south, and conifer-northern hardwoods from the northeast. These biomes, represented by the Prairie Parkland, Midwest Broadleaf Forest, and Laurentian Mixed Forest Provinces, respectively (Cleland et al. 2007), lie diagonally across the state, aligning with a climatic gradient from the warm and dry southwest to the cold and moist northeast. Historically fire was an important ecological driver in all these systems, following a similar southwest-to-northeast gradient, from high-intensity (nearly) annual burns maintaining open grasslands (Grimm 1984) through low-to-mixed intensity burns supporting oak woodlands to a mix of fire regimes supporting the former pine-aspen communities of the Northwoods (Heinselman 1973). (Please refer to Table 1 for scientific and common names of tree species mentioned in this report.) Fire regimes with longer return intervals or lower intensities existed in certain geographical areas that favored fire-sensitive vegetation, such as in the lees of topographic firebreaks (Almendinger 1992, Grimm 1984), within vast peatlands (Glaser et al. 1981, Heinselman 1963), or under the cool-moist maritime influence of Lake Superior (Anderson and Fischer 2015, Flaccus and Ohmann 1964).

Much of what is known about the vegetation of Minnesota before European settlement (hereafter called presettlement) comes from Public Land Survey (PLS) records (Almendinger 1996). Here, the rectangular system for land surveys (1847–1908) resulted in the fortuitous collection of valuable ecological data. Unlike the random and irregular metes-and-bounds survey of colonial America, the PLS in the Midwest was a grid-based survey. Within this grid was the systematic recording of bearing or witness trees to document corners, replete with species/genera identity, diameter, and distance and direction to the survey corner. Moreover, qualitative information was supplied through surveyor notes, which recorded dominant tree species and environmental conditions along survey lines including soil and topographic features (swamps, prairies), and the occurrence of recent disturbances such as burned areas and windthrow.

The documentation of past environmental conditions is steadily gaining momentum in science and land management alike. Information on presettlement conditions, especially vegetation composition and structure and prevailing disturbance processes, serves to inform ecosystem restoration (reference conditions), clarifies the extent of historical land-use impacts, and aids climate-change interpretations and forecasting (Nowacki and Abrams 2015). The vast amount of literature on fire in Minnesota (Cavender-Bares and Reich 2012; Clark 1988, 1990; Frissell 1973; Grimm 1984; Heinselman 1973) has established the evolutionary importance of fire in past landscapes and the deleterious effects of fire suppression, underscoring the need for prescribed burning in vegetation management.

Although questions of timeframe, applicable scale, and unknown future climate exist, reestablishing burning regimes in areas where fire was known to be an important disturbance agent is expected to serve goals of ecosystem restoration. By emulating historical fire regimes through silvicultural practices, land managers can foster the restoration and resilience of pyrogenic (fire-dependent) ecosystems, enhance regeneration opportunities for valuable timber species like pine (Ahlgren 1976) and oak (Brose et al. 2001), or achieve both objectives. To aid managerial efforts in the use of prescribed fire, we applied a geospatial procedure that converts bearing-tree data into pyrophilic percentage maps, which show the percent cover of trees that are fire adapted (pyrophilic) (Thomas-Van Gundy and Nowacki 2013).

Ecological classification, mapping, and inventory serve as the underpinnings of land management for many federal and state agencies. The U.S. Forest Service uses the National Hierarchical Framework of Ecological Units (Cleland et al. 1997), which distinguishes ecological units at multiple scales within a nested hierarchy. Factors used to delineate ecological units vary by hierarchical level, ranging from macroclimate and gross physiography at the coarse scale (ecoregions) through geomorphic processes (lithology, landforms, surficial geology) at mid-scales (subregions and landscapes) to plant communities and soil properties at the fine scale (land units). Although not denoted as a delineation factor per se, disturbance regimes are recognized as processes fundamental to ecosystem development, being captured through other factors such as vegetation (Winthers et al. 2005). We used ecological units at four spatial scales (provinces, sections, subsections, and landtype associations [LTAs]) to organize, interpret, and describe

Table 1.—Scientific names, common names, and fire-category assignment of trees identified in the Minnesota's Bearing Tree Database (Almendinger 1996) for Provinces 212 and 222

Scientific name	Common name	Number of trees		Source	Total number of trees
		Pyrophobic	Pyrophilic		
Abies balsamea	fir	13,687	0	Fire Effects Information System (FEIS) (U.S. Forest Service 2014)	13,687
Acer negundo	box-elder	108	0	FEIS	108
Acer rubrum	red maple	20	0	FEIS	20
Acer rubrum or *A. saccharinum*	soft or white maple	223	0	FEIS	223
Acer rubrum, A. saccharum, A. saccharinum	maple	4,596	0	FEIS	4,596
Acer saccharum	sugar maple	6,871	0	FEIS	6,871
Aesculus glabra	buckeye	1	0	Burns and Honkala (1990), FEIS	1
Alnus incana, A. viridis	alder	102	0	FEIS	102
Betula alleghaniensis	yellow birch	1,211	0	FEIS	1,211
Betula nigra, B. alleghaniensis	black birch	10	0	FEIS	10
Betula papyrifera, B. cordifolia	white birch, birch	0	26,774	FEIS	26,774
Carpinus caroliniana	blue beech	9	0	FEIS	9
Carya cordiformis, C. ovata	hickory	0	752	FEIS	752
Celtis occidentalis	hackberry	171	0	FEIS	171
Crataegus spp.	crab-apple, hawthorn, thorn	0	12	FEIS	12
Fagus grandifolia, possibly *Carpinus caroliniana*	beech	45	0	FEIS	45
Fraxinus americana, F. pennsylvanica	white ash, green ash	304	0	FEIS	304
Fraxinus nigra	black ash	1,849	0	FEIS	1,849
Fraxinus nigra, F. pennsylvanica, F. americana	ash	5,550	0	FEIS	5,550
Hamamelis virginiana	witch hazel	1	0	FEIS	1
Juglans cinerea	butternut	449	0	FEIS	449
Juglans nigra	black walnut	129	0	Burns and Honkala (1990), FEIS	129
Juniperus virginiana	juniper or red cedar	9	0	FEIS	9
Larix laricina	tamarack, larch	44,156	15,426	FEIS	59,582
Ostrya virginiana	hornbeam, ironwood	2,919	0	FEIS	2,919
Picea glauca	white spruce, mountain spruce	5	0	FEIS	5
Picea mariana	black spruce	12	0	FEIS	12
Picea mariana, P. glauca	spruce	33,728	0	FEIS	33,728
Pinus banksiana	jack, pitch, or spruce pine	0	17,829	FEIS	17,829

(Table 1 continued on next page)

(Table 1 continued)

Scientific name	Common name	Number of trees		Source	Total number of trees
		Pyrophobic	Pyrophilic		
Pinus resinosa	red, Norway, or yellow pine	0	11,391	FEIS	11,391
Pinus spp.	burned pine	0	137	FEIS	137
Pinus strobus	white pine	0	13,831	FEIS	13,831
Pinus strobus, P. resinosa, P. banksiana	pine	0	5,851	FEIS	5,851
Platanus occidentalis	buttonwood	7	0	FEIS	7
Populus balsamifera	balm-of-Gilead	2,293	0	FEIS	2,293
Populus deltoides	cottonwood	290	0	FEIS	290
Populus tremuloides, P. grandidentata, P. balsamifera	aspen	0	45,566	FEIS	45,566
Prunus americana	plum	3	0	FEIS	3
Prunus serotina, P. pennsylvanica	cherry	261	0	FEIS	261
Quercus alba, Q. macrocarpa	white oak	0	8,071	FEIS	8,071
Quercus ellipsoidalis	jack or Spanish oak	0	1,633	FEIS	1,633
Quercus macrocarpa	bur oak	0	30,124	FEIS	30,124
Quercus velutina, Q. ellipsoidalis	black oak	0	6,794	FEIS	6,794
Quercus rubra, Q. ellipsoidalis	red oak	0	6,688	FEIS	6,688
Quercus rubra, Q. macrocarpa, Q. ellipsoidalis, Q. alba, Q. bicolor	oak	0	9,044	FEIS	9,044
Salix spp.	willow	993	0	FEIS	993
Sorbus decora, S. americana	mountain ash	4	0	FEIS	4
Thuja occidentalis	white cedar, cedar	11,304	0	FEIS	11,304
Tilia americana	linden, basswood	7,208	0	FEIS	7,208
Ulmus americana, U. rubra, U. thomasii	elm, water elm	13,349	0	FEIS	13,349
Ulmus rubra	red elm	8	0	FEIS	8
Unknown		28	0		28
Total		151,913	199,923		351,836

pyrophilic percentage gradients across Minnesota within an ecological context. Coupling these map products will enable managers to identify locations where fire was common in the landscape before European settlement and thus where prescribed burning is most appropriate today. Moreover, boundaries of ecological units can be drawn more accurately by incorporating information on fire regimes as exhibited through pyrophilic percentage data.

METHODS

Study Area

Our study area spans two forest-dominated provinces in eastern Minnesota with increasing focus on those ecological units that encompass the Chippewa and Superior National Forests (Fig. 1; ecological boundaries and descriptions are from Cleland et al. 2007). All ecological units derive their physical origins from the Laurentide Ice Sheet during the Wisconsin Glaciation, except for Section 222L, which falls within the largely nonglaciated Driftless Area. The Prairie Parkland Province of western Minnesota was excluded from the analysis because it lacks a sufficient number of bearing trees essential to pyrophilic percentage mapping.

The Midwest Broadleaf Forest Province is composed of three sections. The Lake Agassiz-Aspen Parkland Section (222N) is defined by thick glacial drift over granite and greenstone bedrock. Current land use is mainly agriculture although presettlement vegetation was aspen-birch and prairie. The Minnesota and Northeast Iowa Morainal-Oak Savanna Section (222M), now dominated by agriculture, was historically a mix of oak-hickory woodlands and savannas, maple-beech-birch and elm-ash-cottonwood forests, and tallgrass prairies. The level plains and low rolling hills are the result of glaciation, and soils are derived from glacial drift and thin loess over granite, greenstone, dolomite, and sandstone bedrock. Along the Mississippi River, the North Central U.S. Driftless and Escarpment Section (222L) is now mostly urban and agricultural land. Historically this area was oak-hickory, prairie, and elm-ash-cottonwood cover types. The soils of this largely unglaciated upland plateau and associated steep-sided valleys are silt loams and sand loams derived from loess over sandstone, dolomite, and shale bedrock.

The Laurentian Mixed Forest Province is composed of five sections considered transitional between boreal and broadleaf deciduous forests. The Northern Minnesota and Ontario Peatlands Section (212M) is characterized as a flat glacial lake plain of low moraines and ridges. Aspen-birch and white-red-jack pine forests occur on iron-rich bedrock that is mostly granites, gabbro, and quartzite. On the level to gently rolling glacial lowlands of the Northern Minnesota Drift and Lake Plains Section (212N), aspen-birch, white-red-jack pine, and spruce-fir forests are found over granite

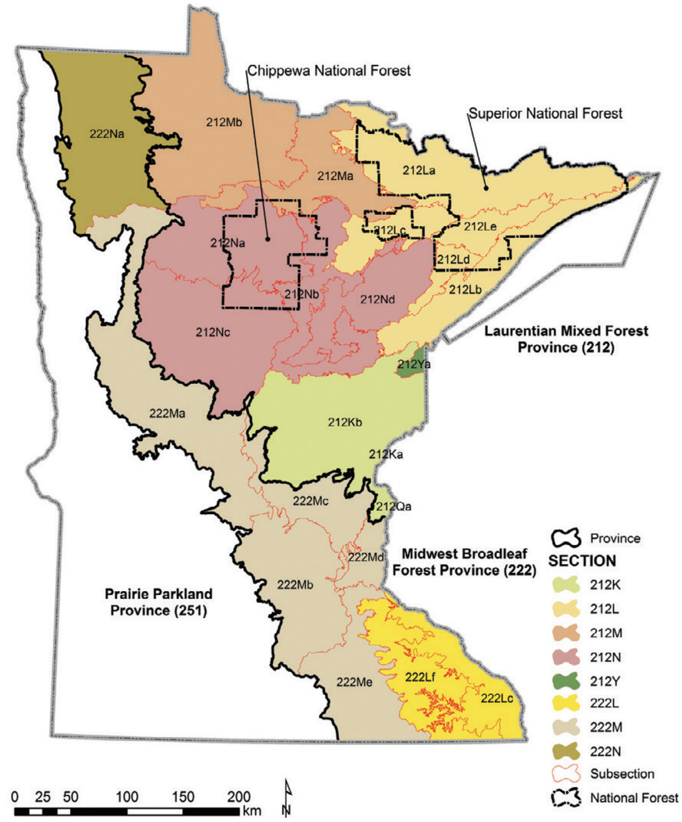


Figure 1.—Ecological provinces, sections, and subsections (Cleland et al. 2007) and National Forest System lands of Minnesota.

bedrock. The Northern Superior Uplands Section (212L) is highly variable. In the north it consists of a glacially scoured peneplain and lake-filled depressions. In the south it consists of drumlins, ground and end moraines, and low hills with thin drift over iron-rich rocks. Bedrock includes quartzite, granites, gabbro, sandstone, and mafic volcanics. Soils range from very poorly drained organics to excessively drained sands and loamy sands and largely support sub-boreal forest types of aspen-birch, spruce-fir, and white-red-jack pine. In contrast, the Western Superior Uplands Section (212K) is a relatively uniform, poorly drained, level to rolling landscape of glacial drift plains with ground and end moraines, and local drumlins. Loam soils formed in thick till that covers sandstone and shale bedrock, supporting aspen-birch, maple-beech-birch, and spruce-fir forests. A small portion of the Southwest Lake Superior Clay Plain Section (212Y) occurs in Minnesota and was excluded from the analysis.

Bearing-tree Data

Bearing-tree information was acquired through the Minnesota's Bearing Tree Database (Almendinger 1996). Bearing trees were recorded at standard township, section, and quarter-section corners and at locations where the surveyor and line were forced to meander around obstacles such as lakes (Almendinger 1996). Survey instructions required four bearing trees at section corners (if within a reasonable distance) along township lines, preferably with one tree in each surrounding section. Two to four bearing trees were marked for “interior” section corners, whereas only two trees were marked at quarter-section and meander corners. Public Land Survey data do contain biases, specifically in the selection of bearing trees (Bourdo 1956). For instance, surveyors were instructed to preferentially select vigorous, mid-sized trees: trees that were large enough to scribe corner location information on their bole yet young and thrifty for maximum monument longevity (Fig. 2). However, this instructional bias was counterbalanced by the fact that bearing trees were to be a reasonable distance from the corner, a restriction that inadvertently allowed capture of a more representative range of tree sizes.

In the bearing-tree database, each record represents one tree with up to four trees per corner. We used the publicly available database without any modifications to point locations. The species and genera represented in the bearing-tree database were classified as either pyrophilic (fire-adapted or fire-dependent) or pyrophobic (fire-sensitive) based on published information of fire-adapted traits (Thomas-Van Gundy and Nowacki 2013). All species/genera partitioned by pyrophilic or pyrophobic tendency are listed and tallied in Table 1. Tamarack occurred in both dry pyrophilic uplands and wet pyrophobic lowlands, so this genus was subdivided into either category based on landscape position or vegetation type (Table 2). Vegetation types and landscape position were derived from the bearing-tree database.

Figure 2.—A longitudinal section of an original bearing-tree scribe housed at the Superior National Forest Supervisor’s Office. Note how the corner location information was scribed vertically on the tree bole due to small diameter size. Approximate size of wood section is 61 cm (24 inches) long by 10 cm (4 inches) high by 4 cm (1.5 inches) wide. Photo by Casey McQuiston, U.S. Forest Service.

A raster was created from the point file by using the ArcMap 10 (Esri, Redlands, CA) point-to-raster tool. Because each record consisted of one tree, a binomial pyrophilic score of either 0 or 100 percent was assigned to each record. In order to calculate a pyrophilic percentage from the coinciding

Table 2.—Number of trees and assignment of tamarack (larch) to fire category by vegetation type or landscape position as given in the Minnesota’s Bearing Tree Database (Almendinger 1996)

	Number of trees	
Vegetation type or landscape position	**Pyrophobic**	**Pyrophilic**
Blank	30	0
Bottom	362	0
Burned area	0	738
Creek	4	0
Dry land	0	9
Dry ridge	0	32
Forest, timber	0	12,209
Grove	0	10
Island	3	0
Lake, slough, pond	78	0
Marsh	2,558	0
Meadow	143	0
Oak barrens	0	17
Oak openings	0	27
Only tree around	0	28
Pine openings, pine barrens, scattered pine	0	34
Plowed field, field	0	1
Prairie	0	33
River	6	0
Scattering oak, scattering timber	0	562
Swamp	40,970	0
Thicket, brush, underbrush	0	956
Valley, ravine	2	0
Windthrow, windfall	0	770
Total	44,156	15,426

points, an 805-m grid (≈ 0.25 square miles) was overlaid onto the point data and mean pyrophilic percentages were calculated from all bearing trees within each cell. The grid size used for averaging and spatially displaying bearing-tree data was commensurate with the spacing of PLS points and recommended usage (Delcourt and Delcourt 1996). Grid data were geospatially smoothed and interpolated by ordinary kriging and outputs were converted to polygons for analysis and display. The Geostatistical Analyst extension in ArcMap 10 was used to create the interpolated surface through ordinary kriging. The semivariogram model was optimized through the extension and a stable model type was used. For the kriging search area, a minimum of 5 and maximum of 50 neighboring grid cells were used in the sample to create the semivariogram and final interpolation surface. This search area resulted in a smoother output surface, where the influence of any given cell is minimized. Cells with no data were retained but did not contribute to pyrophilic percentage interpolation; instead, interpolated pyrophilic percentage values replaced the no-value data. Lakes 4 ha (10 acres) or larger were erased from the final interpolated surface.

The interpolated (kriged) data were also used to characterize the landscapes of the study area. Ecological units at four spatial scales (Table 3) were superimposed on pyrophilic percentage covers to assess how well ecological units related to general fire settings with fire setting defined as the set of vegetation and topographic conditions under which fires occur or are inhibited. The proportion of area in each pyrophilic percentage class (10-percent classes) was plotted and the median pyrophilic percentage calculated for each ecological unit. The median and distributional shape of pyrophilic percentage classes were used to establish the general fire setting of the ecological unit. Landscapes with a median pyrophilic percentage of 33 percent or less and a positively skewed distribution were considered landscapes with a pyrophobic fire setting. Those with a median pyrophilic percentage between 34 and 66 percent and a normal distribution were considered landscapes with an intermediate fire setting. Ecological units with a median pyrophilic percentage of at least 67 percent and a negatively skewed distribution were considered landscapes with pyrogenic fire settings. In support of the National Forest System and for brevity, only those LTAs encompassing the Chippewa and Superior National Forests were included in this analysis.

RESULTS

Fifty-one tree species/genera groups were classified by fire relation, with 37 (including an "unknown" category) assigned to our pyrophobic class (151,913 stems) and 16 assigned to our pyrophilic class (199,923 stems) (Table 1). As noted earlier, tamarack was partitioned and assigned as either pyrophilic or pyrophobic based on landscape position or vegetation type (Table 2).

The spatial projection of pyrophilic percentages was restricted to the forest-dominated provinces (Laurentian Mixed Forest, Midwest Broadleaf Forest) within Minnesota as too few bearing trees existed in the Prairie Parkland Province (Fig. 3). The Midwest Broadleaf Forest Province (222) was dominated by pyrophilic species, with 69.6 percent of the area occurring within the top three classes (>70 percent pyrophilic trees) (Fig. 4). Here, the outline of the "Big Woods" of south-central Minnesota (Grimm 1984, Umbanhower 2004) is quite conspicuous due to its pyrophobic tendency (depicted in shades of green) within an otherwise fire-dominated environment (Fig. 3). Within the Laurentian Mixed Forest Province (212), the pyrophilic-percentage classes formed a broad bell-shaped distribution, with intermediate classes (31- to 70-percent classes) accounting for 51.6 percent of the area (Fig. 4). Here, the pyrophobic tendency of large peatland complexes (e.g., Red Lake Peatland) (Glaser et al. 1981), glacial lake basins (Glacial Lakes Upham and Aitkin and the eastern portion of Glacial Lake Agassiz) (Ojakangas 2009, Wright and Watts 1969), and maritime influences along Lake Superior are all readily apparent (Fig. 3).

The demarcation between these two ecological provinces was largely based on arboreal vegetation, essentially separating oak-dominated central hardwoods (Midwest Broadleaf Forest) from sub-boreal conifers and northern hardwoods (Laurentian Mixed Forest). When this boundary was compared against spatial patterns of pyrophilic percentage (Fig. 3), there was general correspondence along the far eastern segment of the boundary, where highly pyrophilic environments of the southwest (depicted in red) intersect with the more subdued fire environments of the northeast (yellow and green). However, this correspondence was uncommon along the rest of the province line, especially in central Minnesota, where the line juts westward to include

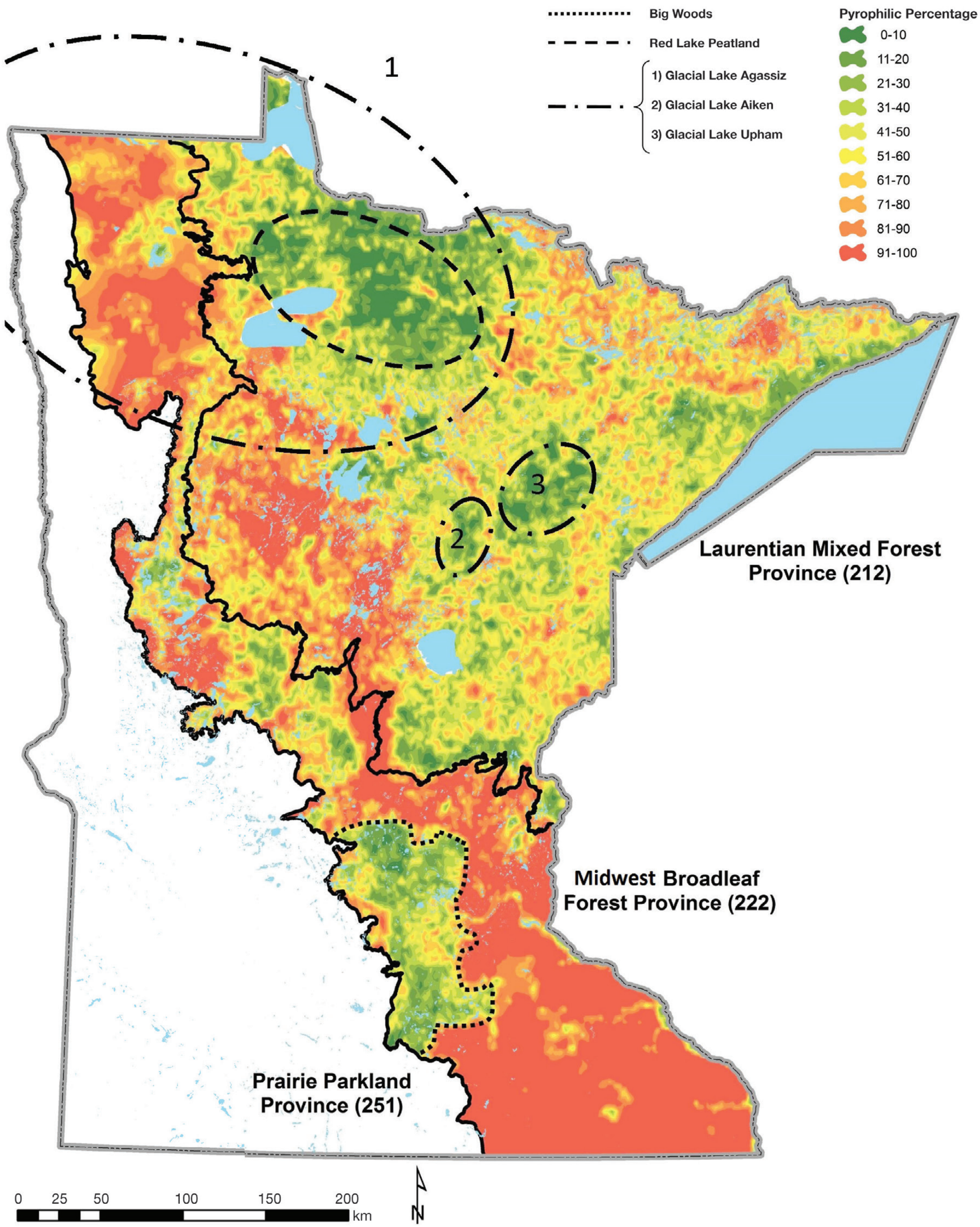
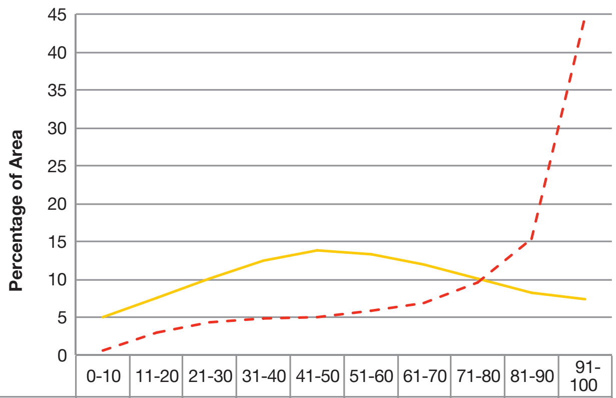


Figure 3.—A pyrophilic percentage map covering two forest-dominated provinces in Minnesota. Prominent landscape features corresponding to spatial changes in pyrophilic percentage are outlined.



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Province 212	5.0	7.6	10.1	12.4	13.8	13.4	12.0	10.2	8.3	7.3
Province 222	0.6	2.9	4.3	4.8	5.0	5.8	7.0	9.6	15.3	44.7

Figure 4.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for the Laurentian Mixed Forest Province (212) and the Midwest Broadleaf Forest Province (222) within Minnesota. An orange line indicates an ecological unit with median pyrophilic percentage between 34 and 66 percent (intermediate landscape), and a red line indicates an ecological unit with median pyrophilic percentage ≥67 percent (pyrogenic landscape).

a highly pyrogenic environment (an area with higher pyrophilic percentage): the pine-dominated sand plains in the Laurentian Mixed Forest Province (Fig. 3). To evaluate the province line further, we charted density isolines for trees diagnostic of the Midwest Broadleaf Forest (oak-hickory) and Laurentian Mixed Forest (pine-larch-spruce) (Fig. 5) to identify deviations from presettlement tree composition and suggest improvements in placement of the province boundary (Fig. 6).

We used distributional histograms and medians of pyrophilic percentage classes to categorize 2 provinces, 3 sections, 10 subsections, and 64 LTAs by general fire setting (summarized in Table 3). Pyrophilic percentage classes had bell-shaped distributions for Section 212L (Northern Superior Uplands) and all component subsections except for Subsection 212Le (Laurentian Uplands), which had a bimodal distribution (upper graphs of Figures 7–11). Upon closer spatial inspection (Fig. 12), the anomalous distribution of Subsection 212Le was due to the inclusion of areas with highly contrasting fire settings: a highly pyrophilic northern portion and a largely pyrophobic southern portion. LTAs were a mix of intermediate (orange) or pyrophilic (red) settings within Subsection 212La (Border Lakes; Fig. 7) and a mix of intermediate and pyrophobic (green) settings within Subsection 212Lb (North Shore Highlands; Fig. 8). All LTAs within Subsections 212Lc (Nashwauk Uplands; Fig. 9) and 212Ld (Toimi Uplands; Fig. 10) had intermediate fire settings. As pointed out earlier, Subsection 212Le contained sharply contrasting LTAs from pyrophilic (212Le02; Kelly-Sawbill Landing Till Plain) to pyrophobic (212Le08-10; Seven Beavers Peatland, Phantom Lake Peatland, and Greenwood Lake Till Plain LTAs; Fig. 11). A mix of contrasting fire settings explains the bimodal distribution of LTA 212Le03 (Timber Freer Till Plain; Figs. 11 and 13).

Both Section 212M (Northern Minnesota and Ontario Peatlands) and Subsection 212Ma (Littlefork-Vermilion Uplands) had pyrophobic class distributions (Fig. 14). Component LTAs had either pyrophobic or intermediate fire settings. A bimodal distribution spanning a large array of classes was evident in LTA 212Ma19 (Rauch Till Plain; Figs. 13 and 14).

Broad, somewhat amorphous distributions were associated with Section 212N (Northern Minnesota Drift and Lake Plains) and Subsection 212Na (Chippewa Plains) (Fig. 15), indicating a mix of contrasting fire settings (Fig. 12). Indeed, fire settings of component LTAs ranged from pyrophilic (212Na07; Bemidji Sand Plain) (Fig. 15) to pyrophobic (212Na10; Deer River Peatlands) (Fig. 19). Subsection 212Nb (St. Louis Moraines) and component LTAs had intermediate fire settings (Fig. 16). Subsection 212Nc (Pine Moraine and Outwash Plains) and all component LTAs had pyrophilic tendencies (Fig. 17). Subsection 212Nd (Tamarack Lowlands) had an intermediate fire setting, with component LTAs being either pyrophobic (212Nd04; Warba Lake Plain) or intermediate (212Nd05; Aurora Till Plain) (Fig. 18).

The fact that 74 out of 79 ecological units had distributions that fit pyrophilic (negatively skewed), intermediate (bell-shaped curve), or pyrophobic (positively skewed) categories was a general indication that ecological units captured different fire settings quite well. Ecological units with flat, bimodal, or amorphous distributions had poor correspondence with general fire settings, indicating that those units may need adjustments if fire is considered an important ecological process driving vegetation expression. Most LTAs occurring on National Forest System land in northeastern Minnesota had an intermediate fire setting, forming a bell-shaped curve among the three categories. Fourteen LTAs were pyrophilic, 37 were intermediate, and 11 were pyrophobic, with two needing possible readjustment of boundaries.

Table 3.—Hierarchical organization, codes, names, and three most numerous genera of bearing trees for ecological units referenced in this report. Pyrophobic ecological units are designated by a green background (median pyrophilic percentage ≤33 percent), ecological units with intermediate fire settings are orange (median pyrophilic percentage between 34 and 66 percent), and pyrophilic ecological units are red (median pyrophilic percentage ≥67 percent). Gray cells represent ecological units with no clear association with fire.

Province	Section	Subsection	Landtype association
212 Laurentian Mixed Forest: *Larix* (22%) *Pinus* (20%) *Picea* (14%)	212L Northern Superior Uplands: *Pinus* (21%) *Picea* (20%) *Betula* (18%)	212La Border Lakes: *Pinus* (27%) *Picea* (19%) *Betula* (16%)	212La07 Johnson Lake Bedrock Complex: *Pinus* (33%), *Populus* (21%), *Picea* (13%)
			212La08 Lac LaCroix Bedrock Complex: *Pinus* (33%), *Picea* (22%), *Populus* (14%)
			212La09 Voyageurs Bedrock Complex: *Pinus* (29%), *Populus* (22%), *Betula* (14%)
			212La11 Swamp River Till Plain: *Picea* (26%), *Betula* (21%), *Thuja* (16%)
			212La13 Gabbro Lake Bedrock Complex: *Pinus* (29%), *Picea* (20%), *Populus* (17%)
			212La14 Rove Slate Bedrock Complex: *Pinus* (33%), *Betula* (21%), *Populus* (13%)
			212La15 Trout Lake Bedrock Complex: *Pinus* (41%), *Picea* (19%), *Larix* (12%)
			212La16 Myrtle Lake Till Plain: *Pinus* (24%), *Betula* (17%), *Populus* (17%)
			212La17 Ash Lake Till Plain: *Picea* (23%), *Abies* (15%), *Larix* (13%)
			212La21 Saganaga Lake Bedrock Complex: *Picea* (37%), *Pinus* (27%), *Betula* (13%)
			212La22 Poplar Lake Bedrock Complex: *Picea* (31%), *Betula* (29%), *Abies* (12%)
			212La23 Ely-Knife Lake Bedrock Complex: *Pinus* (27%), *Betula* (18%), *Picea* (16%)
			212La24 White Iron Lake Bedrock Complex: *Pinus* (32%), *Picea* (21%), *Larix* (13%)
			212La34 Vermilion Bedrock Complex: *Pinus* (27%), *Betula* (19%), *Populus* (16%)
			212La35 Northern Lights Lake Till Plain: *Picea* (26%), *Pinus* (25%), *Betula* (22%)
			212La36 Two Island Lake Moraine: *Betula* (29%), *Picea* (28%), *Pinus* (14%)
			212La37 Vegetable Lakes Till Plain: *Betula* (35%), *Picea* (18%), *Pinus* (14%)
		212Lb North Shore Highlands: *Betula* (22%) *Abies* (18%) *Pinus* (15%)	212Lb02 North Shore Till Plain: *Abies* (30%), *Betula* (24%), *Picea* (19%)
			212Lb03 Highland Moraine: *Betula* (22%), *Larix* (19%), *Picea* (17%)
			212Lb04 Cloquet Sand Plain: *Pinus* (27%), *Betula* (20%), *Larix* (19%)
			212Lb05 Cabin Lake Till Plain: *Picea* (33%), *Betula* (21%), *Abies* (21%)
			212Lb08 Honeymoon Mountain Till Plain: *Abies* (32%), *Picea* (28%), *Betula* (16%)

(Table 3 continued on next page)

(Table 3 continued)

Province	Section	Subsection	Landtype association
			212Lb10 Tettegouche Till Plain: *Betula* (22%), *Abies* (21%), *Picea* (15%)
			212Lb11 Sawtooth Mountain Bedrock Complex: *Betula* (28%), *Picea* (20%), *Abies* (18%)
		212Lc Nashwauk Uplands: *Pinus* (23%) *Betula* (18%) *Picea* (17%)	212Lc05 Pike-Sandy River Sand Plain: *Pinus* (28%), *Larix* (18%), *Picea* (18%)
			212Lc06 Whalsten Till Plain: *Pinus* (29%), *Picea* (15%), *Betula* (14%)
			212Lc07 Big Rice Moraine: *Pinus* (25%), *Picea* (16%), *Abies* (13%)
			212Lc10 Mesabi Range: *Betula* (33%), *Pinus* (15%), *Abies* (12%)
			212Lc20 Nashwauk Moraine: *Picea* (22%), *Pinus* (20%), *Betula* (16%)
		212Ld Toimi Uplands: *Picea* (27%) *Betula* (22%) *Larix* (18%)	212Ld01 Toimi Drumlin Plain: *Picea* (27%), *Betula* (22%), *Larix* (18%)
		212Le Laurentian Uplands: *Picea* (30%) *Pinus* (22%) *Betula* (15%)	212Le01 Isabella Moraine: *Pinus* (34%), *Picea* (21%), *Betula* (15%)
			212Le02 Kelly-Sawbill Landing Till Plain: *Pinus* (41%), *Picea* (17%), *Populus* (14%)
			212Le03 Timber Freer Till Plain: *Betula* (31%), *Pinus* (23%), *Abies* (16%)
			212Le04 Temperance River Till Plain: *Picea* (33%), *Pinus* (25%), *Betula* (17%)
			212Le08 Seven Beavers Peatland: *Picea* (48%), *Larix* (39%), *Pinus* (6%)
			212Le09 Phantom Lake Peatland: *Picea* (54%), *Larix* (22%), *Betula* (11%)
			212Le10 Greenwood Lake Till Plain: *Picea* (44%), *Abies* (15%), *Larix* (13%)
			212Le11 Big-Bird Lake Moraine: *Picea* (30%), *Pinus* (21%), *Betula* (19%)
	212M Northern Minnesota and Ontario Peatlands: *Larix* (40%) *Picea* (21%) *Populus* (12%)	212Ma Littlefork-Vermilion Uplands: *Picea* (25%) *Larix* (21%) *Populus* (14%)	212Ma01 Koochiching Peatlands: *Picea* (42%), *Larix* (41%), *Populus* (5%)
			212Ma13 Haney Till Plain: *Larix* (22%), *Picea* (21%), *Populus* (15%)
			212Ma14 Smith Road Till Plain: *Populus* (48%), *Picea* (12%), *Larix* (12%)
			212Ma18 Effie Till Plain: *Picea* (19%), *Larix* (15%), *Thuja* (14%)
			212Ma19 Rauch Till Plain: *Populus* (33%), *Picea* (20%), *Pinus* (16%)
			212Ma21 Cook Till Plain: *Populus* (31%), *Picea* (27%), *Larix* (16%)

(Table 3 continued on next page)

(Table 3 continued)

Province	Section	Subsection	Landtype association
	212N Northern Minnesota Drift and Lake Plains: *Pinus* (29%) *Larix* (20%) *Populus* (13%)	212Na Chippewa Plains: *Pinus* (31%) *Larix* (19%) *Populus* (14%)	212Na03 Guthrie Till Plain: *Pinus* (24%), *Populus* (17%), *Acer* (10%)
			212Na07 Bemidji Sand Plain: *Pinus* (55%), *Larix* (18%), *Populus* (9%)
			212Na08 Bena Dunes and Peatlands: *Larix* (36%), *Pinus* (34%), *Populus* (11%)
			212Na09 Rosey Lake Plain: *Larix* (27%), *Pinus* (14%), *Picea* (14%)
			212Na10 Deer River Peatlands: *Larix* (53%), *Picea* (19%), *Thuja* (11%)
			212Na11 Bowstring Till Plain: *Acer* (29%), *Larix* (21%), *Betula* (21%)
			212Na16 Blackduck Till Plain: *Larix* (19%), *Picea* (16%), *Betula* (13%)
			212Na18 Blackduck Moraine: *Pinus* (23%), *Larix* (22%), *Populus* (13%)
		212Nb St. Louis Moraines: *Larix* (18%) *Betula* (17%) *Pinus* (17%)	212Nb02 Aitkin Moraine: *Pinus* (23%), *Larix* (18%), *Populus* (17%)
			212Nb03 Sugar Hills Moraine: *Betula* (21%), *Acer* (18%), *Pinus* (18%)
			212Nb07 Marcell Moraine: *Betula* (23%), *Pinus* (22%), *Larix* (12%)
			212Nb08 Coon Lake Till Plain: *Larix* (20%), *Pinus* (19%), *Picea* (18%)
			212Nb12 Hill City Till Plain: *Larix* (18%), *Pinus* (16%), *Betula* (15%)
		212Nc Pine Moraine and Outwash Plains: *Pinus* (45%) *Populus* (16%) *Larix* (13%)	212Nc11 Park Rapids Sand Plain: *Pinus* (83%), *Populus* (5%), *Larix* (5%)
			212Nc13 Spring Brook Till Plain: *Pinus* (27%), *Populus* (18%), *Betula* (15%)
			212Nc14 Outing Moraine: *Pinus* (37%), *Betula* (14%), *Larix* (14%)
			212Nc16 Itasca Moraine: *Pinus* (42%), *Populus* (15%), *Larix* (11%)
			212Nc30 Itasca Moraine, Steep: *Pinus* (55%), *Populus* (23%), *Betula* (8%)
		212Nd Tamarack Lowlands: *Larix* (70%) *Picea* (17%) *Betula* (10%)	212Nd04 Warba Lake Plain: *Larix* (32%), *Picea* (22%), *Betula* (12%)
			212Nd05 Aurora Till Plain: *Larix* (23%), *Picea* (23%), *Betula* (17%)
222 Midwest Broadleaf Forest: *Quercus* (50%) *Populus* (16%) *Ulmus* (9%)			

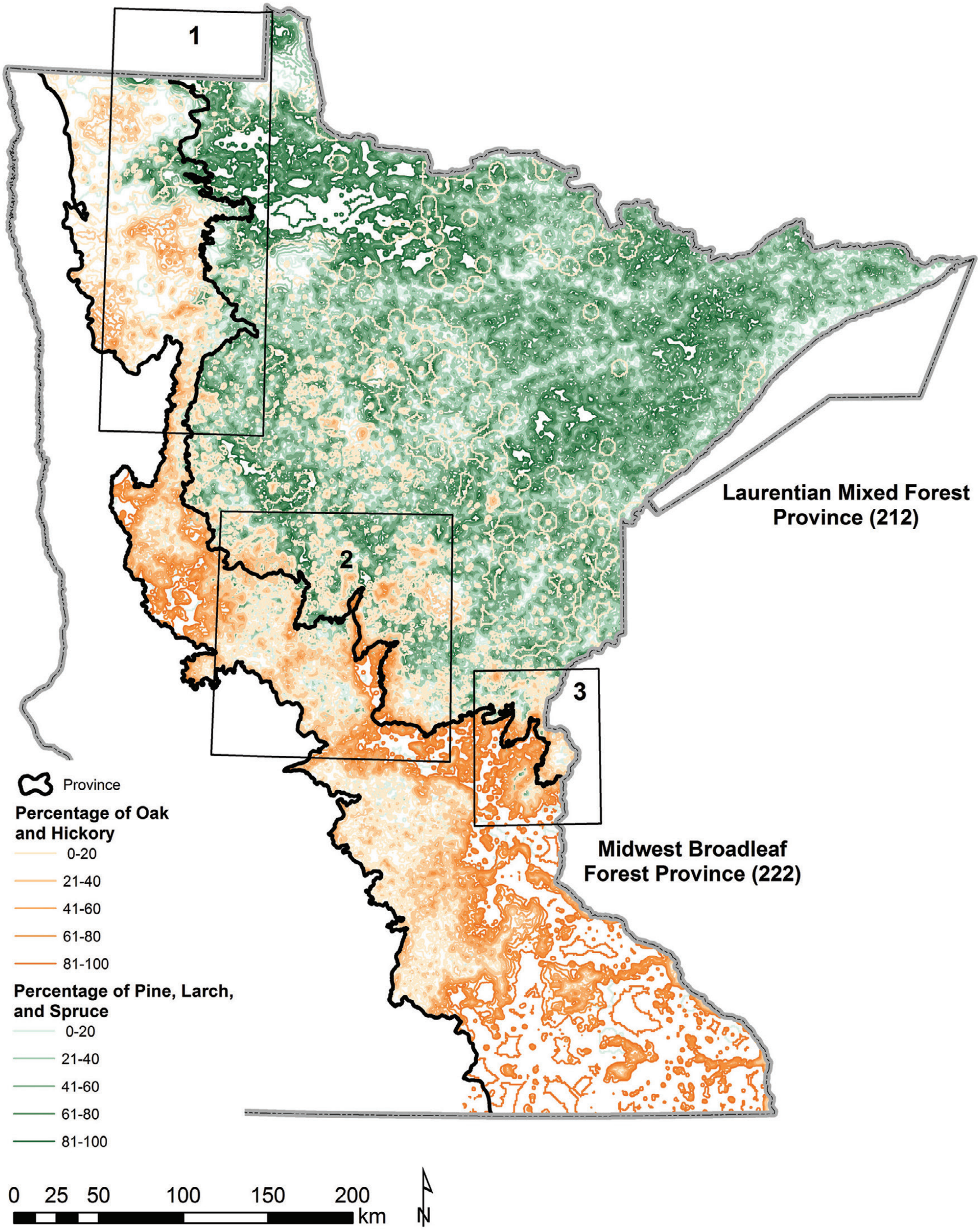


Figure 5.—Bearing-tree percentages of tree genera diagnostic of the Laurentian Mixed Forest Province (*Pinus-Larix-Picea*) and Midwest Broadleaf Forest Province (*Quercus-Carya*). Numbered segments along the province line are shown in greater detail in Figure 6.

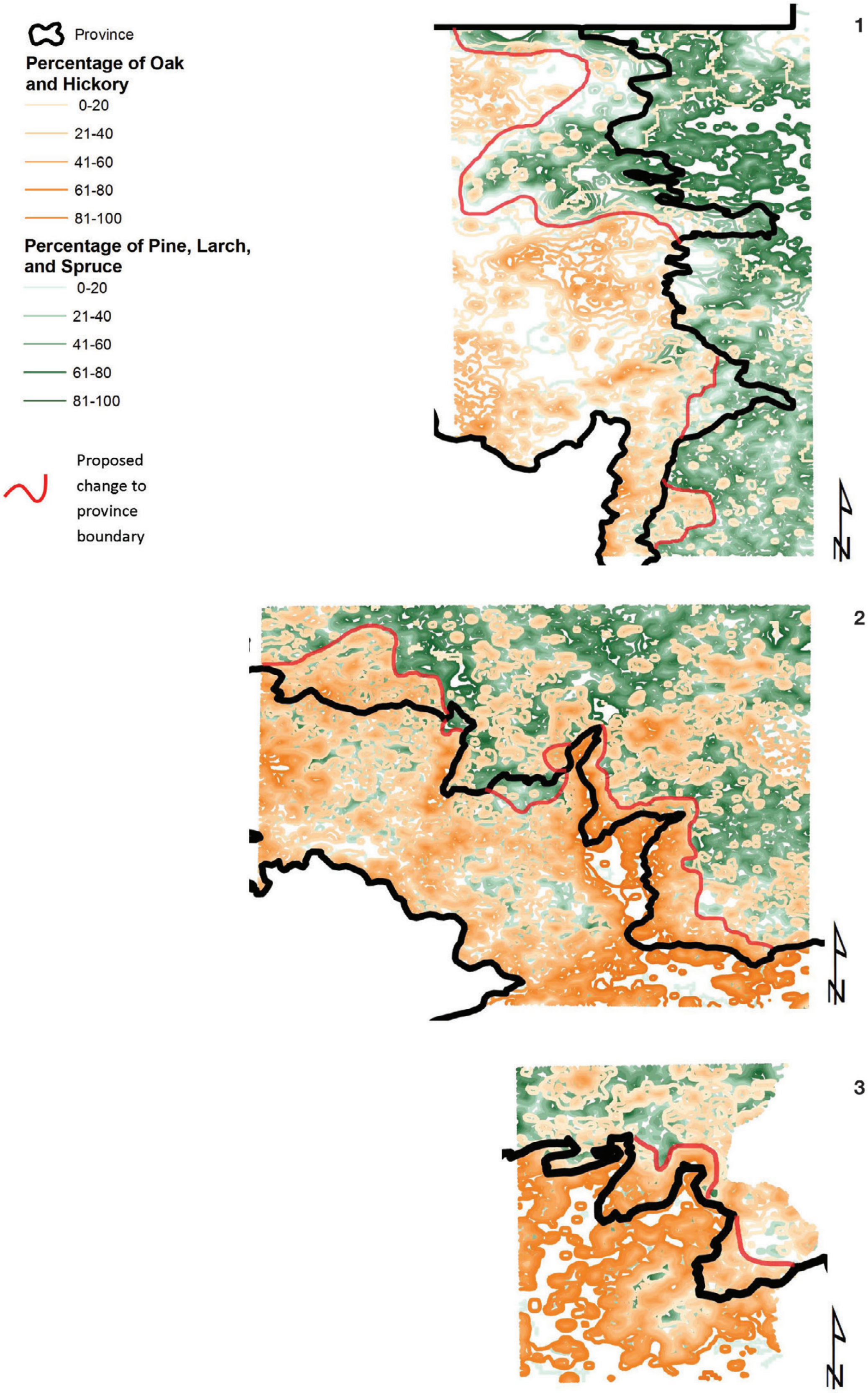
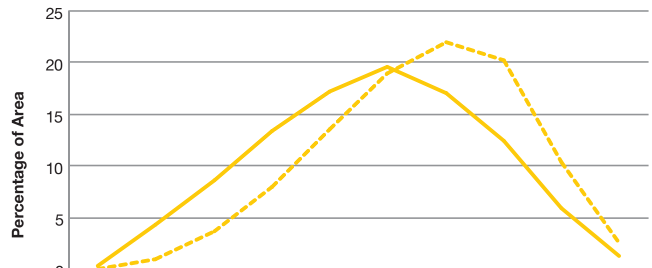
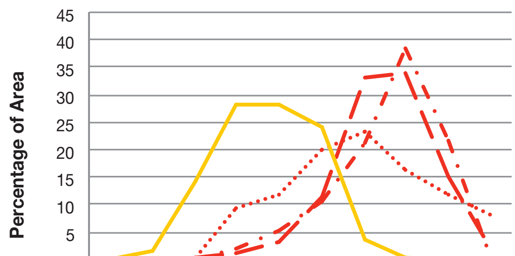


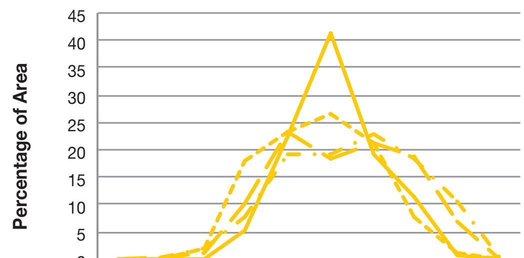
Figure 6.—Discrepancies and suggested improvements (red lines) in the boundaries along three segments of the Laurentian Mixed Forest Province based on diagnostic tree abundance. Refer to Figure 5 for segment locations. (Selected areas were clipped from the geographic information systems layers and suggested lines drawn by using graphics software, so map scale is unknown.)



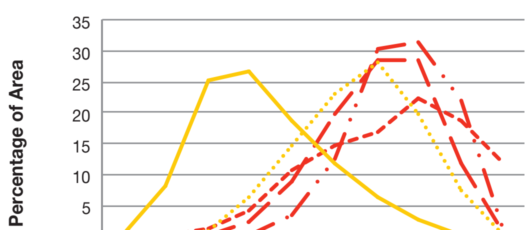
	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Section 212L	0.3	4.2	8.7	13.4	17.2	19.6	17.1	12.4	5.9	1.3
Subsection212La	0.0	1.0	3.6	7.9	13.6	18.9	21.9	20.2	10.3	2.6



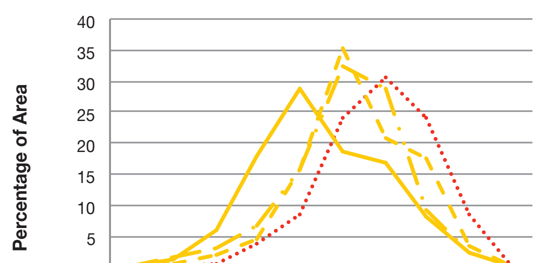
	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212La07	0.0	0.0	0.1	2.0	5.3	10.8	21.1	38.6	21.8	0.4
LTA 212La08	0.0	0.0	0.1	9.2	11.7	19.9	23.1	16.4	11.6	8.0
LTA 212La09	0.0	0.0	0.3	1.1	3.1	11.4	33.1	34.1	15.0	1.8
LTA 212La11	0.0	1.5	14.2	28.1	28.3	24.2	3.5	0.2	0.0	0.0



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212La21	0.0	0.0	0.1	5.0	22.4	41.3	19.4	11.2	0.6	0.0
LTA 212La22	0.0	0.0	2.1	18.1	23.1	26.5	21.2	7.9	1.0	0.0
LTA 212La23	0.0	0.1	1.1	10.3	23.1	18.3	21.3	19.0	6.8	0.0
LTA 212La24	0.0	0.1	2.0	7.6	19.2	19.4	22.8	18.2	10.4	0.3

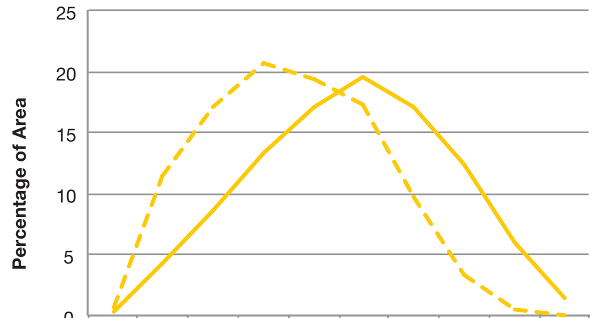


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212La13	0.0	0.0	1.3	4.1	10.7	14.5	17.0	22.3	18.6	11.6
LTA 212La14	0.0	0.0	0.0	0.0	3.3	12.6	30.1	31.2	21.8	0.9
LTA 212La15	0.0	0.0	0.2	2.2	8.7	19.9	28.3	28.4	11.8	0.6
LTA 212La16	0.0	0.0	0.9	6.1	14.6	23.0	28.0	19.9	7.3	0.0
LTA 212La17	0.0	8.3	25.2	26.7	18.6	11.8	6.4	2.8	0.2	0.0

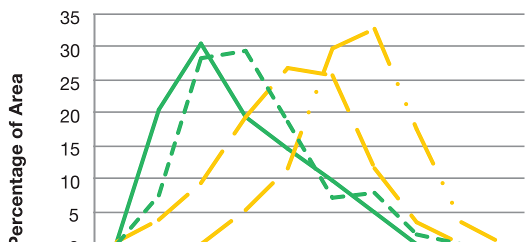


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212La34	0.0	0.0	0.6	3.8	8.5	24.0	30.6	23.9	8.6	0.0
LTA 212La35	0.0	0.3	2.1	4.5	15.6	35.4	20.8	17.7	3.4	0.0
LTA 212La36	0.0	1.4	6.1	17.8	28.9	18.7	16.7	8.2	2.2	0.0
LTA 212La37	0.0	1.6	3.1	6.8	15.9	32.4	28.7	9.3	2.2	0.2

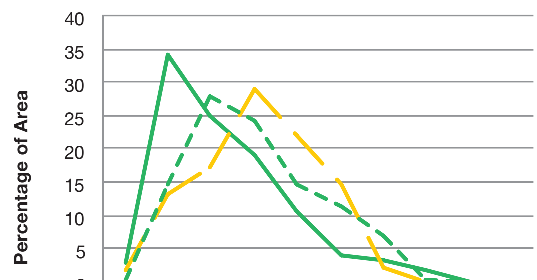
Figure 7.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for Section 212L and Subsection 212La (upper graph), and component landtype associations within or partially within the proclamation boundary of the Superior National Forest (lower graphs). An orange line indicates an ecological unit with median pyrophilic percentage between 34 and 66 percent (intermediate landscape). A red line indicates an ecological unit with median pyrophilic percentage ≥67% (pyrogenic landscape).



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Section 212L	0.3	4.2	8.7	13.4	17.2	19.6	17.1	12.4	5.9	1.3
Subsection 212Lb	0.7	11.5	17.1	20.7	19.3	17.3	9.7	3.3	0.4	0.0

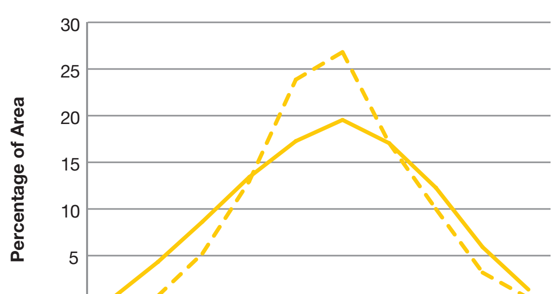


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Lb02	0.2	20.4	30.6	19.5	14.7	9.8	4.8	0.0	0.0	0.0
LTA 212Lb03	0.3	3.8	9.2	19.4	26.6	25.7	11.5	3.4	0.1	0.0
LTA 212Lb04	0.0	0.0	0.0	5.1	11.6	29.7	32.6	17.5	3.5	0.0
LTA 212Lb05	0.0	7.5	28.4	29.3	18.6	6.9	7.8	1.5	0.0	0.0

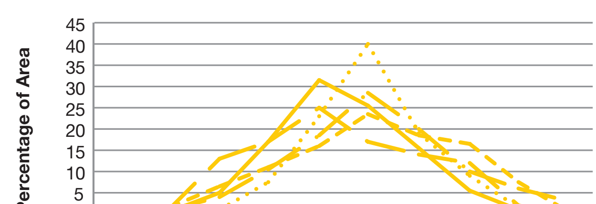


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Lb08	2.9	34.0	24.9	19.1	10.4	3.9	3.1	1.6	0.0	0.0
LTA 212Lb10	1.6	13.3	17.1	29.0	22.0	14.8	2.1	0.0	0.0	0.0
LTA 212Lb11	0.4	14.5	27.9	24.3	14.6	11.3	6.7	0.3	0.0	0.0

Figure 8.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for Section 212L and Subsection 212Lb (upper graph), and component landtype associations within or partially within the proclamation boundary of the Superior National Forest (lower graphs). An orange line indicates an ecological unit with median pyrophilic percentage between 34 and 66 percent (intermediate landscape). A green line indicates an ecological unit with median pyrophilic percentage ≤33 percent (pyrophobic landscape).

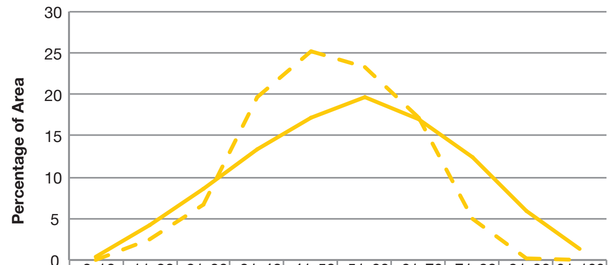


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Section 212L	0.3	4.2	8.7	13.4	17.2	19.6	17.1	12.4	5.9	1.3
Subsection 212Lc	0.0	0.6	5.2	13.0	23.9	26.7	17.0	9.9	3.1	0.5



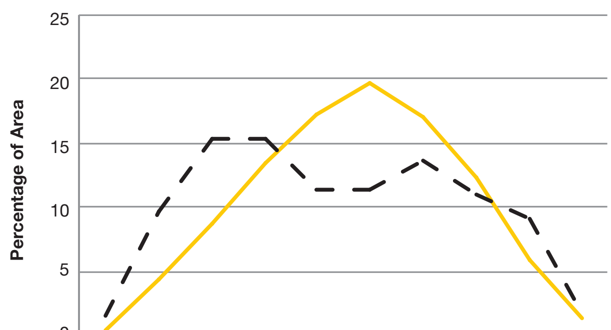
	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Lc05	0.0	1.4	6.4	10.9	15.7	23.3	18.2	16.5	7.3	0.5
LTA 212Lc06	0.0	0.7	3.8	10.6	18.4	28.2	20.0	9.9	5.7	2.7
LTA 212Lc07	0.0	1.0	12.9	16.9	24.9	16.8	13.6	12.0	2.0	0.0
LTA 212Lc10	0.0	0.0	1.0	7.5	22.9	39.8	18.8	8.8	1.2	0.0
LTA 212Lc20	0.0	0.1	4.8	16.6	31.3	25.4	15.5	5.4	0.7	0.1

Figure 9.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for Section 212L and Subsection 212Lc (left graph), and component landtype associations within or partially within the proclamation boundary of the Superior National Forest (right graph). An orange line indicates an ecological unit with median pyrophilic percentage between 34 and 66 percent (intermediate landscape).

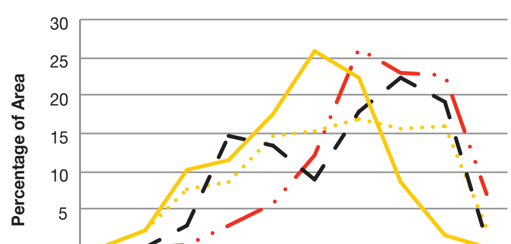


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Section 212L	0.3	4.2	8.7	13.4	17.2	19.6	17.1	12.4	5.9	1.3
Subsection 212Ld	0.0	2.6	6.8	19.7	25.2	23.4	17.1	5.1	0.2	0.0

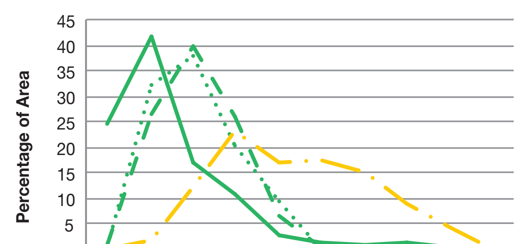
Figure 10.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for Section 212L and Subsection 212Ld within or partially within the proclamation boundary of the Superior National Forest; note that LTA 212Ld01 is represented by Subsection 212Ld as this subsection has only one LTA. An orange line indicates an ecological unit with median pyrophilic percentage between 34 and 66 percent (intermediate landscape).



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Section 212L	0.3	4.2	8.7	13.4	17.2	19.6	17.1	12.4	5.9	1.3
Subsection 212Le	1.5	9.7	15.4	15.4	11.3	11.3	13.7	11.0	9.1	1.6



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Le01	0.0	2.3	7.8	8.7	14.8	15.4	16.9	15.7	16.1	2.4
LTA 212Le02	0.0	0.0	0.2	2.9	5.8	12.2	26.2	22.9	22.7	7.1
LTA 212Le03	0.0	0.0	3.0	14.6	13.3	9.0	17.8	22.4	19.1	0.9
LTA 212Le04	0.0	2.4	10.3	11.6	17.4	25.7	22.3	8.7	1.6	0.0



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Le08	24.5	41.7	16.9	10.8	2.7	1.1	0.9	1.3	0.2	0.0
LTA 212Le09	0.4	32.0	38.0	20.5	9.2	0.0	0.0	0.0	0.0	0.0
LTA 212Le10	0.8	26.7	39.8	25.9	6.4	0.4	0.0	0.0	0.0	0.0
LTA 212Le11	0.0	1.6	12.3	23.0	17.1	17.6	15.3	9.0	4.1	0.0

Figure 11.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for Section 212L and Subsection 212Le (upper graph), and component landtype associations within or partially within the proclamation boundary of the Superior National Forest (lower graphs). A green line indicates an ecological unit with median pyrophilic percentage ≤33 percent (pyrophobic landscape). An orange line indicates an ecological unit with median pyrophilic percentage between 34 and 66 percent (intermediate landscape). A red line indicates an ecological unit with median pyrophilic percentage ≥67 percent (pyrogenic landscape). A black line represents an ecological unit with no clear pattern (flat or bimodal distribution).

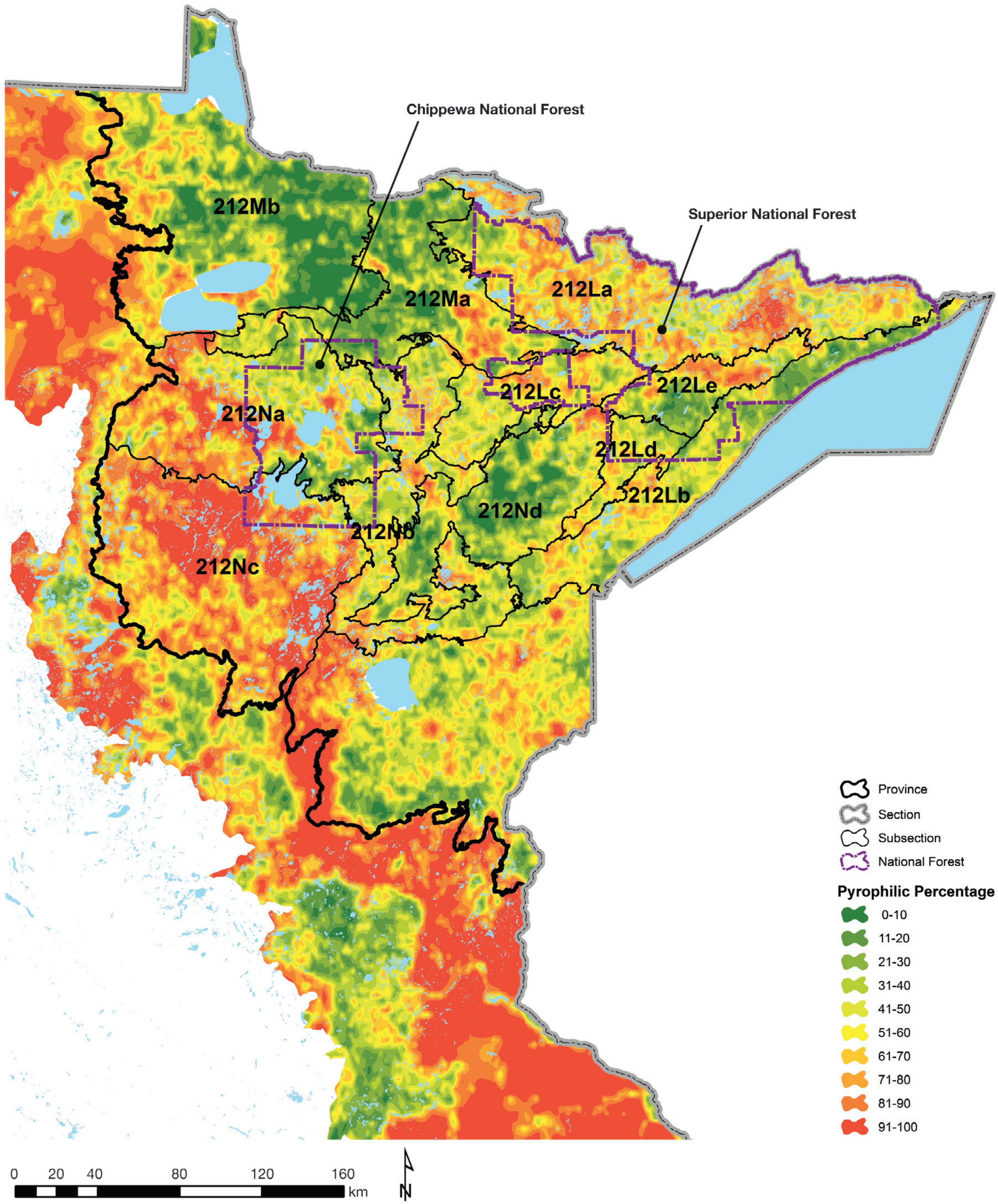


Figure 12.—A pyrophilic percentage map of northeastern Minnesota covering Sections 212L, 212M, and 212N and their component subsections.

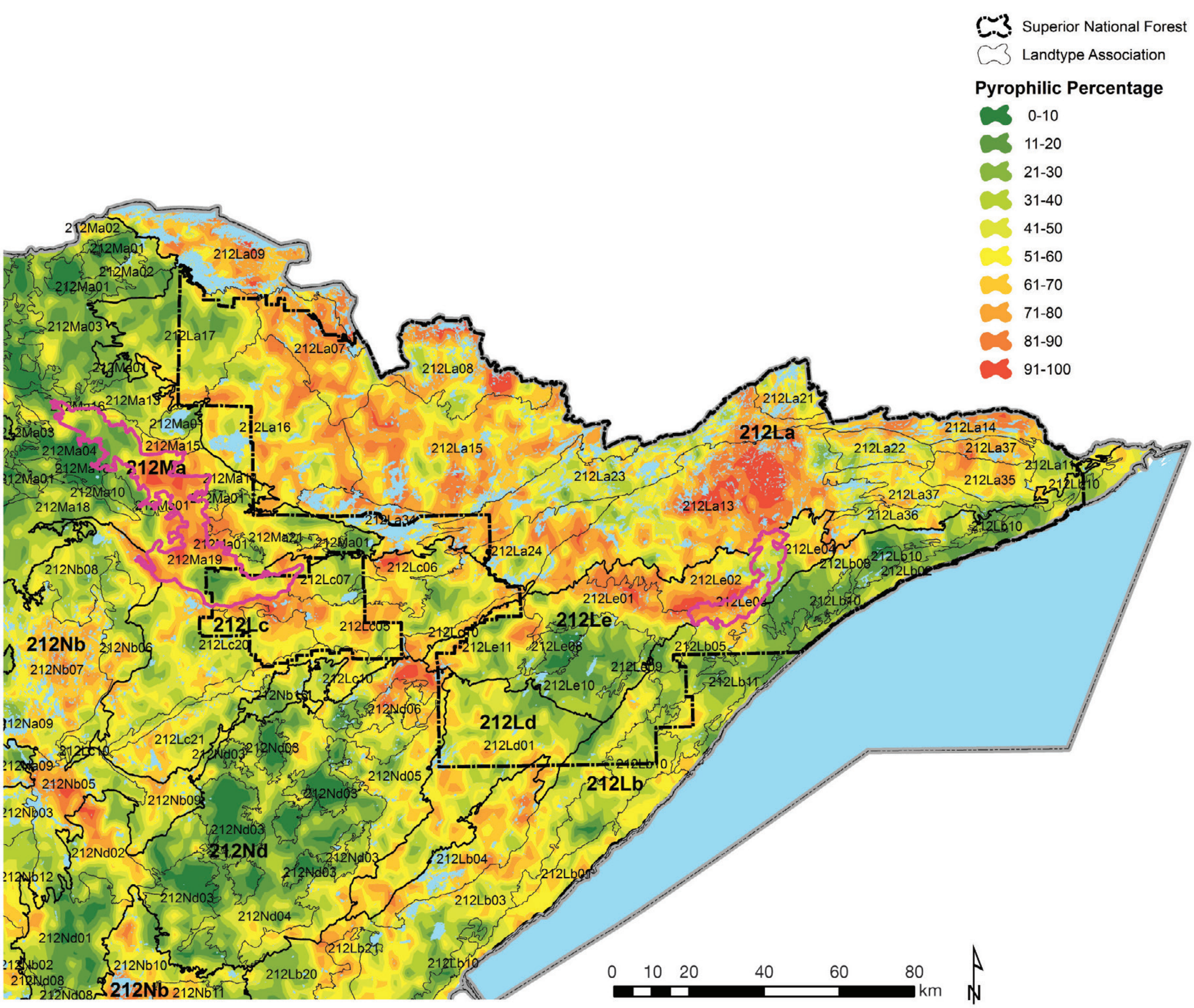
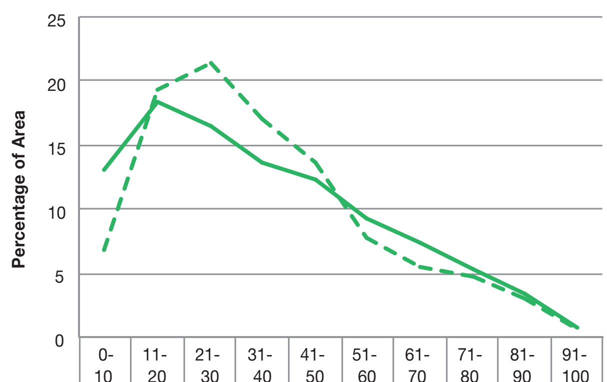
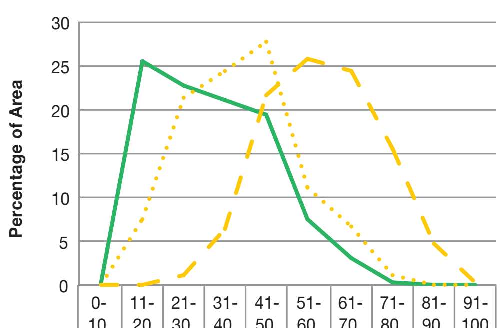


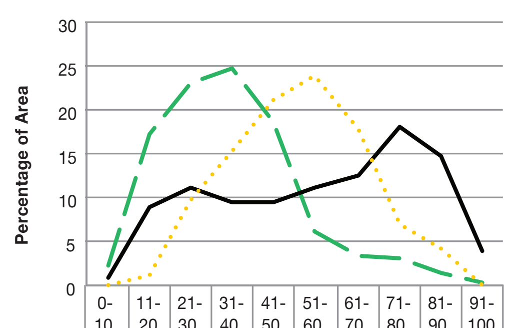
Figure 13.—Pyrophilic percentage for the Superior National Forest with landtype associations. Two landtype associations with no clear association with fire (212Le03 [east] and 212Ma19 [west]) are highlighted.



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Section 212M	13.1	18.4	16.5	13.7	12.2	9.3	7.4	5.3	3.4	0.6
Subsection 212Ma	6.8	19.4	21.5	17.1	13.6	7.8	5.4	4.8	3.0	0.6

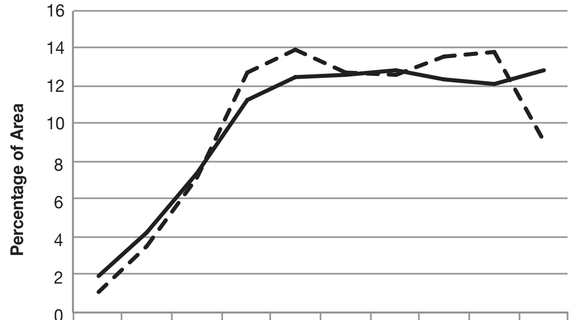


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Ma01	0.2	25.5	22.7	21.1	19.4	7.5	3.1	0.4	0.1	0.0
LTA 212Ma13	0.0	7.5	21.4	24.4	27.9	11.0	6.6	1.1	0.0	0.0
LTA 212Ma14	0.0	0.0	1.0	6.5	21.8	25.8	24.3	15.7	4.7	0.2

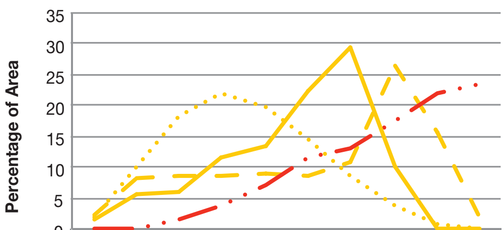


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Ma18	2.3	17.1	23.0	24.8	18.7	6.3	3.3	3.0	1.3	0.3
LTA 212Ma19	0.9	8.9	11.1	9.3	9.4	11.1	12.4	18.0	14.8	4.1
LTA 212Ma21	0.0	1.0	9.8	15.3	21.0	23.8	17.7	7.0	4.2	0.1

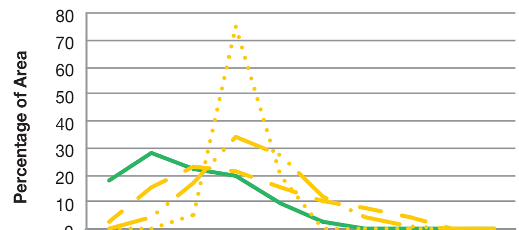
Figure 14.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for Section 212M and Subsection 212Ma (upper graph), and component landtype association within or partially within the proclamation boundaries of the Superior and Chippewa National Forests (lower graphs). A green line indicates an ecological unit with median pyrophilic percentage ≤33 percent (pyrophobic landscape). An orange line indicates an ecological unit with median pyrophilic percentage between 34 and 66 percent (intermediate landscape). A black line represents an LTA with no clear pattern (flat or bimodal distribution).



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Section 212N	1.9	4.2	7.3	11.3	12.5	12.6	12.8	12.4	12.1	12.9
Subsection 212Na	1.0	3.5	7.1	12.8	14.0	12.7	12.6	13.6	13.8	9.0

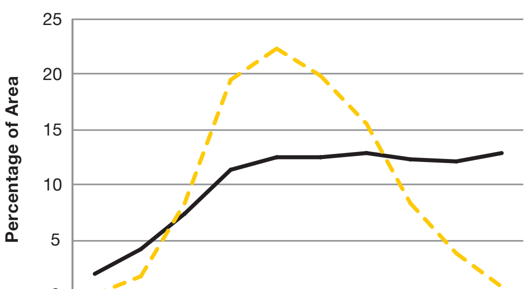


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Na03	2.4	8.4	8.6	8.6	8.9	8.7	10.8	26.3	15.5	1.7
LTA 212Na07	0.0	0.0	1.4	3.9	7.2	11.5	13.1	17.6	21.9	23.4
LTA 212Na08	1.5	5.7	5.8	11.7	13.6	22.3	29.5	9.9	0.1	0.0
LTA 212Na09	1.8	10.1	18.3	22.2	19.9	14.4	8.6	3.8	0.9	0.0

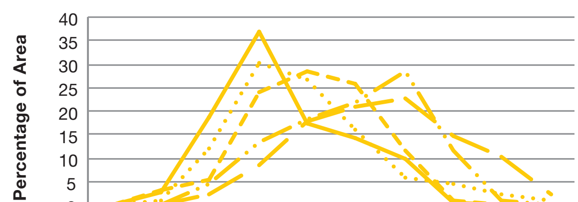


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Na10	18.0	28.2	22.1	19.6	9.6	2.3	0.2	0.0	0.0	0.0
LTA 212Na11	0.0	0.0	5.4	74.6	19.9	0.0	0.0	0.0	0.0	0.0
LTA 212Na16	0.3	4.1	17.4	33.8	27.6	11.7	4.2	0.9	0.0	0.0
LTA 212Na18	3.0	15.3	22.6	21.3	15.3	10.3	7.6	4.6	0.0	0.0

Figure 15.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for Section 212N and Subsection 212Na (upper graph), and component landtype associations within or partially within the proclamation boundary of the Chippewa National Forest (lower graphs). A green line indicates an ecological unit with median pyrophilic percentage ≤33 percent (pyrophobic landscape). An orange line indicates an ecological unit with median pyrophilic percentage between 34 and 66 percent (intermediate landscape). A red line indicates an ecological unit with median pyrophilic percentage ≥67 percent (pyrogenic landscape). A black line represents an ecological unit with no clear pattern (flat or bimodal distribution).

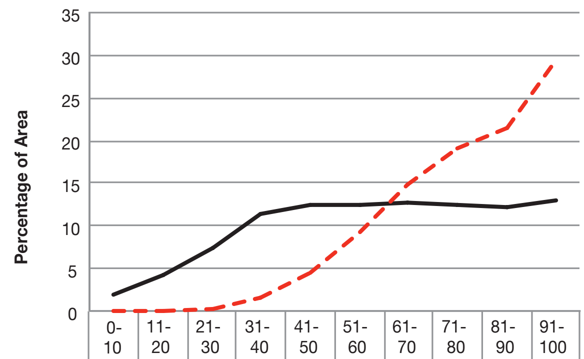


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Section 212N	1.9	4.2	7.3	11.3	12.5	12.6	12.8	12.4	12.1	12.9
Subsection 212Nb	0.0	1.7	8.4	19.5	22.3	19.9	15.5	8.3	3.8	0.7

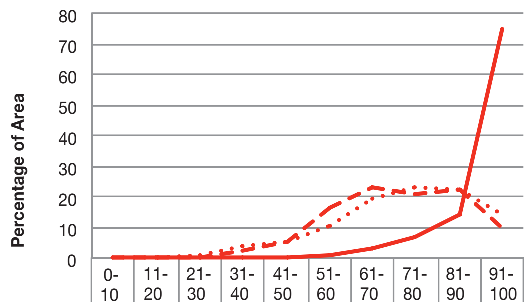


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Nb02	0.0	0.1	2.1	8.6	18.0	21.1	22.5	14.8	10.5	2.3
LTA 212Nb03	0.0	3.3	5.4	24.2	28.5	25.7	11.7	1.2	0.0	0.0
LTA 212Nb07	0.0	0.2	4.6	13.4	18.4	21.8	28.7	11.8	1.1	0.0
LTA 212Nb08	0.0	1.2	12.2	30.5	26.6	16.1	6.0	4.6	2.2	0.8
LTA 212Nb12	0.0	2.6	18.5	36.8	17.2	14.5	10.1	0.4	0.0	0.0

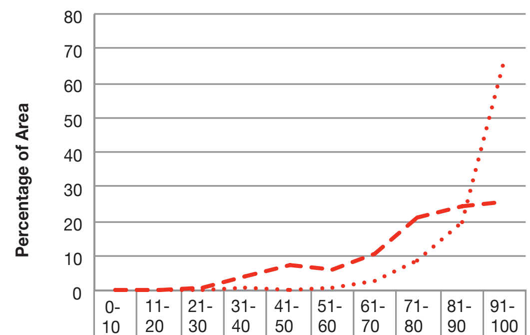
Figure 16.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for Section 212N and Subsection 212Nb (left graph), and component landtype associations within or partially within the proclamation boundary of the Chippewa National Forest (right graph). An orange line indicates an ecological unit with median pyrophilic percentage between 34 and 66 percent (intermediate landscape). A black line represents an ecological unit with no clear pattern (flat or bimodal distribution).



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Section 212N	1.9	4.2	7.3	11.3	12.5	12.6	12.8	12.4	12.1	12.9
Subsection 212Nc	0.0	0.0	0.2	1.5	4.5	9.2	14.8	19.0	21.5	29.4

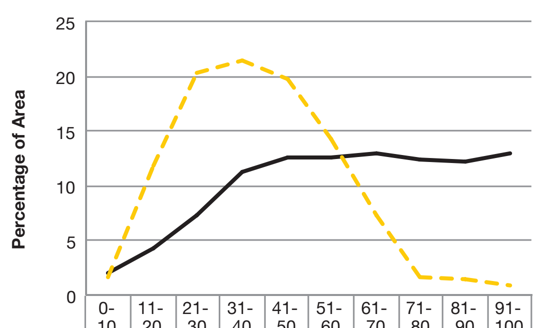


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Nc11	0.0	0.0	0.0	0.0	0.1	1.1	3.2	6.5	14.4	74.7
LTA 212Nc13	0.0	0.0	0.4	2.2	5.2	16.5	23.0	21.0	22.1	9.7
LTA 212Nc14	0.0	0.0	0.9	3.7	5.3	10.8	19.4	23.0	22.6	14.2

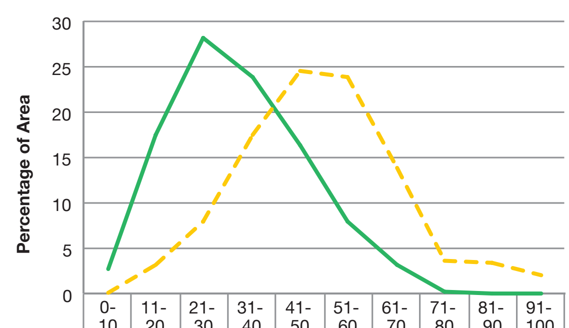


	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Nc16	0.0	0.1	0.6	4.4	7.2	6.2	10.9	20.9	24.3	25.4
LTA 212Nc30	0.0	0.0	0.0	0.6	0.5	1.0	2.7	8.7	19.8	66.8

Figure 17.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for Section 212N and Subsection 212Nc (upper graph), and component landtype associations within or partially within the proclamation boundary of the Chippewa National Forest (lower graphs). A red line indicates an ecological unit with median pyrophilic percentage ≥67 percent (pyrogenic landscape). A black line represents an ecological unit with no clear pattern (flat or bimodal distribution).



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Section 212N	1.9	4.2	7.3	11.3	12.5	12.6	12.8	12.4	12.1	12.9
Subsection 212Nd	1.7	11.8	20.2	21.4	19.6	14.2	7.3	1.6	1.4	0.8



	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
LTA 212Nd04	2.8	17.5	28.2	23.9	16.4	8.0	3.0	0.3	0.0	0.0
LTA 212Nd05	0.1	3.2	7.9	17.6	24.6	23.8	13.8	3.7	3.5	2.0

Figure 18.—Mean pyrophilic percentage as a portion of the total area grouped by 10-percent classes for Section 212N and Subsection 212Nd (left graph), and component landtype associations within or partially within the proclamation boundary of the Chippewa National Forest (right graph). An orange line indicates an ecological unit with median pyrophilic percentage between 34 and 66 percent (intermediate landscape). A green line indicates an ecological unit with median pyrophilic percentage ≤33 percent (pyrophobic landscape). A black line represents an ecological unit with no clear pattern (flat or bimodal distribution).

DISCUSSION

Public Land Survey records probably represent our best window on the arboreal vegetation prior to European settlement (Bourdo 1956, Curtis 1959, Manies and Mladenoff 2000, Whitney 1987). The early application of corner, witness, and bearing trees to characterize past vegetation stands is a testament to their inherent qualities, especially ease of use and interpretation (Gleason 1913; Kenoyer 1929, 1933; Lutz 1930; Sears 1921, 1925; Torbert 1935; Trewartha 1940). Various methods have been developed to elucidate presettlement composition and structure from land survey records, including the testing and correction of surveyor bias (Anderson et al. 2006, Bourdo 1956, Hanberry et al. 2012c, Kronenfeld and Wang 2007) and recommendations on data usage/extrapolation (Delcourt and Delcourt 1996, Wang and Larsen 2006). Vegetation types have been approximated by grouping bearing-tree data by 1) soil type (Leahy and Pregitzer 2003, Lindsey 1961, Lindsey et al. 1965, Shanks 1953), 2) ecological units (Fralish and McArdle 2009, Fralish et al. 1991, Hanberry et al. 2012b, Silbernagel et al. 1997), 3) elevation zones (Siccama 1971), 4) physiography and landscape position (Abrams and McCay 1996, Abrams and Ruffner 1995, Delcourt 1976, Delcourt and Delcourt 1977, Friedman and Reich 2005, Nelson 1997, Whitney 1986, Whitney and DeCant 2003), and 5) tree density (prairie, savanna, woodland, forest) (Anderson and Anderson 1975, Bolliger et al. 2003, Brewer and Vankat 2004, Rodgers and Anderson 1979). Increasingly sophisticated approaches to classify and map vegetation types have been added over time, including the application of multivariate statistics (Black et al. 2002, Grimm 1984, Predmore et al. 2007, Schulte et al. 2002), fuzzy logic (Bolliger and Mladenoff 2005; Brown 1998a, 1998b), and spatial modeling and interpolation (Batek et al. 1999; He et al. 2000, 2007; Hanberry et al. 2012a; Manies and Mladenoff 2000; Rathbun and Black 2006; White and Mladenoff 1994). Even techniques for reducing ambiguity in names of tree species have been proffered (Mladenoff et al. 2002).

Curiously, with few exceptions (e.g., Batek et al. 1999), the use of bearing-tree data to reconstruct past disturbance regimes has been largely overlooked in favor of qualitative information, specifically surveyor notes that recorded entry into and exit from disturbance patches (blowdowns, burned areas) along survey lines (Canham and Loucks 1984, Lorimer 1977, Schulte and Mladenoff 2005, Schulte et al. 2004, Seischab and Orwig 1991, Whitney 1986, Zhang et al. 1999). As an alternative, we developed and applied a novel approach that directly used bearing trees, effectively converting them into spatial indicators of fire (Thomas-Van Gundy and Nowacki 2013). Species/genera were partitioned based on their general relationship to fire as either pyrophilic or pyrophobic. By applying this classification to bearing-tree points, calculating cell-based pyrophilic percentage means, then interpolating through kriging, we were able to produce spatial covers depicting the impact of fire as expressed in presettlement tree composition. In essence, variation in pyrophilic percentages across the landscape can be interpreted as increases or decreases in the importance of fire to the ecosystem.

It should be noted that our binomial classification does not capture a particular fire regime, but simply serves as a first step in converting the trees present on the presettlement landscape into an index that estimates the historical importance of fire. Distinguishing between whether a species (for example, jack pine) represents a periodic intense canopy fire regime or, in the case of oaks, represents a frequent, low-to-moderate surface fire regime was immaterial to our broader objective. In both of the above instances, jack pine and oak benefit from and are indicative of fire. Understandably, the inclusion of certain shade-intolerant species/genera (e.g., *Populus*) that respond positively to an array of disturbance types (e.g., fire, insect, and wind disturbance) in the pyrophilic category may lead to an overprediction of fire importance in some instances. However, even though the classification of species is binary, the calculation of the pyrophilic percentage is continuous so that areas where both pyrophilic and pyrophobic species existed together are displayed.

Our maps reflect the general fire setting during and immediately prior to the period of 1847–1908 when bearing-tree data were recorded in Minnesota. As such, these data represent a snapshot in time along a long continuum of changing climatic regimes (Clark 1988, 1990). The period falls at the end of the Little Ice Age (1600–1860 AD), when cooler and moister conditions and longer fire intervals prevailed (ca. 88-yr return cycle). Harmonic fire cycles (corresponding to multiples of 22-yr drought cycles) reigned over Minnesota for more than 750 years, effectively ending with regional fire suppression in 1910 (Clark 1988, 1990). Ironically, 20th-century fire suppression took place during a warmer climate, thus thwarting favorable fire conditions that otherwise could have led to shorter fire cycles. Because of long-term oscillations in climate and fire-cycle length, uncertainty exists regarding how well the bearing-tree data period corresponds to past fire regimes (Clark 1988). However, even though fire regimes may have fluctuated through time, multiple independent data sources (fire scar, charcoal stratigraphy, stand-origin mapping) indicate that fire was the primary disturbance force controlling vegetation expression throughout most of Minnesota over many millennia, regardless of the specifics of the fire regime (Clark 1988, 1990; Frissell 1973; Grimm 1984; Heinselman 1973). Our products build on and complement past research by providing a finer-scale depiction of presettlement fire settings.

The pyrophilic percentage maps corroborate the conclusion that fire was the preeminent force in the Midwest Broadleaf Forest Province, as expressed in the literature (Cottam 1949, Curtis 1959, Grimm 1984, Hanberry et al. 2012b, Knoot et al. 2015, Nowacki and Abrams 2008, Peters 1978). Located between the highly flammable prairie (Province 251) and the less flammable conifer-northern hardwoods (Province 212), the Midwest Broadleaf Forest Province was a transition zone resulting from high-frequency surface burns estimated at every 5–30 years (Wheeler et al. 1992). Its "downwind" (eastward) location from the fire-prone Central Plains grasslands ensured fire regularity in presettlement times. The westward edge of this province, representing the prairie-forest interface, generally corresponds to moisture availability, with finer-level crenulations linked to topographical controls over fire (Danz et al. 2013). The boundary is most clearly defined (abrupt) along its central portion, where topographic roughness impeded the spread of fire (McAndrews 1966).

Within the province, firebreaks, whether in the form of water bodies (streams, lakes, and marshes) or broken topography, had a profound effect on landscape-scale fire dynamics and provided refuges for mesophytic, fire-sensitive trees and community types (Dorney 1981, Gleason 1913, Goder 1956, Kilburn 1959, Kline and Cottam 1979, Leitner et al. 1991). The pyrophobic tendency of one such fire refuge, the "Big Woods," was vividly expressed in our maps (Fig. 3), having nearly identical dimensions as those drawn by previous researchers (compare with Grimm 1984 and Umbanhower 2004). In addition, our maps revealed similar (albeit smaller) pockets of fire-sensitive vegetation dotting the landscape northwestward from the Big Woods (see green "islands" in Fig. 3). Apparently similar firebreaks existed along the west sides of these mesophytic refuges as well, thwarting the advance of presettlement fires carried by prevailing westerly winds. Without west-flanking firebreaks, these mesophytic inclusions would not have existed; instead the vegetation would have been similar to the surrounding oak-dominated matrix.

The Laurentian Mixed Forest Province was a mix of fire settings, ranging from highly pyrophilic pine-dominated outwash sands in the southwest, across a subdued setting in the center, to highly pyrophilic, drought-prone, shallow-to-bedrock landscapes in the northeast along the Canadian border. Because of this province's close proximity to the Central Plains, historical prairie fires could easily move onto flat conifer-dominated sand plains (Subsections 212Na and 212Nc), which explains the sand plains' high degree of pyrophilic tendency. Immediately northeastward across this province, the moderating effect of large peatlands, glacial lake basins, and numerous lakes and streams on the general fire setting is clearly evident. Together these surfaces served as broad-scale firebreaks, limiting the extent of fires driven by prevailing westerly winds (Foster 1983, Heinselman 1973). The effects of a cool, humid maritime climate along Lake Superior were also evident. Here, the northwesternmost vestiges of mesic, fire-intolerant northern hardwoods occur (Steele and Risley 2014).

Potential Changes to the Delineation of Ecological Units

The importance of integrating disturbance regimes into ecological mapping served as an impetus to evaluate how well ecological units performed in encapsulating general fire settings as portrayed by pyrophilic percentages. Overall, ecological units corresponded well with fire gradients: 74 out of 79 units had pyrophilic distributions that could be classified as pyrophilic, intermediate, or pyrophobic. Because the province line essentially represents a break between biomes, diagnostic trees were used to more precisely denote the line between the highly pyrophilic Midwest Broadleaf

Forest Province (oak and hickory) and the intermediate Laurentian Mixed Forest (northern conifers and hardwoods) (Figs. 5 and 6).

Of the three sections evaluated, the Northern Minnesota Drift and Lake Plains (212N) was found to be a "catch-all" spanning a west-to-east fire gradient from pyrophilic to pyrophobic. The ecological factors used in the original delineation of this section did not capture this ecologically significant gradation in the fire environment as expressed in presettlement vegetation. Our mapping results demonstrate the additive value of including disturbance factors in ecological mapping. This section could be substantially improved by differentiating between the highly pyrophilic sand plains (Subsection 212Nc and the western portion of Subsection 212Na) (Fig. 12) and the more pyrophobic eastern lake plains. Under this scenario, the pronounced fire shadow immediately east of Leech Lake would fall into the latter section (Fig. 19).

Two subsections were identified as having anomalous "catch-all" pyrophilic percentage distributions: Laurentian Uplands (212Le) and Chippewa Plains (212Na). In these subsections, factors other than the fire regime, such as mesoclimate, geomorphology, and soils, were the primary drivers of the ecological boundaries. Based on the past fire environment, the distinctly bimodal Laurentian Uplands (Fig. 11) should be divided in half, with the northern pyrophilic portion absorbed into the adjacent Border Lakes (212La) Subsection and the southern pyrophobic portion combined with the Toimi Uplands (212Ld). This latter adjoining would allow the Toimi Uplands to be represented by more than one LTA. As suggested earlier with the subdivision of Section 212N, the Chippewa Plains Subsection should be divided in half along a northwest-southeast diagonal. If large enough in size, these two units could form new subsections. Otherwise the units could be absorbed into adjacent subsections (e.g., the western half combined with Subsection 212Nc).

At the finest level, landtype associations were effective in capturing the general fire setting as displayed by pyrophilic percentages with 62 out of 64 units classified as pyrophilic, intermediate, or pyrophobic. The bimodal nature of the Timber Freer Till Plain (212Le03) and Rauch Till Plain (212Ma19) suggests subdividing these LTAs, separating their pyrophilic and pyrophobic sectors, and perhaps absorbing these areas into adjacent LTAs.

CONCLUSIONS

European settlement and associated land-use changes have greatly affected ecosystems throughout the eastern United States (Nowacki and Abrams 2008, 2015). Fire suppression since European settlement has had a profound effect on formerly pyrogenic landscapes, leading to an increase in fire-sensitive, shade-tolerant species and a decrease in ground flora diversity. This phenomenon, dubbed mesophication, is quite apparent in the Midwest Broadleaf Province of Minnesota (Grimm 1984, Hanberry et al. 2012b, Knoot et al. 2015). Through the projection of presettlement fire settings, our work supports restoration efforts by identifying past ecosystems that formerly burned.

Our pyrophilic percentage effectively converts presettlement vegetation into a meaningful ecological index linking vegetation to prevailing historical disturbance regimes and projecting the degree of fire importance on past landscapes. Community types differ profoundly based on whether fire was part of their development or not. For example fire-dependent, shade-intolerant, oftentimes open vegetation types and associated ground flora (e.g., pine-oak woodlands with grasses) may be contrasted with fire-sensitive, shade-tolerant, closed-canopied forest types with heavily shaded understories (conifer-northern hardwoods with spring ephemeral ground flora). Thus, we recommend that the formative role fire played in the ecological development and expression of vegetation be directly reflected in ecological mapping as an important delineation factor **additive** to other factors at various spatial scales. The current ecological units capture fire gradients (as represented by our pyrophilic percentages) in Minnesota and reinforce the fact that fire regimes are related to edaphic factors (as indicated, for example, by the more frequent fires on dry sand surfaces than on mesic ice-contact tills and wet peatlands). We identified a few exceptions where it appears that fire trumped other ecological factors in driving ecosystem development. Considering the variety of ecological phenomena that pyrophilic percentages embody—climate, vegetation, topography (including firebreaks), soils—the unit boundary changes suggested here seem well founded and robust.

It is well established that fire was an important ecological process and evolutionary filter across the Minnesota landscape (Cavender-Bares and Reich 2012, Heinselman

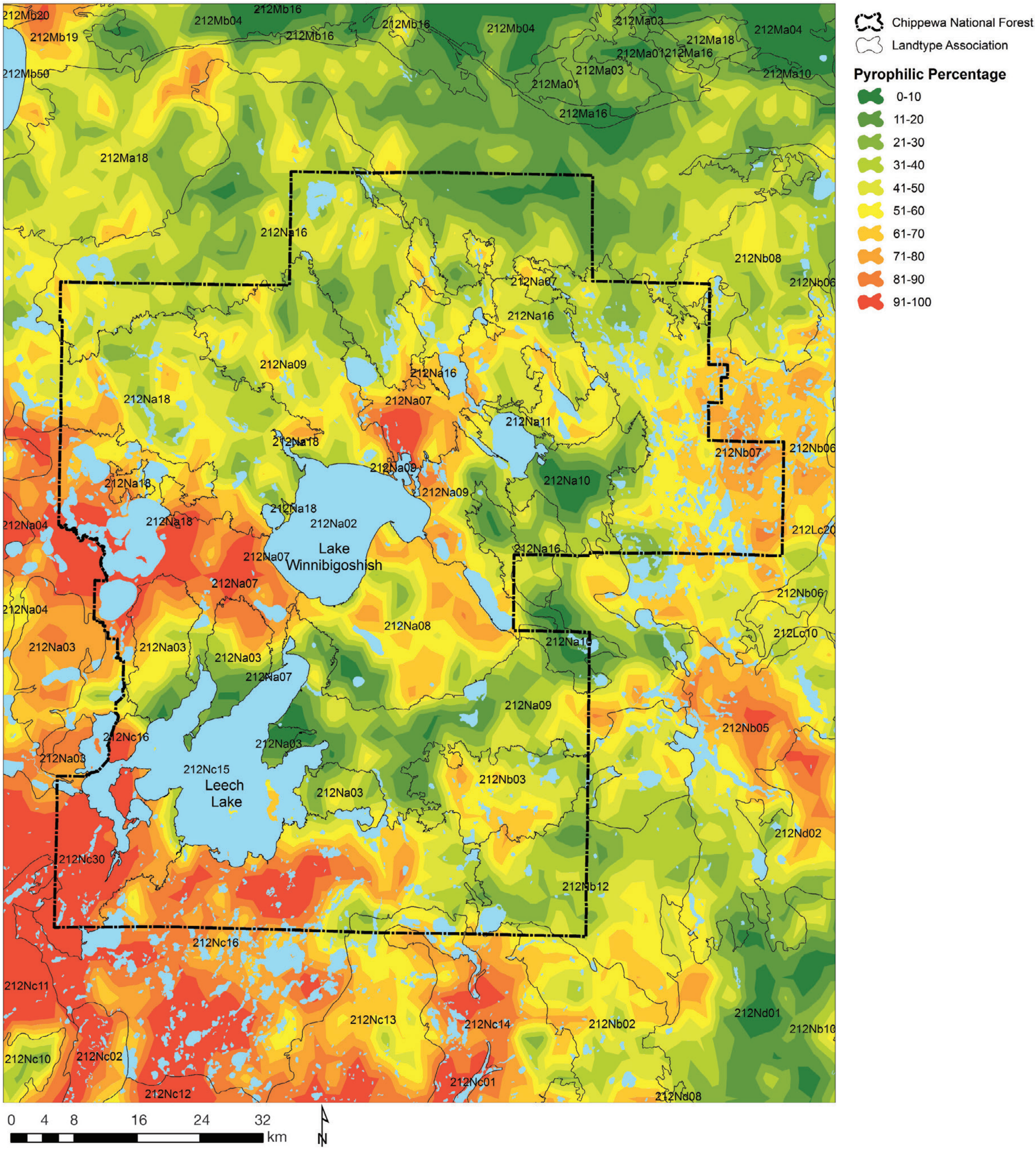


Figure 19.—Pyrophilic percentage for the Chippewa National Forest with landtype associations.

1973, Wheeler et al. 1992). Even though fire has deep evolutionary roots in the plant world, favoring fire-tolerant plants that diverged from fire-sensitive plants some 80–140 million years ago (Cavender-Bares and Reich 2012), there is strong evidence that Holocene fire regimes were largely driven by Native American ignitions (Abrams and Nowacki 2008, Grimm 1984, Guyette et al. 2002, Kay 2007, Moore 1972). Particularly if fires were primarily of human origin in the past, prescribed burning will be essential for the reinitiation of fire on today's landscape for ecosystem restoration purposes. In this analysis, we projected the importance of presettlement fire across Minnesota by harnessing the power of bearing trees as indicators of past fires (Thomas-Van Gundy and Nowacki 2013). Our maps provide a strong basis for locating areas where centuries of burning left an indelible mark on plant composition in the past and thus where prescribed burning for ecosystem restoration is most appropriate in the present.

ACKNOWLEDGMENTS

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We display the influence of pre-European settlement fire on vegetation across Minnesota by harnessing the power of bearing trees as indicators of past fires on the landscape. Species and genera of trees used as bearing trees in Public Land Surveys were categorized as either pyrophilic (fire-adapted) or pyrophobic (fire-sensitive) and the percentage of pyrophilic trees was calculated and interpolated to create a map showing the inferred importance of fire. Ecological units at four spatial scales (province, section, subsection, and landtype association) were examined against our pyrophilic percentage maps, irregularities noted, and line improvements suggested based on the prevailing fire setting (the set of vegetation and topographic conditions under which fires occur or are inhibited) before European settlement. Our maps and analyses for Minnesota, the Chippewa National Forest, and the Superior National Forest provide a strong ecological basis for locating areas where long-term burning left an indelible mark on plant composition, structure, and biodiversity and thus where prescribed burning for ecosystem restoration is most appropriate today.

KEYWORDS: fire, presettlement disturbance regimes, ecological units, biogeography

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