CHANGES IN DISTURBANCE FREQUENCY, AGE AND PATCH STRUCTURE FROM PRE-EURO-AMERICAN TO SETTLEMENT TO PRESENT IN NORTH-CENTRAL AND NORTHEASTERN MINNESOTA

Mark A. White and George E. Host
Natural Resources Research Institute
University of Minnesota, Duluth
5013 Miller Trunk Highway
Duluth, MN 55811

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Abstract

We used General Land Office survey data (1850-1890) and interpreted aerial photography data from 3 time periods to characterize forest disturbance frequency, spatial patterns, and age-structure for the 4 time periods in the Mixed Forest Province of Minnesota. The study region was composed of 8 Subsections within 2 sections (Northern Superior Uplands, Drift and Lake Plains) of the Minnesota Ecological Classification System. Results from line note data for disturbance frequency were similar to others in the region derived from tree-ring and GLO data analysis. Historic disturbance frequency and severity and spatial pattern estimates showed significant variability across the study region. The 1900-1940 period was characterized by a short-term increase in fire frequency across the study region. The disturbance frequencies were relatively uniform across the two sections during this time period, in contrast to the significant variability in the pre-Euro-American landscape. Age-structure in the region shifted from the pre-Euro-American dominance of later successional stages to the closed-canopy and understory re-initiation phases in the post-settlement era. In the post-settlement period (1940-1995), timber harvest replaced fire as the dominant disturbance factor. Similar management practices across subsections created more similar rotation periods across the study region. These management practices also imposed a pattern dominated by small (10-25 ha) patches across the landscape. Management practices now have a greater influence than natural processes in the generation of landscape pattern and forest age-structure in the Mixed Forest Province of Minnesota. The GLO data have been shown to be a valuable information source for assessing historic forest conditions. Interpreted aerial photography data is a useful tool for monitoring forest conditions including age-structure.

Introduction

Knowledge of the natural variability of forest ecosystem composition, structure and spatial pattern is an important component in developing ecologically sustainable forest management (Morgan et al. 1994). Natural variability analysis defines the reference or baseline forest conditions that prevailed prior to the influence of Euro-Americans. Knowledge of reference conditions allows us to determine the extent of change from reference conditions and to develop management strategies that restore or maintain elements of natural forest variability (Moore et al 1999). The biota of a particular region have existed with and to some degree adapted to the prevailing natural disturbance patterns (Landres et al. 1999). Managing for natural variability may serve as a coarse filter in helping maintain forest ecosystem processes and species habitat in managed forests (Haufler et al.1996). While forest composition and structure are important components of natural variability, the frequency and size of disturbance patches creates the grain of the landscape and has implications for forest management (Hunter 1993).

Heinselman (1973) using tree-ring data developed natural disturbance chronologies for the 420,000 ha (1,030,000 acres) Boundary Waters Wilderness Canoe area (BWCAW) for the period from 1577 to 1972. However, because of the widespread logging and catastrophic fires fueled by slash that occurred during the settlement period (1880-1920), there is little extant tree-ring material which could be used to develop natural disturbance chronologies for much of the mixed forest province of Minnesota. The best remaining record of forest conditions for the mixed forest province is contained in the General Land Office Survey. This rectangular survey parceled the land into mi^2 sections. Witness trees were recorded at section and quarter corners along with land and vegetation conditions.

In the northern lake states, these data have been used to map pre-Euro-American vegetation (Marschner 1946, White and Mladenoff 1994, Shadis 2000, White and Host 2000, Schulte et al. 2002), estimate disturbance frequencies and forest composition and structure (Frelich 1999, White 2001a & b, Schulte and Mladenoff 2003). Friedman et al. (2001) used GLO bearing tree data to analyze tree species composition and spatial distribution patterns in northeastern Minnesota. These data are also useful assessing vegetation changes from pre- Euro-American settlement to present (White and Mladenoff 1994, Zhang et al. 2000). Natural disturbance-spatial pattern relationships have been examined in northern Wisconsin and Michigan. Zhang et al. (1999) examined disturbance frequency and spatial patterns in Michigan's Upper Peninsula, Canham and Loucks analyzed catastrophic windthrow frequency and size in Wisconsin, While Schulte and Mladenoff (2003) examined disturbance frequency and spatial patterns in the mixed forest province of Wisconsin. In Minnesota, with the exception of the work on fire in the BWCAW (Heinselman 1973) little work has been done on the spatial patterns of natural disturbances in the pre-Euro-American period.

We selected two sections within the Mixed Forest Province of Minnesota as our study region; the Northern Superior Uplands (NSU) and Northern Drift and Lake Plains (DLP). Samples were stratified across the eight subsections of the two sections. Our objectives for the eight subsections in the study region were 1) estimate the sizes and frequency of disturbance patches, 2) estimate disturbance rotation periods and corresponding age structure, 3) compare age structure with 1930s, 1970s and 1990s age structure from aerial photo study, 4) compare pre-Euro-American disturbance patch sizes with disturbance patches from the1930s, 1970s and 1990s from the aerial photo study.

Study Region

The Laurentian Mixed Forest Province of Minnesota covers approximately 94,000 km^2 (Fig. 1) (Minnesota Department of Natural Resources 1999a). This is a glacial landscape dominated by Wisonsinan-age glacial drift and landforms. Glacial lacustrine features such as glacial lakes Agassiz, Upham and Aitkin, and morainal features cover large land areas in this region. Sandy outwash plains and channels are also common (Albert 1995). The climate is characterized by long, cool winters and short, mild summers. Annual precipitation ranges from approximately 530 to 780 mm (McNab and Avers 1994). At the time of settlement, conifers dominated both upland and lowland forests. On upland areas, jack pine (*Pinus banksiana* Lamb.) dominated on dry, fire prone sites such as outwash plains and thin soils over bedrock. White and red pine (*Pinus resinosa* Ait.) occurred on sandy moraines. Post-disturbance aspen-birch forests were present on a wide variety of upland soil types. Wetland types included large areas of lowland conifer forest dominated by black spruce (*Picea mariana* (Moench) Voss) and tamarack (*Larix laricina* (Duroi) Koch) as well as open bogs and patterned peatlands (Albert 1995). For this study, we focused on subsections in the NSU and DLP sections (Figure 1). The NSU and DLP provide a representative sample of forest ecosystems, and soil, landform and climate conditions (MN DNR 1999). These sections are among the most important timber producing regions of Minnesota (USDA Forest Service 1991).

Methods

Presettlement landscape patterns were assessed by direct analysis and interpretation of digitized General Land Office Survey (GLO) line notes. Land surveyors made notes describing the condition of the land as they traversed section lines. When they encountered change along the line, this was noted by entry and exit distances along the line and with descriptions describing notable features of the line segment. These included, wetlands, lake and river boundaries, fire, windthrow, flooding, soil conditions, timber quality, and general vegetation descriptions. Summary notes described the general condition of that section line, but often also included distance specific descriptions (e.g. “last 20 chains all burned land”). Because of the specific descriptions tied to line segments, we can reconstruct important aspects of natural disturbances based on the surveyor’s observations.

General Land Office Survey Line Note Digitizing

Individual plots for the GLO analyses were interpreted for 42 144 mi^2 (4 township) plots that were centered as close as possible to the center of the 9 mi^2 aerial photography plots (Host and White 2003). The plots were distributed based on the proportional area of subsections in the NSU and DLP Ecological sections (Figure 1). There are an identical number of line note and air photo plots. Line note plots comprised from 25 to 50% of the total section line length per subsection. Surveyors line notes were georeferenced to line segments along survey lines, and entered as text strings by the Minnesota Department of Natural Resources Resource Assessment Division. Line segments were coded by disturbance type based on information in the line note descriptions. The primary disturbance types were fire, wind, wind-fire, and dead. Database queries on keywords (fire, wind, burned, dead) were used to ensure that all disturbed segments were recorded.

Patch Delineation

Disturbance patches were created by manually digitizing boundaries of disturbed areas, as designated by adjacent disturbed line segments (Figure 2, 3). Digital topographic maps, national wetland inventory data, and digital orthophotos were used to help construct disturbance boundaries. Lakes, rivers, emergent wetlands, and extreme topographic breaks along with the presence or absence of disturbed line segments were used to define patch boundaries (Zhang et al.1999, Comer et al. 1995). Surveyor descriptions were also used, as notes frequently described the direction of the long axis of the disturbance ("windthrow NE-SW'). We developed general decision rules for patch boundaries. For example, if 2 line segments of section were disturbed, the boundary would bisect the section on the diagonal, unless a water body or emergent wetland was present. If 3 line segments were disturbed, the 4th segment was omitted unless segments in adjacent segments were disturbed. In general, patch sizes were proportional to the length of line segments. Patches were coded with unique identifiers for disturbance type, plot, and subsection.

Aerial Photo Interpretation

Aerial photographs from the 1930s, 1970s and 1990s were interpreted and used to assess post-settlement changes in disturbance landscape pattern. Plots for the air photo analysis consisted of 9 square miles (quarter-townships), centered within the GLO line note plots. Forest patches were classified according to cover type, growth stage, and, when possible, type of originating disturbance. Photo-interpretation detail and classification system are more thoroughly described in Host and White (2003).

Determining Disturbance Frequency

We used three related sets of information derived from the GLO to estimate pre-Euro-American disturbance frequencies: Line note segments, disturbance patches, and section corners. Rotation period *C*, is defined as the length of time (years) required for disturbance to cover an area equal to the total area of the study landscape. Some elements in the landscape may not be disturbed, and some may be disturbed more than once. For line note segments, lengths for each disturbance class are summed and divided by the total available line length to determine proportion (*P*) disturbed in each class. The total available line length was determined by subtracting the line length of open water from the total plot line length. Disturbance points were not included in the line-based estimates. The rotation period *C* is defined as *1/P* where *P* is the annual probability of disturbance. Because surveyors observed disturbances that occurred at different points in time prior to the survey, a time window in which disturbances can be recognized is required. We used a 15-year recognition window for high severity or stand replacing disturbance, and a 10-year interval for moderate severity. The 15-year window has been used in other studies of high severity disturbance in the northern lake states forests (Canham and Loucks 1984, Zhang et al. 1999, Schulte and Mladenoff 2003). The 10-year recognition window was used because evidence of low to moderate disturbance severity likely disappears more quickly than more severe events. Therefore rotation period *C* for class *i* is defined as:

1) $$Ci = \frac{15}{P_i}$$

where *p* is the proportion disturbed line segments for class *i*. The numerator value becomes 10 for moderate severity disturbance. Rotation periods were calculated for fire, windthrow, flooded, dead, and all disturbances combined. The disturbance severity estimates were calculated for the line note data.

We also calculated fire and windthrow rotation periods based on delineated and estimated disturbance patches, and GLO section corner point data for each subsection. For the disturbance patch data, equation 1 was applied to the proportion of disturbed area in each subsection. We applied equation 1 to the proportion of disturbed corners in a subsection. All corners within a subsection were included with the exception of open water corners and marsh corners.

We estimated disturbance rotation periods for fire and timber harvest at the subsection level using the interpreted aerial photography data from the 42 corresponding plots. We applied equation 1 based on areal proportions of disturbance within a subsection. The aerial photo interpreter estimated a 25-30 year time window for disturbance recognition. We used the 25-year interval for disturbance frequency estimates. There were not sufficient observations of windthrow in the aerial photo database for disturbance frequency and patch size distribution estimates.

Determining Disturbance Severity

We classified disturbed line segments into 2 classes; high and moderate severity. High severity equates to stand replacing disturbance, while moderate indicates disturbance in which large canopy trees survive and mortality may be high in the understory size classes. The following data in the line note database were used for disturbance severity classification: tree density, mean distance from corner or quarter corner, mean tree diameter, and unambiguous descriptions from surveyors.

Decision rules:

High severity

1) Less than full compliment of trees at quarter (2) or section corner (4).
2) If full compliment present, then mean diameter less than 5’ and unambiguous surveyor description (e.g “timber nearly all burnt, dense brush”).
3) If full compliment present, mean distance > 100 chains (66’) and mean diameter < 6”.

Moderate Severity

1) Full compliment of trees at quarter (2) or section corner (4).
2) If less than full compliment present; mean diameter > 9” and distance < 30 chains
3) If less than full compliment present: mean diameter > 14” and mean distance < 100 chains.
4) If less than full compliment present; unambiguous surveyor description (e.g. “timber partially burnt”) and mean diameter > 5” and mean distance < 30 chains.

Because the time since disturbance for a given event would have varied from 0 to at least 15 years when surveyors traversed a disturbed area, vegetation conditions likely varied significantly depending on the severity, productivity and elapsed time. By applying the criteria listed above, we accounted for the variation in vegetation conditions. In general, high severity disturbances were identified by lower tree density and longer distances, or by very small diameters and longer distances. Moderate severity was characterized by larger trees (> 10” dbh) and shorter distances (<100 chains), or by smaller trees (> 5” dbh) and very short distances (< 30 chains).

Patch Size Frequency estimation

Because the GLO was a 1.6 km ($1mi^2$) rectangular survey, all patches with lengths greater than 2.24 km should be recorded by the survey. Therefore, some proportion of patches less than 2.24 km in length were sampled by GLO survey. We applied transect theory (Devries 1974) to estimate the frequency of patches with lengths less than 2.24 km (Canham and Loucks 1984, Zhang et al. 1999). Following Canham and Loucks (1984), patch size distributions were created based on polygon size frequency distributions. We selected the following patch size distribution (1-5, 5-10, 10-50, 50-100, 100-500, 500-1,000, 1,000-5,000, 5,000-10,000 hectares) (Wolter and White 2002). We measured the long axis of each patch and calculated the mean patch length for each size class for the set of plots in each subsection. We estimated patch frequency for those size classes with mean patch lengths less than 2.24 km using the simplified transect equation provided by Canham and Loucks (1984):

2) $$x = 1.24 \sum_{i=1}^{n} 1/y$$

Where x is the total count of disturbance patches in size class j, n is the number of sampled disturbances, and y is the length of the i^{th} intercepted patch. The total area for each size class was calculated by multiplying the total number of patches in a size class by the average area of sampled patches.

Patch size distributions for the post-settlement period fire and timber harvest patches were estimated for each subsection using the corresponding interpreted aerial photography plots. For the aerial photo data, patches were dissolved based on disturbance classification (burned, windthrow, timber harvest, dead, insect and disease and unknown) and age structure class (stand initiation, closed canopy, demographic transition, mature).

Pre-Euro-American Age Structure

Forest ecologists have defined four generic vegetation growth stages for forests in the north-temperate region that relate to disturbance and stand development over time; stand initiation, stem exclusion, understory re-initiation, and mature-old growth (Oliver and Larson 1996). Frelich (2002) modified these to conform more closely to forest conditions in the northern lake states region; stand initiation, stem exclusion, demographic transition, and old-multi-aged forest. The expected landscape age-class structure can be estimated by applying the negative exponential distribution to disturbance rotation estimates (Johnson and Van Wagner 1985, Van Wagner 1978).

Probability-based fire history models provide a useful, conceptual approach to understanding natural disturbance data. Johnson and Van Wagner (1985) detailed the use of two fire history models, the Weibull and the negative exponential. The Weibull is an age selection model, and indicates that fire probability, or the hazard of burning rate increases with stand age, or time since fire. This has been interpreted as fuel accumulation model, indicating that ignition sources are relatively constant, and ignition and fire spread depends on sufficient fuel. The negative exponential model states that the hazard of burning rate is constant over time, and is not related to time since fire, or fuel accumulation. Studies from the boreal forest region suggest that the negative exponential is the best fit for cumulative fire frequency distributions, although there are some relationships to stand age, forest structure and resulting fuel distributions (Johnson 1992). Although disturbance regimes in the Mixed Forest Province of Minnesota may not conform to the negative exponential model, this model can still be used to approximate expected age-class distributions. In the RNV models applied to the NSU and DLP, maintenance fire effects composition, but not the probability of crown fire, which remains constant across growth stage (Frelich 1999). The more simple, negative exponential model provides similar results to more detailed successional models (Frelich 1999) when assessing age-class distribution. We applied the negative exponential disturbance model to subsection level high severity disturbance rotation data to predict expected age-class distributions. The cumulative proportion of all stands up to age x can be estimated by:

3) $$f(x) = 1 - e^{-px}$$

Where *x* equal stand age in years and *p* equals the annual probability of disturbance. In order to determine the age-range for vegetation growth stages, we compared the aerial photo derived age classes with public forest inventory data from 2001 for each subsection (Brown and White 2002). We selected the following generic age-classes to represent stand initiation, closed canopy, understory re-initiation, and Mature forest respectively for subsections in the study region:

1-20, 20-50, 50-100, > 100 (Pine Moraines, Chippewa Plains, Border Lakes, Nashwauk Uplands, St. Louis Moraines)
1-20, 20-60, 60-100, > 100 (North Shore Highlands, Laurentian/Toimi)
1-20, 20-60, 00-85, > 85 (Tamarack Lowlands)

These age-class distributions were then compared to age-class distributions derived from aerial photography from 1930s, 1970s and 1990s.

Statistical Methods

We employed descriptive statistics in the analysis of these data sets. The line note and patch data were analyzed at the subsection level because in many cases plots were adjacent to one another and disturbance patches crossed plot boundaries. We chose to preserve these larger patches rather than arbitrarily dividing them by plot boundaries. In addition, measures of variance are problematic with the disturbance patch data derived from line notes. The areas of estimated patches (<2.24 km in length) were based on the mean patch size for sampled patches in each size class. Size class distributions along with mean patch size and range were used to analyze the variability of disturbance patch size data.

Results

Natural Disturbance Frequency and Severity

In general, natural disturbance frequency estimates derived from the GLO data using three different methods show similar values for subsections in the study region. The section corner data tends to show longer disturbance rotation periods than the line and patch data, however values are generally similar (Table 1). The patch-derived estimates tend to show shorter disturbance rotation periods. The Border Lakes shows fire rotation range from 158 for the patch data to 201 years derived from the section corner database. For the Nashwauk Uplands, line note and patch data show nearly identical values for fire rotation (260, 249 years respectively) while corner data predicts less frequent fire (324 years). While values are similar among the three methods, there are some notable exceptions. In the North Shore highlands, line and patch data show fire rotation estimates of 609 and 492 years, while section corners show a 2,050 period (Table 1). Wind estimates for the Nashwauk Uplands are similar for the line and patch data (561 and 461) but are substantially longer with the section corner data (4,242). Because the values are generally similar, we used the line note derived estimates when comparing disturbance regimes in the Mixed Forest Province of Minnesota.

Table 1. Natural disturbance rotation estimates (years) based on GLO data using line segments, patches, and section corner points. Estimates combine high and moderate severity disturbance.

Subsection	Fire-Line	Fire-Patch	Fire-Corner	Wind-Line	Wind-Patch	Wind-Corner
Border Lakes	166	158	201	1,365	1,496	2,489
North Shore Highlands	609	492	2,050	3,048	2,084	4,921
Nashwauk Uplands	260	249	324	561	461	4,242
Laurentian-Toimi Uplands	1,001	482	262	6,390	4,608	6,910
Chippewa Plains	253	224	334	409	345	613
St. Louis Moraines	1,428	1,330	1,191	1,567	1,207	1,295
Pine Moraines	315	272	375	348	351	954
Tamarack Lowlands	170	138	411	528	497	582

Table 2a. Rotation period estimates for subsections in the a) Drift and Lake Plains.

a)	Chippewa Plains		St. Louis Moraines		Pine moraines		Tamarack Lowlands	
Disturbance Class	Rotation period	Annual % disturbed	Rotation period	Annual % disturbed	Rotation period	Annual % disturbed	Rotation period	Annual % disturbed
Fire-high severity	383	0.26	2,775	0.04	620	0.16	220	0.45
Fire-moderate	497	0.20	1,960	0.05	428	0.23	498	0.20
Fall-all	253	0.40	1,428	0.07	315	0.32	170	0.59
Wind-high severity	643	0.16	2,775	0.04	520	0.19	655	0.15
Wind-moderate	751	0.13	1,960	0.05	701	0.14	1,818	0.05
Wind-all	409	0.24	1,567	0.06	348	0.29	528	0.19
Dead-high severity	7,813	0.01	5,974	0.02	4,563	0.02	438	0.23
Dead-moderate	16,583	0.01	13,952	0.01	6,040	0.02	4,915	0.02
Dead-all	5,311	0.02	4,183	0.02	2,599	0.04	402	0.25
Flooded	15,858	0.01	na	na	150,270	0.00	na	na
All-high severity	229	0.44	1,115	0.09	266	0.38	120	0.84
All-moderate	437	0.23	1,468	0.07	374	0.27	524	0.19
All	150	0.66	634	0.16	155	0.64	97	1.03

The analysis of disturbance frequency with combined high and moderate severity classes (Table 2, fire-all, wind-all etc.) shows significant variability between subsections in the study area. The subsections of the DLP section, with the exception of the St. Louis Moraines, tend to have higher wind and fire frequencies, while the NSU are more variable (Table 2). The Chippewa Plains, Pine Moraines and Tamarack Lowlands all showed relatively frequent wind and fire disturbance. The Tamarack Lowlands also exhibited a large area dead forest, which contributes to an overall combined disturbance rotation period of 97 years (Table 2). In the NSU, fire rotation periods were relatively short in the Border Lakes and Nashwauk Uplands (166, 260) and longer in the North Shore Highlands and Laurentian/Toimi Uplands. Wind disturbance ranged from 561 in the Nashwauk Uplands to 6,365 years in the Laurentian/Toimi Uplands. The Laurentian/Toimi also showed a significant amount of dead forest.

Disturbance severity also showed significant variation across the 8 subsections. The Border Lakes and Tamarack lowlands exhibited the highest frequency of high severity fire (210, 220 year rotation periods respectively) and high severity disturbances combined (182, 120 year rotation periods respectively) (Table 2a, 2b). Moderate severity fire was more frequent in subsections with the highest overall fire rates (Border Lakes, Nashwauk Uplands, Chippewa Plains, Tamarack Lowlands). High severity wind was highest in three DLP Subsections (Chippewa Plains, Pine Moraines and Tamarack Lowlands). Moderate severity wind was higher in the Chippewa Plains, Pine Moraines and Naswauk Uplands (Table 2a, 2b). The St. Louis Moraines, North Shore Highlands and Laurentian/Toimi showed the lowest frequency of high severity wind and fire. The percent of disturbance severity shows that the St. Louis Moraines, Pine Moraines, and Nashwauk Uplands were characterized by relatively even amounts of high and moderate severity disturbance. The Border Lakes and Tamarack Lowlands were dominated by higher severity disturbances (Figure 4a, 4b).

Table 2b. Rotation period estimates for subsections in the b) Northern Superior Uplands.

b)	Border Lakes		North Shore Highlands		Nashwauk Uplands		Laurentian/Toimi	
Disturbance Class	Rotation period	Annual % disturbed	Rotation period	Annual % disturbed	Rotation period	Annual % disturbed	Rotation period	Annual % disturbed
Fire-high severity	205	0.49	892	0.11	418	0.24	2,310	0.04
Fire-moderate	587	0.17	1,280	0.08	459	0.22	1,178	0.08
Fall-all	166	0.60	609	0.16	260	0.38	1,001	0.10
Wind-high severity	2,158	0.05	3,675	0.03	1,297	0.08	21,105	0.00
Wind-moderate	2,474	0.04	11,913	0.01	660	0.15	6,110	0.02
Wind-all	1,365	0.07	3,048	0.03	561	0.18	6,390	0.02
Dead-high severity	na	na	na	na	24,960	0.00	337	0.30
Dead-moderate	na	na	na	na	na	na	4,329	0.02
Dead-all	na	na	na	na	24,960	0.00	321	0.31
Flooded	5,952	0.02	37,923	0.00	na	na	128,072	0.00
All-high severity	182	0.55	705	0.14	312	0.32	290	0.35
All-moderate	712	0.14	1,734	0.06	406	0.25	1,206	0.08
All	145	0.69	501	0.20	177	0.57	234	0.43

<u>Settlement and Post-Euro-American Settlement Periods (1900-1995)</u>

Analysis of 1930s aerial photography data revealed substantial increases in fire frequency from the pre-Euro-American era in most subsections for the 1900-1940 period (Table 3). Interpreted fires were primarily stand replacing events. The Chippewa plains (383, 300 years) and Tamarack Lowlands (220, 175 years) showed similar values for both periods for high severity rotation estimates (Table 3a). Values for the 1900-1940 period varied little compared to the pre-Euro-American variability. Estimates for the 1900-1940 period (1930s photography) ranged from 87 years in the Laurentian/Toimi to 300 years in the Chippewa Plains. The greatest increases were in the St. Louis Moraines and North Shore Highlands, and Laurentian/Toimi, the subsections that showed the lowest probability of fire during the pre-Euro-American period. The St. Louis Moraines rotation periods for high severity fire changed from 2,775 years in the 1850-1890 period to 110 years in the

1900-1940 period, while the North Shore Highlands changed from 892 to 98 years, and the Laurentian/Toimi from 2,310 to 87 years. The more fire prone landscapes changed less over the two time periods (Table 3a).

Table 3a. Estimated fire rotation periods (years) for four time periods.1850s era data derive from GLO line note data, 1930s, 1970s and 1990s derived from interpreted aerial photography

	1850-1890			1930's	1970's	1990's
	High severity	Moderate	All fire			
Border Lakes	205	587	166	97	136	468
North Shore Highlands	892	1,280	609	98	200	1,032
Nashwauk Uplands	418	459	260	127	95	2,296
Laurentian/Toimi Uplands	2,310	1,178	1,001	87	168	675
Chippewa Plains	383	497	253	300	465	686
St. Louis Moraines	2,775	1,960	1,428	110	170	1,179
Pine Moraines	620	428	348	110	405	506
Tamarack Lowlands	220	498	170	175	637	916
Entire study area			296	116	190	725

The major trends in disturbance from 1940-1995 are decreases in fire frequency (longer rotation periods) and increases in timber harvest acres (shorter rotation periods)(Table 3a, 3b). By the 1990s, fire frequency had decreased significantly across all subsections. The more fire prone landscapes (Border Lakes, Chippewa Plains), with the exception of the Tamarack Lowlands, exhibited lower rates of change during the 1940-1995 period, while the St. Louis Moraines and North Shore Highlands showed the greatest decrease in fire frequency (Table 3a). The 1970s data shows variable changes in harvest rates, with strong increases in some subsections (Border Lakes, Laurentian/Toimi, Tamarack Lowlands), modest increases in others (St. Louis Moraines, Nashwauk Uplands, Pine Moraines) and decreases in others (North Shore Highlands, Chippewa Plains) (Table 3b). 1990s harvest rotation estimates reveal an increase in timber harvest rates from the 1970s across all subsections, although the Tamarack Lowlands showed negligible change (287-258 years). Rotation values were more uniform across subsections with only 1 subsection showing values over 200 years (Tamarack Lowlands) (Table 3b).

Table 3b. Timber harvest estimates derived from aerial photograph interpreted harvest patches.

	1930's		1970's		1990's	
Subsection	Annual % harvest	Rotation period (years)	Annual % harvest	Rotation period (years)	Annual % harvest	Rotation period (years)
Border Lakes	0.07	1,338	0.24	423	0.52	193
North Shore Highlands	0.30	330	0.20	495	0.73	136
Nashwauk Uplands	0.19	519	0.26	383	0.74	135
Laurentian/Toimi Uplands	0.22	455	0.54	184	0.98	102
Chippewa Plains	0.76	132	0.51	195	0.69	145
St. Louis Moraines	0.24	415	0.29	341	0.66	153
Pine Moraines	0.16	626	0.20	496	0.61	163
Tamarack Lowlands	0.18	557	0.35	287	0.39	258
Entire study area	0.26	385	0.31	323	0.66	152

Age Structure

Estimates of the expected pre-Euro-American age structure indicate variability across subsections. The Tamarack Lowlands, with the most frequent high severity disturbance showed both the highest value in the stand initiation phase and lowest value in the mature class. The Border Lakes, Pine Moraines, and Chippewa Plains show similar expected age structure with approximately 60% in the mature-multi-age class. The North Shore Highlands and St. Louis Moraines showed greater than 80% in the mature-multi-aged class. These subsections had the lowest frequency of high severity disturbances and disturbance patch sizes tended to be relatively small (Figure 5, Figure 6). The Laurentian\Toimi a combination of two subsections exhibited an age-structure intermediate between high and low frequency disturbance.

A comparison of expected age-structure classes from the pre-Euro-American period to 20th century age-structure estimated from aerial photography shows similar trends across subsections (Figure 5, Figure 6). In general, the 1930s and 1970s showed most of the area in the closed canopy and understory re-initiation phases with small percentages in the mature class. The 1990s revealed significant increases in the mature class as forest transitioned from the understory re-initiation class. Although, these values are well below those predicted from natural disturbance frequencies (1850s). All subsections, with the exception of the Border Lakes, and Tamarack Lowlands showed higher values in the stand initiation phase in the 1930s than would be expected under natural disturbance. The stand initiation phase declined in the 1970s and then increased in all subsections except the Tamarack Lowlands. The Border Lakes and North Shore Highlands showed the greatest increases in this category (Figure 5, Figure 6).

Aerial photography data for the 1990s compared with 2001 public land forest inventory reveals a strong correspondence between the 2 data sets (Figure 7, Figure 8). In general values for each age-class are within 5%. The Border Lakes shows a larger difference in the mature class, with the aerial photo indicating 18% and the inventory database showing 28%. This may be due to an under-sampling of the BWCAW by the aerial photo plot data.

Patch Size Analysis

<u>Sensitivity Analysis</u>

Applying transect theory calculations estimates the numbers of patches less than 2.24 km in length. We compared the delineated patch frequency and area to the totals derived from applying transect theory calculations (Table 4). The addition of transect estimated windthrow patches showed the greatest increase in frequency and area for both sections. Adding transect estimated windthrow patches showed increases of 187% in the NSU and 221% in the DLP compared with the original delineated patches. The addition of transect derived wind area yielded increases of 21% in the NSU, and 31% in the DLP. Transect estimated fire patches increased the total by 131% in the DLP and 148% in the NSU. Fire area in the DLP increased by 9% and by 17% in the NSU by adding transect estimated patches.

Table 4. Changes in disturbance patch frequency a) and patch area b) due to applying transect sampling to line note delineated patches.

a)

Section	Orig. Patches	Add. Patches	Total Patches	% Change
NSU-Wind	60	170	230	283
NSU-Fire	115	169	284	148
DLP-Wind	196	433	629	221
DLP-Fire	144	194	338	134

b)

Section	Orig. Area	Add. Area	Total Area (ha)	% Change
NSU-Wind	7,168	1,621	8,789	23
NSU-Fire	38,207	6,427	44,634	17
DLP-Wind	17,485	5,488	22,973	31
DLP-Fire	37,559	3,633	41,192	10

Section-Level Disturbance Patch Size

For sampled patches, mean patch sizes for fire were substantially higher than those for wind disturbance (Table 5). Maximum sampled patch sizes for fire were much greater than for wind. Adding estimated patches lowered the means and revealed similar values across sections. Mean patch size in hectares for sampled and estimated wind disturbance was 39 ha in the NSU and 37 in the DLP, while mean fire patch size ranged from 122 ha in the DLP to 157 in the NSU (Table 5).

Table 5. Mean patch size for delineated and total patches (sum of delineated and estimated patches).

	Delineated Patches				Total Patches	
Section	Frequency	Mean Patch Size (ha)	Std Dev	Range	Frequency	Mean Patch Size (ha)
DLP-fire	144	260	737	6,307	338	122
DLP-wind	196	89	257	2,395	315	37
NSU-wind	60	119	550	4,150	228	39
NSU-fire	115	332	1,037	8,150	284	157

Disturbance Patch Size Distributions

Analysis of disturbance patch sizes also showed significant variability between sections and subsections. The Border Lakes data indicate relatively high numbers of small windthrow patches (Figure 9a), but much of the area disturbed is accounted for by a few larger blowdowns in the 100-500 and 1000-5000 ha classes. The North Shore Highlands show a high frequency of small blowdowns (1-10 ha), but a most of the disturbed area comes from the 10-100 ha classes (Figure 9c). The Laurentian/Toimi and Nashwauk uplands show fewer wind disturbances with most occurring in the smaller size classes (1-10 ha). The Nashwauk Uplands have a much greater area in wind disturbance due to a few larger disturbances in the 100-500 and 1000-5000 ha classes (Figure 10a, 10c).

The Border Lakes exhibit high fire patch frequency in the 10-100 ha class, but with most of the area burned accounted for by the greater than 1000 ha classes. Most of the fire patches in the North Shore Highlands were small, (< 50 ha) (Figures 9b, 9d). The area burned was relatively evenly distributed between the smaller classes (< 50 ha) and the medium (50-100 ha) and larger size classes (> 1000 ha). The Nashwauk and Laurentian/Toimi uplands show fewer fire disturbance patches with the majority occurring in the 5-100 ha size classes. In the Nashwauk, most of the area was burned in a few large fire events (1000-5000 ha). The mid-range of size classes (50-500 ha) accounted for most of the burned area in the Laurentian/Toimi (Figure 10b, 10d).

In the DLP, the Pine Moraines and Tamarack Lowlands exhibited high frequency of windthrow patches in the smaller size classes (< 50 ha) (Figure 12a, 12c). Windthrow area in the Tamarack Lowlands was relatively evenly distributed among the small and medium patch size classes (10-50, 50-100, 100-500), while the Pine Moraine had high areas in the 10-50, 100-500 and 1000-5000 ha classes (Figure 12a, 12c). The Chippewa Plains and the St. Louis Moraines reveal a similar frequency distribution for windthrow, but with the Chippewa Plains showing patches in the 500-5000 ha classes (Figure 11a). This difference is reflected in the area disturbed, in which the Chippewa Plains shows a much greater windthrow area and substantial area in the larger size classes (> 500 ha) (Figures 11a, 11c).

The Pine Moraines had a high frequency of fire patches in the small classes, but also had patches in the medium and larger size classes (100-5000 ha) where most of the disturbed area occurs (Figure 12b). The Chippewa Plains had an even distribution of patches in classes ranging from 1-500 ha with some patches in the > 500 ha classes (Figure 11b). Area burned was concentrated in the 100-1000 and > 5000 ha classes (Figure 11b). The St. Louis Moraines showed relatively high numbers of small patches (< 50 ha) and a low area burned (Figure 11d). The Tamarack Lowlands exhibited high fire patch frequency in the 10-100 ha classes, but also had significant numbers in the 100-500 and 500-5000 ha classes (Figure 12d). Disturbed area was concentrated in the 100-5000 ha classes.

<u>Pre-Euro-American, 1930s, 1970s, and 1990s Fire Disturbance Patches</u>

Because of the differences in data sources, plot sizes and interpretation methods, patch size comparisons between GLO line note derived data and interpreted aerial photography should be made with qualifications. Fire patch sizes are limited in size by the spatial extent of the aerial photo plots, so some recorded fires likely were significantly larger than recorded in the aerial photo sample. Aerial photo interpretation allowed for more discrete interpretation of disturbance patches. However, given the overall changes in fire frequency from the 1850s to the 1990s, it is likely that mean fire patch size has declined from the 1850-1890 period to the 1990s (Table 7). Data indicate that fire patch size has become both smaller and more uniform as evidenced by subsection mean and range values. Some subsections showed relatively small changes in mean size, but much greater changes in the range of sizes, again this is limited to some degree by the difference in plot size. Mean patch sizes during the 1900-1940 period were generally larger than those detected in the 1970s and 1990s. The Border Lakes and North Shore Highlands had relatively higher mean patch size in the 1990s, however this was due to the effect of a few larger fire events (Table 7).

Table 6. Mean hectares for windthrow disturbances for the pre-Euro-American period.

	Mean	Range
Border Lakes	30	1,155
North Shore Highlands	13	88
Nashwauk Uplands	207	4,151
Toimi-Laurentian Uplands	17	146
Chippewa Plains	119	2,260
St. Louis Moraines	37	201
Pine Moraines	30	2,395
Tamarack Lowlands	22	399

Table 7. Mean hectares for subsection level fire patch size for four dates.

	1850		1930		1970		1990	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Border Lakes	235	8,148	27	499	40	737	275	799
North Shore Highlands	54	2,671	47	641	37	336	102	153
Nashwauk Uplands	415	2,826	35	206	34	342	19	41
Toimi-Laurentian Uplands	87	634	34	397	20	174	33	177
Chippewa Plains	220	6,306	65	329	25	89	19	101
St. Louis Moraines	23	324	53	599	32	309	30	113
Pine Moraines	89	4,302	25	295	52	152	42	131
Tamarack Lowlands	226	4,004	60	299	20	119	16	61

A comparison of relative patch size distributions also for the 1850s-1900 and 1900-1940s periods showed both similarities and differences within subsections. The 1930s Border Lakes data showed higher proportions of patches in the < 50 ha size class (87%) and 55% of the area burned in the < 100 ha size classes. The 1850s era data showed about 60% of patches in the < 50 ha classes and 85% of the area burned in the > 500 ha classes (Figure 13a, 13b). The North Shore Highlands exhibited strong similarities in both the percent distribution of patches and in percent area burned by size class. Both time periods show > 80% of patches in the < 50 ha size classes, and 60% or more of the area burned in the > 100 ha size classes (Figure 13c, 13d).

The Nashwauk Uplands showed much higher proportions of patches in the < 10 ha classes in the 1930s data, but both 1850s and 1930s data had > 70% of the area burned in the > 100 ha size classes (Table 9e, 9f). Both the Chippewa plains and the Pine Moraines revealed similar percent distribution by patch size class between the 2 dates. The main differences between the two dates for these two patch size distributions are the presence of patches in the > 500 ha size classes in the 1850s data (Figure 14a, 14c). Percent area burned also showed similar patterns across the two dates for these subsections (Figure 14b, 14d).

<u>1930s, 1970s, and 1990s Harvest Patches</u>

Mean harvest patch size showed an overall decline from the 1930s to the 1990s (Table 8). The North Shore Highlands (-68%), Chippewa Plains (-50%), and St. Louis Moraines (-41%) exhibited the greatest decreases in mean harvest patch from the 1930s-1990s. The Tamarack Lowlands and Laurentian/Toimi showed little change in mean harvest patch size. An examination of size class distributions for all three time periods revealed that 80-85% of patches were in the less than 50 ha size classes, and greater than 90% occurred in the less than 100 ha classes (Table 11, Table 12). The Chippewa Plains and Nashwauk Uplands exhibited declines in the percent of area in size classes greater than 100 ha. The Border Lakes and St. Louis Moraines showed increases in the greater than 100 ha size classes.

Table 8.Mean hectares and range for timber harvest patch size.

	1930		1970		1990	
	Mean	Range	Mean	Range	Mean	Range
Border Lakes	15	65	15	94	23	200
North Shore Highlands	57	707	20	110	18	152
Nashwauk Uplands	19	125	18	122	12	74
Toimi-Laurentian Uplands	17	62	16	231	19	203
Chippewa Plains	20	118	10	79	10	81
St. Louis Moraines	17	79	14	100	14	194
Pine Moraines	17	96	8	38	10	110
Tamarack Lowlands	14	44	15	68	11	96

Mean fire patch sizes for the pre-Euro-American period (1850-1890) were substantially larger than mean harvest patch sizes for the 1930s, 1970s, and 1990s, with the exception of the St. Louis Moraines, which had small and infrequent fire disturbances in the pre-Euro-American period (Table 7, Table 8). A comparison of natural disturbance patch size distributions (1850-1890) with harvest patches showed that in general, a much greater proportion of the area disturbed occurred in the > 100 ha size classes during the 1850-1890 period (Tables 9,10, 11, 12). In most subsections, the > 100 ha size classes accounted for 60-90 of area burned. By the middle of the 20^{th} century, timber harvest had replaced fire as the primary disturbance factor in these forests. By the 1990s, with the exception of the Border Lakes and Laurentian/Toimi Uplands, harvest in > 100 ha classes accounted for < 15% of area harvested by subsection (Table 11, Table 12). The St. Louis Moraines showed more similarity in pattern between pre-Euro-American fire and 1930s era timber harvest patches (Tables 10, 12).

Mean harvest patch sizes and pre-Euro-American windthrow were generally similar in size; mean patch size for wind disturbance patches during the pre-Euro-American period were less than 40 ha for most subsections (Table 6, Table 8). The Nashwauk Uplands and Chippewa Plains, both with high windthrow frequencies, had larger mean patch sizes (207 ha, 119 ha).

Discussion

Pre-Euro-American Settlement Disturbance estimates

Although section line notes, interpreted patches and section corner data all provided generally similar disturbance frequency estimates, there were some notable differences. Section corner data tended to estimate longer rotation periods, particularly for windthrow. Based on our patch data, windthrow patch sizes are typically smaller than fire. One explanation for the differences in rotation estimates may be that section corners do not sample small wind disturbances as well as section lines that traverse the landscape. Essentially, small disturbance may be less likely to be recorded at section corners.

Fire rotation estimates derived in this study are similar to estimates from other studies in the mixed forest province of Minnesota. The BWCAW, encompassed by the Border Lakes subsection has the most complete record of fire history in the region. The fire chronology, developed from tree-ring data ranges from 1577 to 1972 (Heinselman 1973). Heinselman estimated a 100 year rotation period for stand replacing fires in the BWCAW as a whole but noted substantial variability related to fuel distributions, vegetation type, physiographic factors, lightning and human ignition, and climatic variation. Frelich (1999) summarized the disturbance rotation period estimates for ecosystems in the Northern Superior Uplands ecological section. Fire rotation estimates were based primarily on BWCAW fire history data. Stand replacing fire rotation ranged from 150-300 years for mesic white pine-red pine, dry-mesic Jack pine-black spruce ranged from 50-100 years, and mesic-birch-aspen-fir-spruce ranged from 100-200 years (Frelich 1999). Analysis of the tree-ring fire scar record for red-white pine ecosystems in Itasca State showed frequent maintenance fire (10-40 years) and stand replacing fire at 100-300 year cycles (Frissel 1973). Our estimates of 200 years for stand replacing fire in the Border Lakes and 383 for the Chippewa Plains were on the long end of the range that these studies show. In hemlock-hardwood forests of Michigan's Upper Peninsula, Frelich and Lorimer (1991) reported stand replacing fire rotation periods ranging from 800 to 3,687 years for 3 sites, and a value of 2,797 for all sites combined. The subsections with significant amounts of northern hardwood forest (North Shore Highlands, St. Louis Moraines) all showed values within this range. These results indicate that the GLO data can produce similar result to studies involving detailed tree-ring sampling and analysis.

Moderate severity fire rotation estimates from this study are substantially longer than those reported the literature (Frissel 1973, Heinselman 1973). Our estimates are for the whole subsection landscape and include fire dependent and non-fire dependent ecosystems. In addition, GLO line note data may not have recorded low severity maintenance fire events that can be recorded by fire-scarred trees. After initial scarring, fire scarred trees can become relatively sensitive recorders of lower severity fire events (Arno and Sneck 1977). Whitney (1986) and Schulte and Mladenoff (2003) suggest that surveyors only recorded higher severity disturbance events. Our classification of disturbance severity fits well with the native plant communities that predominate in each subsection. In the Border Lakes Subsection where Jack pine and mesic-aspen-birch conifer systems high severity fire comprised 80% of fire disturbance (Figure 4b). The primary plant communities in the Pine Moraines subsection were dry-mesic pine systems maintained by low intensity fire. High and moderate severity fire has equal proportions in this subsection (Figure 4a).

Our estimates of catastrophic windthrow are within the ranges recorded in other studies. Canham and Loucks (1984) estimated 1210 rotation period for catastrophic windthrow in the forested region of Wisconsin. Zhang et al. (1999) determined a 546-year wind rotation period for the Luce District landscape in Michigan's Upper Peninsula. Frelich and Lorimer (1991) estimated a rotation period of > 1500 years for high intensity windthrow (> 60% canopy removal) for hemlock-northern hardwood forests in Michigan's Upper Peninsula. In the mixed forest region of Wisconsin, Schulte and Mladenoff (2003) showed wind rotation estimates ranging from 465 to > 10,000 years. Estimates in this study where northern hardwood systems are prominent (St. Louis Moraines, 2,775 years, North Shore Highlands, 3,675 years) are within the range of values derived by Frelich and Lorimer (1991).

Disturbance Frequency Changes: 1900-1995

Results indicate a period of increased fire frequency from approximately 1900 to the middle 1930s. Heinselman (1973) documented increased fire frequency in the BWCAW region from 1868 to 1911, which was at least partially attributed to settlement activity. Heinselman notes that this difference may be due in part to an artifact of fire scar sampling in which subsequent fires remove evidence of earlier fires. Numerous large fire events have been documented during the settlement period, fueled by logging slash and extreme climate conditions, however, this study is the first to quantify changes in fire frequency from pre-Euro-American settlement, through the settlement and post-settlement periods to current conditions. Fires recorded in the 1930s era photography represent disturbances that occurred from approximately 1900 to the late 1930s (S. Robinson pers. Comm..).

It is notable that high disturbance frequencies derived from the 1930s data were relatively uniform across the both sections (Table 3a). During the pre-Euro-American period, fire frequency varied considerably across subsections (Table 3a). In some subsections, fire frequency was likely still within the natural ranges (Border Lakes, Chippewa Plains, Tamarack Lowlands), but in other subsections the rate or hazard of burning increased dramatically (North Shore Highlands, St. Louis Moraines). This led to a large pulse of regenerating forest and created more uniform forest composition and age-structure across the DLP and NSU (Brown and White 2002a, 2002b) (Figure 5, Figure 6). Analysis of the distribution of native ecosystems during the pre-Euro-American period (Shadis 2000, White and Host 2002), their age structure (Frelich 1999, Frelich 2000) and composition (White 2001a, 2001b, 2001c) showed significant variation across the NSU and DLP. The legacy of this pulse of frequent, high intensity disturbance was a more homogeneous forest landscape where dominance shifted from later successional or mid-seral conifer and hardwood species (white pine, white spruce, black spruce, balsam fir, white cedar, tamarack, red oak, yellow birch) to early successional sprouting hardwood species (Populus spp., paper birch) (White 2001a, 2001b, 2001c).

During the post-1930s period, timber harvest replaced fire as the primary disturbance factor in NSU and DLP (Table 3b). By the 1990s rotation periods for timber harvest were relatively similar across the region (Table 3b). Wolter and White (2002) used Landsat Thematic Mapper data from 1990 and 1995 to quantify short- term change in northeastern MN. They found similar rates of harvest disturbance (0.84 % per year, 120 year rotation period) to the values reported in this study. Puettman et al. (1996) surveyed landowners and managers in Minnesota on harvested acres and silvicultural practices. Their data showed approximately 1%/year harvest rate for commercial timberland. Deegan et al. (2001) also determined a rate of approximately 1%/year for commercial forestland. This study and Wolter and White (2002) showed lower annual rates, however both studies included lands in addition to commercial forestland. The predominately even-aged management practiced during this time period favors the regeneration of sprouting hardwood species (Wolter and White 2002). The relatively uniform application of even-aged management across the study region should tend to perpetuate the composition and structure changes brought about by the combination of timber harvest and high severity fire during the 1990-1940 period.

Landscape Scale Age-Structure Change

The expected age-structure estimates derived from disturbance frequency values were calculated at the subsection level, and thus do not take into account variability by ecosystem type within a subsection. Many of the native plant communities of the DLP and NSU were maintained by lower severity understory fire (e.g. dry-mesic white pine-red pine, dry-mesic pine-oak, mesic white pine-red pine). The expected age-structures presented here may not account for these types of disturbances, but they do show similar age distributions to native plant community based disturbance models (Frelich 1999, 2000). In the RNV models developed for the NSU and DLP maintenance fire effects composition of growth stages but not stand replacing fire probability (Frelich 1999, 2000).

Age-structure in the region shifted from the pre-Euro-American dominance of later successional stages to the closed-canopy and understory re-initiation phases in the post-settlement era (Figure 5, 6). The landscape age-structure that developed post 1930 showed similar patterns across subsections with 70-90% of the forest in the closed canopy and understory-reinitiation phases recorded in the 1930s and 1970s. The 1990s showed movement from the understory-reinitiation to the mature-multi-aged phase, with higher values occurring in the Border Lakes and Tamarack Lowlands. The higher amounts of mature forest in the Border Lakes are likely due to the protected status of much of the land area limiting timber harvest (BWCAW and Voyageurs National Park). The Tamarack Lowlands landscape bears the most similarity to the pre-Euro-American expected age distribution with 31% in the mature class. Harvest rotation rates for this area have been significantly lower than natural disturbance frequencies (Table 2a, 3b) allowing more land area to move into the mature class. As this landscape is dominated by lowland conifer ecosystems, it may be that low demand for these wood products led to the lower harvest rates.

The strong correspondence between the aerial photography interpreted age-classes and the age classes derived from public inventory indicate that the aerial photography can be a useful tool for monitoring forest composition and age-structure or vegetation growth stages (Figures 7, 8).

Pre-European Landscape Structure and Post-settlement Changes

We believe that the application of transect theory calculations produced reasonable results for estimating disturbance patches with mean patch lengths < 2.24 km. Estimates of disturbance frequencies based the patch data produced slightly shorter rotation estimates that the line data, but still well within documented disturbance values. In general, landscapes characterized by small patches had the greatest increases in patch numbers when adding patches estimated from transect calculations (St. Louis Moraines, North Shore Highlands). This is reasonable as the smallest disturbances have the lowest probability of meeting a section line.

Relative patch size and area distributions for the 1850s and 1930s periods revealed similar patterns for a number of subsections including the Border Lakes, North Shore Highlands, Chippewa Plains and Pine Moraines. The similarities in patch size distribution from two similar time periods indicate that these different methods and data sources can produce reasonably comparable results when using broad size class distributions (Figure 13, 14). The major limitation to this comparison may be the smaller plot size for the aerial photo interpretation. It is well known that during the 1900-1940 period there were large catastrophic fires that covered > 100,000 ha in the region (Haines and Sando 1969). Thus, differences in the larger size classes should be viewed with caution.

This analysis of disturbance patch size distribution highlights the variability in patch sizes and frequency across the NSU and DLP landscapes and helps in describing the natural character of these landscapes. Although the mean patches sizes for fire and wind respectively, are similar at the section level (Table 5) analysis of subsection level means and distributions shows considerable variability (Table 6, 7, Figures 9-12). The North Shore Highlands and St. Louis Moraines were characterized by less frequent, smaller disturbances creating a fine-grained structure. The Border Lakes, Nashwauk Uplands, and Tamarack Lowlands had large infrequent large fires punctuated with smaller fire and wind events. The Chippewa plains had both large wind and fire events. The Pine Moraines were characterized by frequent smaller wind and fire disturbances with a more even areal distribution. The disturbance patch size distributions should also be viewed in the context of disturbance severity. In the Border Lakes and Tamarack Lowlands, approximately 80% of fire disturbance was classified as high severity, whereas the proportions were more even in the Pine Moraines and St. Louis Moraines (Figure 4).

With the subsequent shift to timber harvest as the primary disturbance factor a new pattern has been imposed on the forest landscape distinguished by a more uniform structure dominated by small forest patches in the 10-25 ha range (Table 8). Although there is variability between subsections likely related to soil and landform differences, management likely exerts the greatest influence on forest landscape pattern and structure (Host and White 2003, Wolter and White 2002).

Conclusions

1) GLO line note data can produce similar fire frequency values to estimates derived from tree-ring analysis in the Mixed Forest Province of the lake states region.

2) Estimates for catastrophic windthrow derived from GLO data in this study are similar to or within the range of those derived in other studies in northern lake states forests.

3) GLO section corner data tended to provide longer rotation periods for wind disturbance than GLO line and patch data. We hypothesize that since windthrow patches were typically small, they are more likely to be sampled by line traverse

4) Natural disturbance frequency, severity and accompanying patch size distributions varied considerably across the eight subsections we studied. Natural disturbance, interacting with soils, landforms and climate produced characteristic landscape pattern and structure in eight subsections.

5) The settlement period 1900-1930 produced a short-term increase in fire frequency across the DLP and NSU creating a pulse of regeneration favoring sprouting species. The disturbance frequencies were relatively uniform across the two sections during this time period, in contrast the significant variability in the pre-Euro-American landscape.

6) The high and relatively uniform disturbance frequencies across the DLP and NSU led to greater homogeneity across the landscape in terms of composition, age-structure and spatial patterns.

7) Age-structure in the region shifted from the pre-Euro-American dominance of later successional stages to the closed-canopy and understory re-initiation phases in the post-settlement era. The landscape age-structure that developed post 1930 showed similar patterns across subsections with 70-90% of the forest in the closed canopy and understory-reinitiation phases recorded in the 1930s and 1970s. The 1990s showed movement from the understory-reinitiation to the mature-multi-aged phase, with higher values occurring in subsections with lower management intensity (Border Lakes and Tamarack Lowlands).

8) Harvest rates increased from the 1930s to 1990s, and by the 1990s were relatively uniform across the landscape. Harvest rate estimates from this study were in the same range as reported by other studies using different methods. The relatively uniform application of even-aged management across the study region should tend to perpetuate the composition and structure changes brought about by the combination of timber harvest and high severity fire during the 1900-1940 period.

9) In the post-settlement period (1940-1995), timber harvest replaced fire as the dominant disturbance factor. Similar management practices across subsections created more similar rotation periods across the study region. These management practices also imposed a pattern dominated by small (10-25 ha) patches across the landscape. Management practices now have a greater influence than natural processes in the generation of landscape pattern and forest age-structure in the Mixed Forest Province of Minnesota.

10) The GLO data have been shown to be a valuable information source for assessing historic forest conditions. Interpreted aerial photography data is a useful tool for monitoring forest conditions including age-structure classes.

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Additional Tables

Table 9. Percent area burned and percent patches by size class (ha) for the NSU.

Border Lakes: Percent area burned a)

	1850	1930	1970	1990
1-5	0.1	2.4	1.7	0.3
5-10	0.5	5.8	3.9	0.0
10-50	4.3	31.6	16.5	2.6
50-100	6.9	15.6	10.6	0.0
100-500	5.0	44.6	41.2	0.0
500-1000	7.5	0.0	26.1	97.0
1000-5000	17.4	0.0	0.0	0.0
5000-10000	58.1	0.0	0.0	0.0

Border Lakes: Percent burned patches b)

	1850	1930	1970	1990
1-5	9.4	26.8	31.4	33.3
5-10	15.1	20.3	22.9	0.0
10-50	36.6	40.5	30.0	33.3
50-100	24.7	5.9	5.7	0.0
100-500	7.1	6.5	8.6	0.0
500-1000	3.1	0.0	1.4	33.3
1000-5000	2.0	0.0	0.0	0.0
5000-1000	2.0	0.0	0.0	0.0

North Shore:Percent area burned c)

	1850	1930	1970	1990
1-5	0.7	0.9	2.9	1.1
5-10	2.0	2.7	3.0	0.0
10-50	23.7	20.2	15.0	0.0
50-100	15.1	14.9	21.1	0.0
100-500	10.4	40.4	58.1	98.9
500-1000	0.0	20.8	0.0	0.0
1000-5000	48.0	0.0	0.0	0.0
5000-10000	0.0	0.0	0.0	0.0

North Shore: Percent burned patches d)

	1850	1930	1970	1990
1-5	22.3	23.1	33.3	33.3
5-10	14.4	16.9	16.7	0.0
10-50	48.6	40.0	31.0	0.0
50-100	10.9	9.2	11.9	0.0
100-500	2.9	9.2	7.1	66.7
500-1000	0.0	1.5	0.0	0.0
1000-5000	1.0	0.0	0.0	0.0
5000-1000	0.0	0.0	0.0	0.0

Nashwauk Uplands: Percent area burned e)

	1850	1930	1970	1990
1-5	0.0	0.6	1.7	0.9
5-10	0.2	4.4	5.9	7.7
10-50	0.6	28.7	20.3	91.4
50-100	7.2	23.3	14.5	0.0
100-500	6.6	43.0	57.5	0.0
500-1000	5.6	0.0	0.0	0.0
1000-5000	79.9	0.0	0.0	0.0
5000-10000	0.0	0.0	0.0	0.0

Nashwauk Uplands: Percent burned patche f)

	1850	1930	1970	1990
1-5	0.0	18.0	27.5	20.0
5-10	12.6	22.0	27.5	20.0
10-50	9.6	38.0	30.4	60.0
50-100	41.0	12.0	7.2	0.0
100-500	22.3	10.0	7.2	0.0
500-1000	3.6	0.0	0.0	0.0
1000-5000	10.9	0.0	0.0	0.0
5000-1000	0.0	0.0	0.0	0.0

Toimi-Laurentian: Percent area burned g)

	1850	1930	1970	1990
1-5	0.3	1.4	4.4	2.3
5-10	1.2	3.6	10.3	2.1
10-50	5.2	34.8	39.3	25.9
50-100	17.2	21.4	20.6	15.5
100-500	62.0	38.8	25.4	54.2
500-1000	14.1	0.0	0.0	0.0
1000-5000	0.0	0.0	0.0	0.0
5000-10000	0.0	0.0	0.0	0.0

Toimi-Laurentian: Percent burned patches h)

	1850	1930	1970	1990
1-5	9.4	18.7	28.8	30.0
5-10	12.9	17.3	27.3	10.0
10-50	20.9	46.7	34.8	40.0
50-100	21.2	10.7	6.1	10.0
100-500	33.7	6.7	3.0	10.0
500-1000	1.9	0.0	0.0	0.0
1000-5000	0.0	0.0	0.0	0.0
5000-1000	0.0	0.0	0.0	0.0

Table 10. Percent area burned and percent patches by size class (ha) for the DLP.

Chippewa Plains: Percent area burned a)

	1850	1930	1970	1990
1-5	0.3	0.9	1.8	4.1
5-10	0.8	1.4	6.0	6.0
10-50	1.1	7.8	46.9	46.5
50-100	3.8	21.7	45.4	16.2
100-500	29.7	68.3	0.0	27.3
500-1000	7.4	0.0	0.0	0.0
1000-5000	0.0	0.0	0.0	0.0
5000-10000	56.9	0.0	0.0	0.0

Chippewa Plains: Percent burned patches b)

	1850	1930	1970	1990
1-5	25.0	23.1	22.7	30.0
5-10	23.8	15.4	18.2	15.0
10-50	10.5	23.1	45.5	45.0
50-100	11.0	15.4	13.6	5.0
100-500	25.8	23.1	0.0	5.0
500-1000	2.0	0.0	0.0	0.0
1000-5000	0.0	0.0	0.0	0.0
5000-10000	2.0	0.0	0.0	0.0

St. Louis Moraines: Percent area burned c)

	1850	1930	1970	1990
1-5	3.4	0.5	2.0	5.0
5-10	1.3	2.3	2.9	4.6
10-50	49.6	15.4	37.6	24.4
50-100	26.1	32.4	5.4	0.0
100-500	19.6	17.9	52.1	65.9
500-1000	0.0	31.5	0.0	0.0
1000-5000	0.0	0.0	0.0	0.0
5000-10000	0.0	0.0	0.0	0.0

St. Louis Moraines: Percent burned patches d)

	1850	1930	1970	1990
1-5	35.9	19.4	26.3	33.3
5-10	5.4	16.7	13.2	16.7
10-50	49.1	30.6	50.0	33.3
50-100	8.2	25.0	2.6	0.0
100-500	1.4	5.6	7.9	16.7
500-1000	0.0	2.8	0.0	0.0
1000-5000	0.0	0.0	0.0	0.0
5000-10000	0.0	0.0	0.0	0.0

Pine Moraines: Percent area burned e)

	1850	1930	1970	1990
1-5	0.9	3.3	0.5	0.1
5-10	0.1	5.4	0.0	1.2
10-50	11.1	28.0	17.3	34.6
50-100	6.4	13.3	22.1	39.9
100-500	22.4	50.0	60.1	24.2
500-1000	17.0	0.0	0.0	0.0
1000-5000	42.1	0.0	0.0	0.0
5000-10000	0.0	0.0	0.0	0.0

Pine Moraines: Percent burned patches f)

	1850	1930	1970	1990
1-5	35.8	34.6	23.1	7.7
5-10	1.9	19.2	0.0	7.7
10-50	43.6	34.6	38.5	53.8
50-100	7.2	4.8	15.4	23.1
100-500	8.2	6.7	23.1	7.7
500-1000	2.0	0.0	0.0	0.0
1000-5000	1.4	0.0	0.0	0.0
5000-10000	0.0	0.0	0.0	0.0

Tamarack Lowlands: Percent area burned g)

	1850	1930	1970	1990
1-5	0.0	0.5	0.5	3.7
5-10	0.0	1.8	0.0	0.0
10-50	5.3	7.7	19.9	63.2
50-100	7.6	30.1	22.1	33.1
100-500	18.8	59.9	57.5	0.0
500-1000	18.2	0.0	0.0	0.0
1000-5000	50.0	0.0	0.0	0.0
5000-10000	0.0	0.0	0.0	0.0

Tamarack Lowlands: Percent burned patches h)

	1850	1930	1970	1990
1-5	2.2	17.6	23.1	33.3
5-10	0.0	17.6	30.8	0.0
10-50	40.1	23.5	38.5	58.3
50-100	23.5	23.5	0.0	8.3
100-500	22.3	17.6	7.7	0.0
500-1000	5.9	0.0	0.0	0.0
1000-5000	5.9	0.0	0.0	0.0
5000-10000	0.0	0.0	0.0	0.0

Table 11. Percent area harvested and percent patches for the NSU.

Border Lakes: Percent harvested area a)

Size Class (ha)	1930	1970	1990
1-5	4	6	4
5-10	8	11	5
10-50	66	66	39
50-100	22	16	3
100-500	0	0	49
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Border Lakes: percent patches b)

Size Class (ha)	1930	1970	1990
1-5	26	32	37
5-10	16	22	15
10-50	53	42	40
50-100	5	3	1
100-500	0	0	7
500-1000	0	0	1
1000-5000	0	0	0
5000-10000	0	0	0

North Shore: Percent harvested area c)

Size Class (ha)	1930	1970	1990
1-5	1	4	5
5-10	1	9	9
10-50	20	37	54
50-100	0	32	13
100-500	0	17	19
500-1000	77	0	0
1000-5000	0	0	0
5000-10000	0	0	0

North Shore: percent patches d)

Size Class (ha)	1930	1970	1990
1-5	31	28	31
5-10	13	28	21
10-50	50	31	42
50-100	0	9	4
100-500	0	3	2
500-1000	6	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Nashwauk Uplands: Percent harvested area e)

Size Class (ha)	1930	1970	1990
1-5	6	3	6
5-10	9	17	14
10-50	39	48	66
50-100	17	11	14
100-500	29	21	0
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Nashwauk Uplands: percent patches f)

Size Class (ha)	1930	1970	1990
1-5	35	15	33
5-10	22	36	24
10-50	35	42	40
50-100	4	3	3
100-500	4	3	0
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Toimi-Laurentian:Percent harvested area g)

Size Class (ha)	1930	1970	1990
1-5	4	6	4
5-10	7	14	10
10-50	52	39	46
50-100	37	22	18
100-500	0	19	22
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Toimi-Laurentian: percent patches h)

Size Class (ha)	1930	1970	1990
1-5	29	35	24
5-10	18	28	24
10-50	43	31	44
50-100	11	5	5
100-500	0	1	3
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Table 12. Percent area harvested and percent patches for the DLP.

Chippewa Plains:Percent harvested area a)

Size Class (ha)	1930	1970	1990
1-5	3	11	13
5-10	6	18	17
10-50	65	59	61
50-100	14	12	9
100-500	12	0	0
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Chippewa Plains: percent patches b)

Size Class (ha)	1930	1970	1990
1-5	22	44	48
5-10	16	24	23
10-50	56	30	28
50-100	4	1	1
100-500	2	0	0
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

St. Louis Moraines:Percent harvested area c)

Size Class (ha)	1930	1970	1990
1-5	5	7	7
5-10	6	11	16
10-50	73	66	55
50-100	16	16	8
100-500	0	0	14
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

St. Louis Moraines: percent patches d)

Size Class (ha)	1930	1970	1990
1-5	30	37	33
5-10	13	23	30
10-50	53	37	35
50-100	3	2	2
100-500	0	0	1
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Pine Moraines:Percent harvested area e)

Size Class (ha)	1930	1970	1990
1-5	3	13	12
5-10	13	18	17
10-50	35	69	50
50-100	48	0	15
100-500	0	0	7
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Pine Moraines: percent patches f)

Size Class (ha)	1930	1970	1990
1-5	21	48	47
5-10	32	19	23
10-50	36	33	27
50-100	11	0	2
100-500	0	0	1
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Tamarack Lowlands:Percent harvested area g)

Size Class (ha)	1930	1970	1990
1-5	2	5	9
5-10	9	9	19
10-50	89	54	48
50-100	0	31	24
100-500	0	0	0
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Tamarack Lowlands: percent patches h)

Size Class (ha)	1930	1970	1990
1-5	18	40	41
5-10	18	18	28
10-50	64	35	28
50-100	0	8	3
100-500	0	0	0
500-1000	0	0	0
1000-5000	0	0	0
5000-10000	0	0	0

Figures

Figure 1. Aerial photography and GLO line note plot locations within subsections of the Northern Superior Uplands and Drift and Lake Plains Sections of the Laurentian Mixed Forest Province

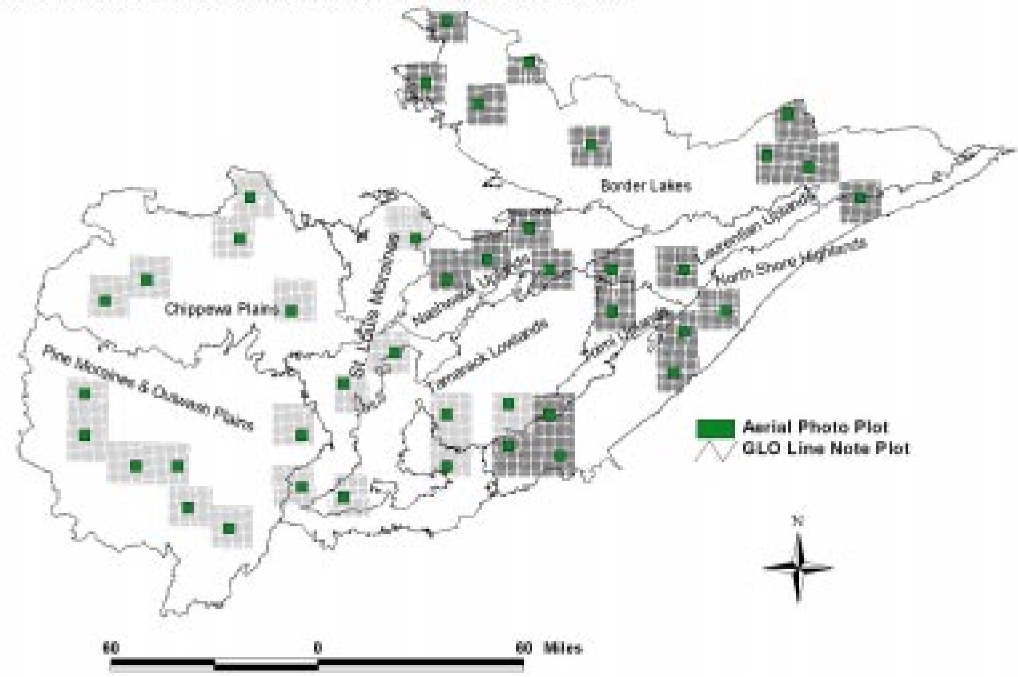


Figure 2. Delineated disturbance patches in plots la-17, 18, and 9.

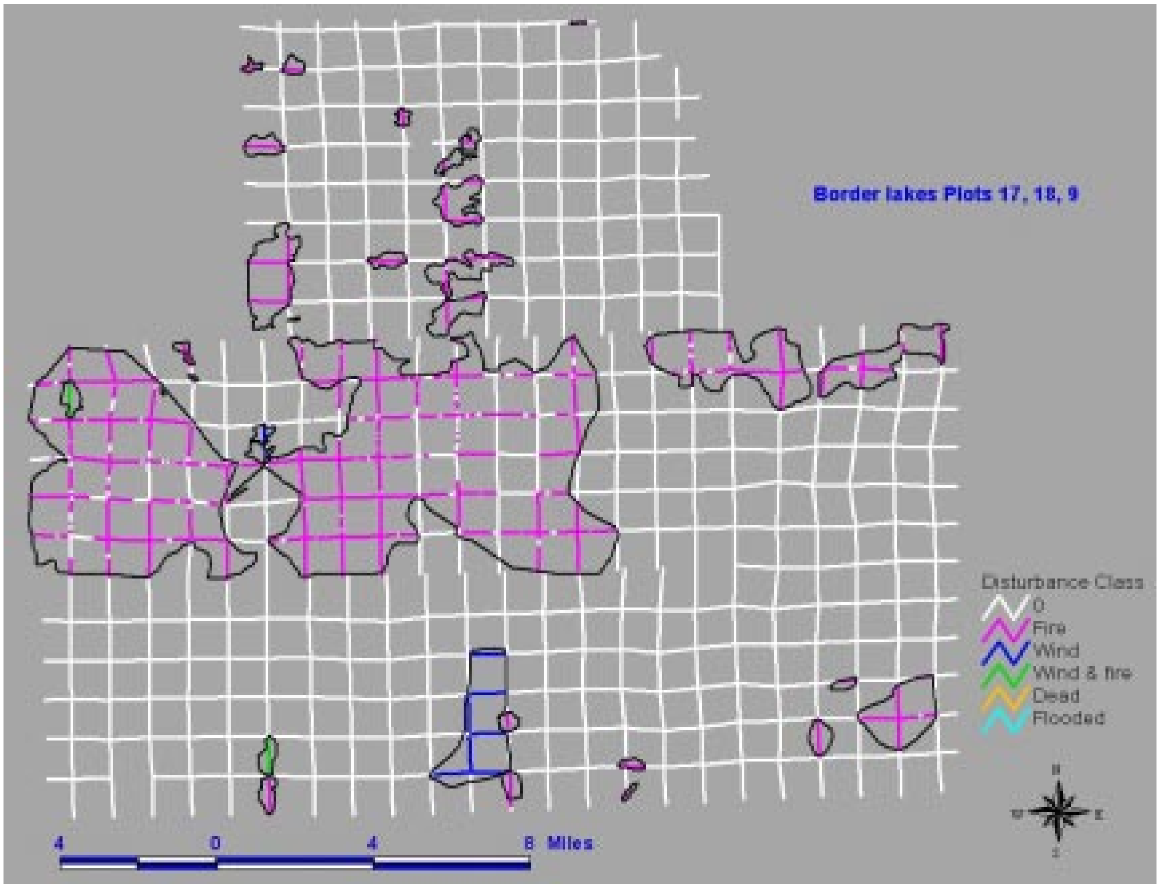


Figure 3. Delineated disturbance patches with water and topographic features (plot la-17).

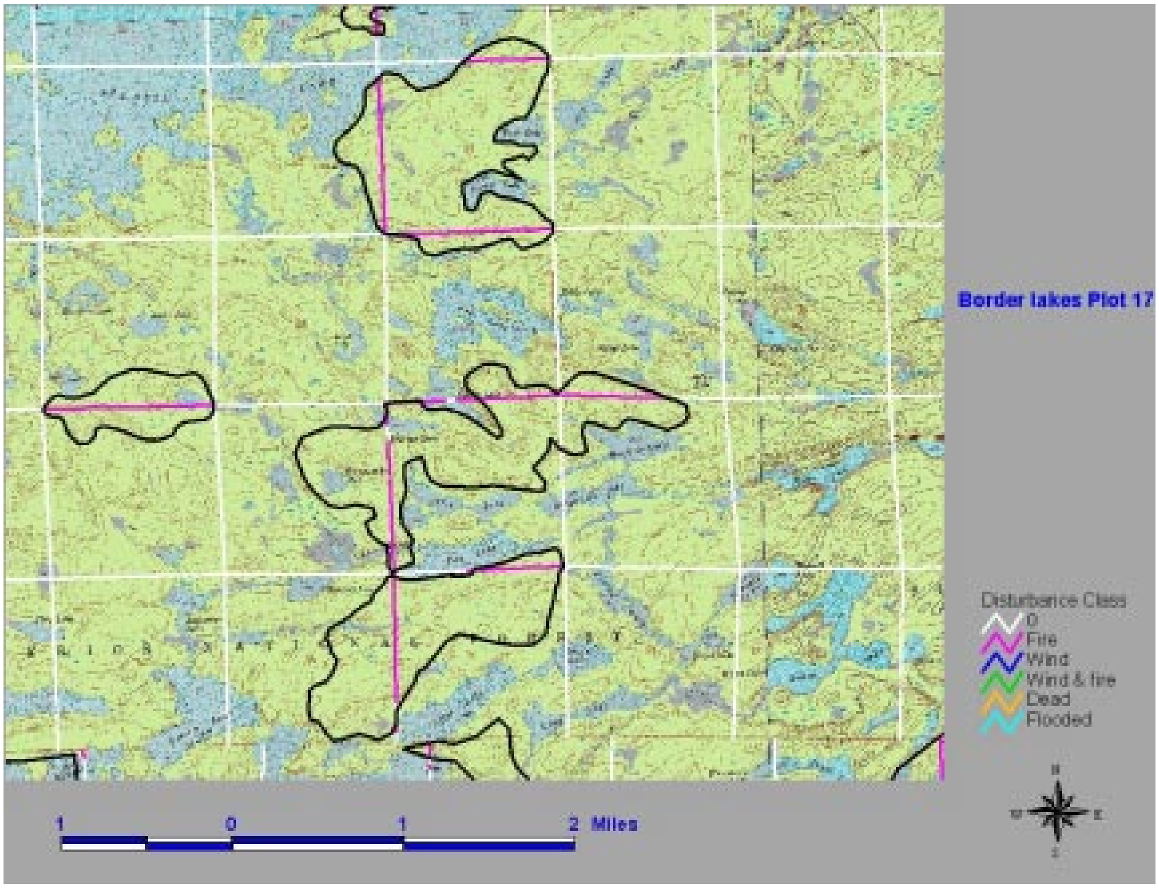
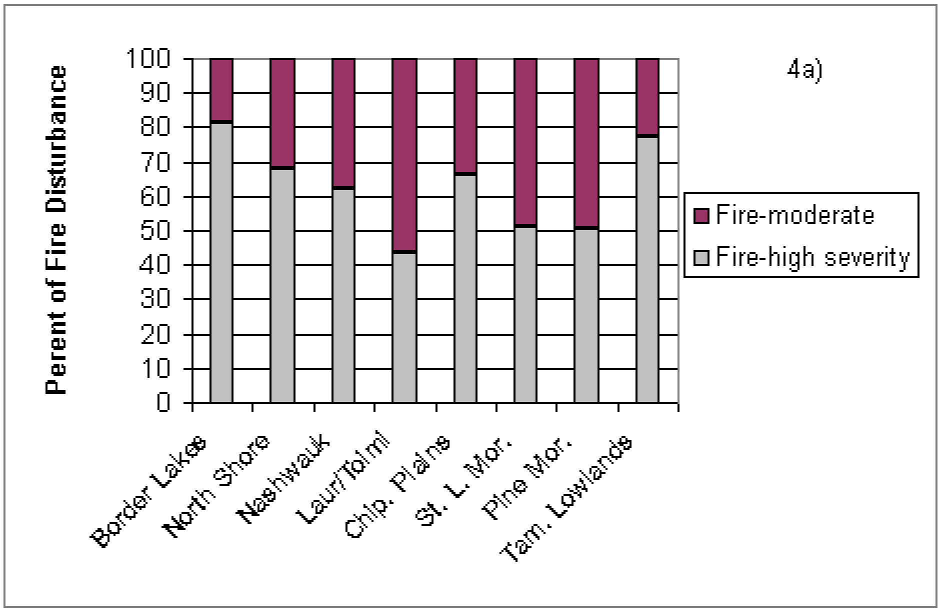


Figure 4. Percent of fire a) and wind disturbance b) by severity class. Percentages are calculated as the percent of line length in each severity class for fire and wind disturbances.



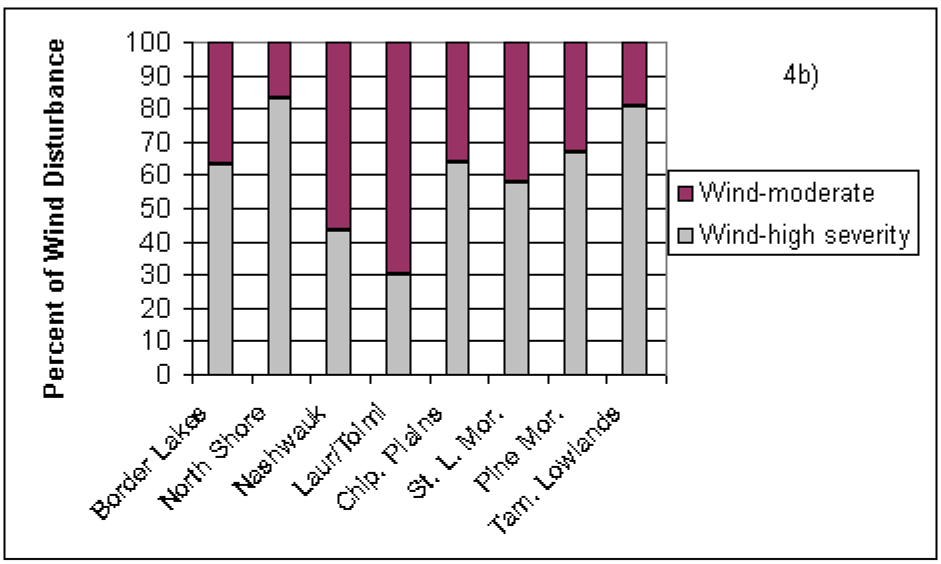
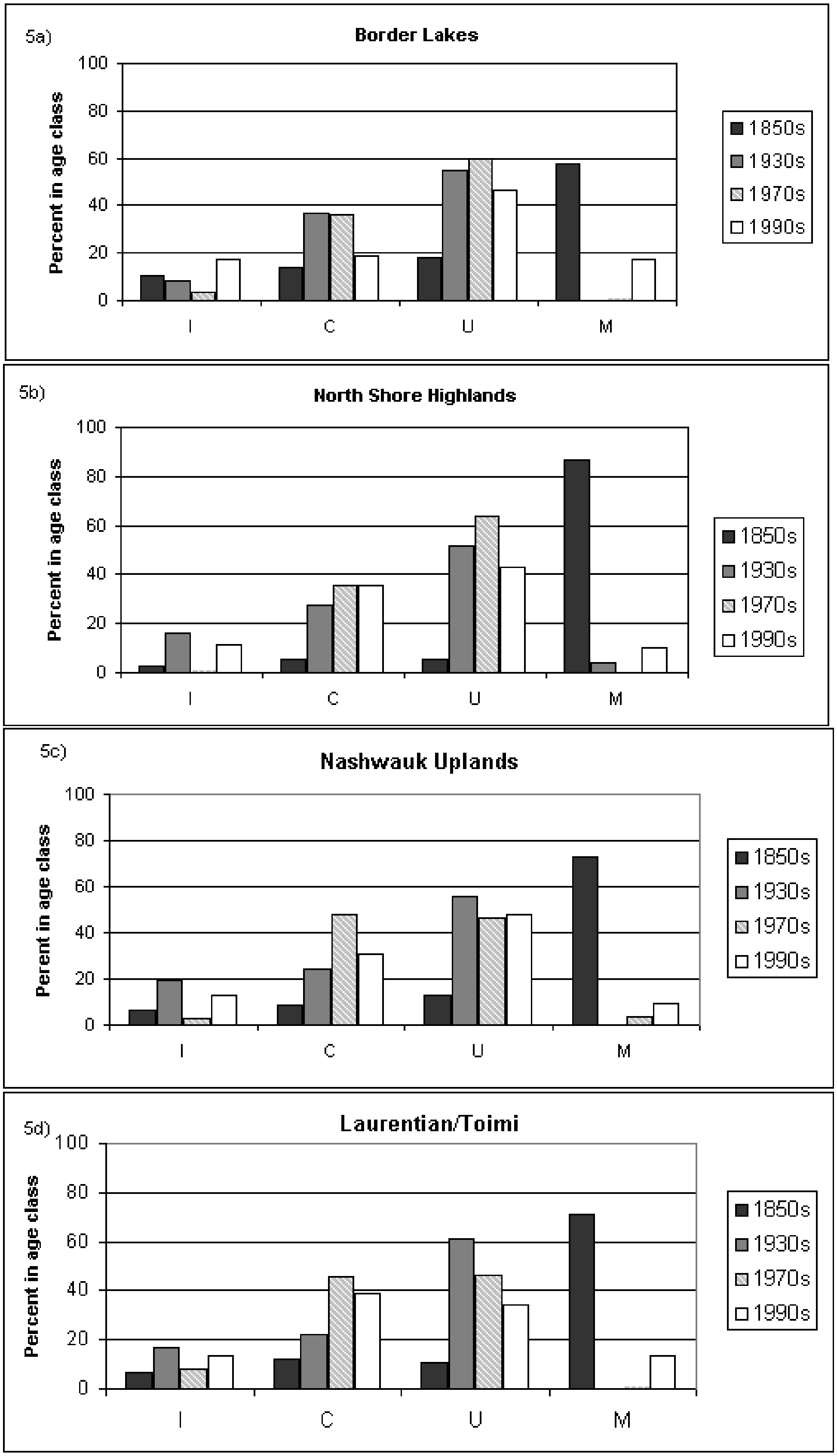
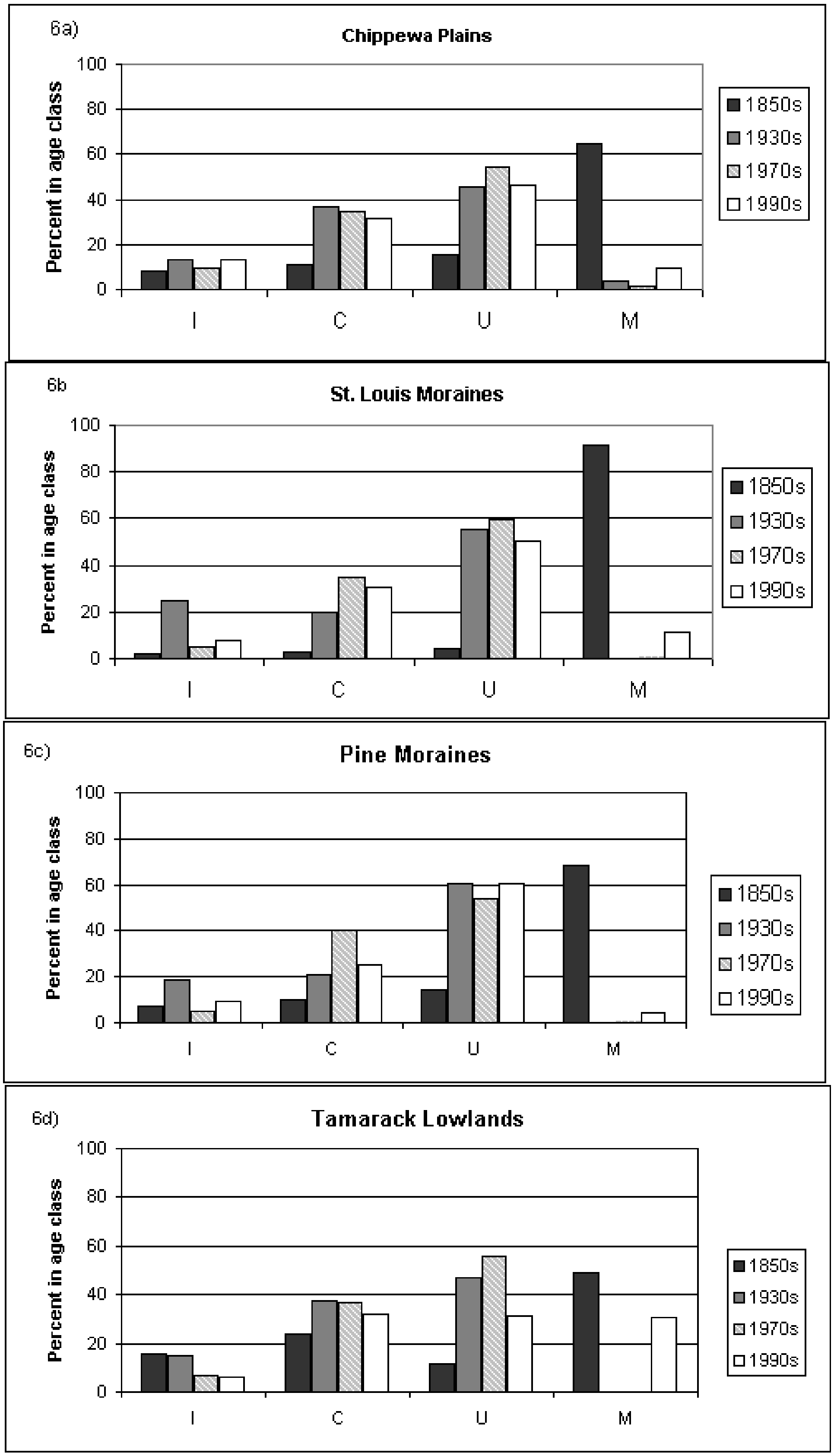


Figure 5. Age structure estimates for four time periods for the Northern Superior Uplands subsections. 1850s data derived from line note disturbance estimates. 1930-1990 derived from classified aerial photography



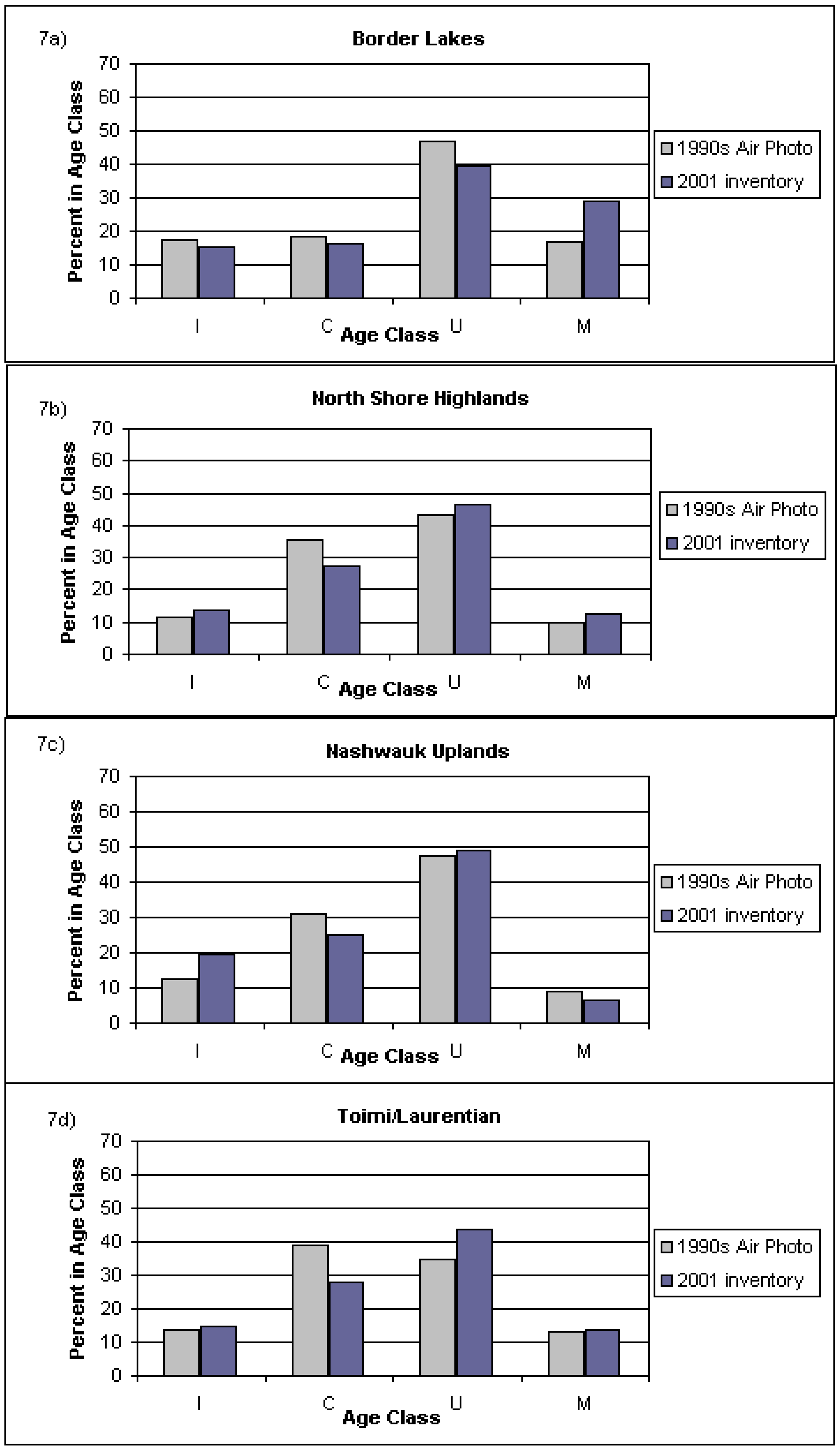
I = Initiation, C = Closed canopy, U = Understory re-initiation, M = Mature-multi-aged

Figure 6. Age structure estimates for four time periods for the Drift and Lake Plains subsections. 1850s data derived from line note disturbance estimates. 1930-1990 derived from classified aerial photography.



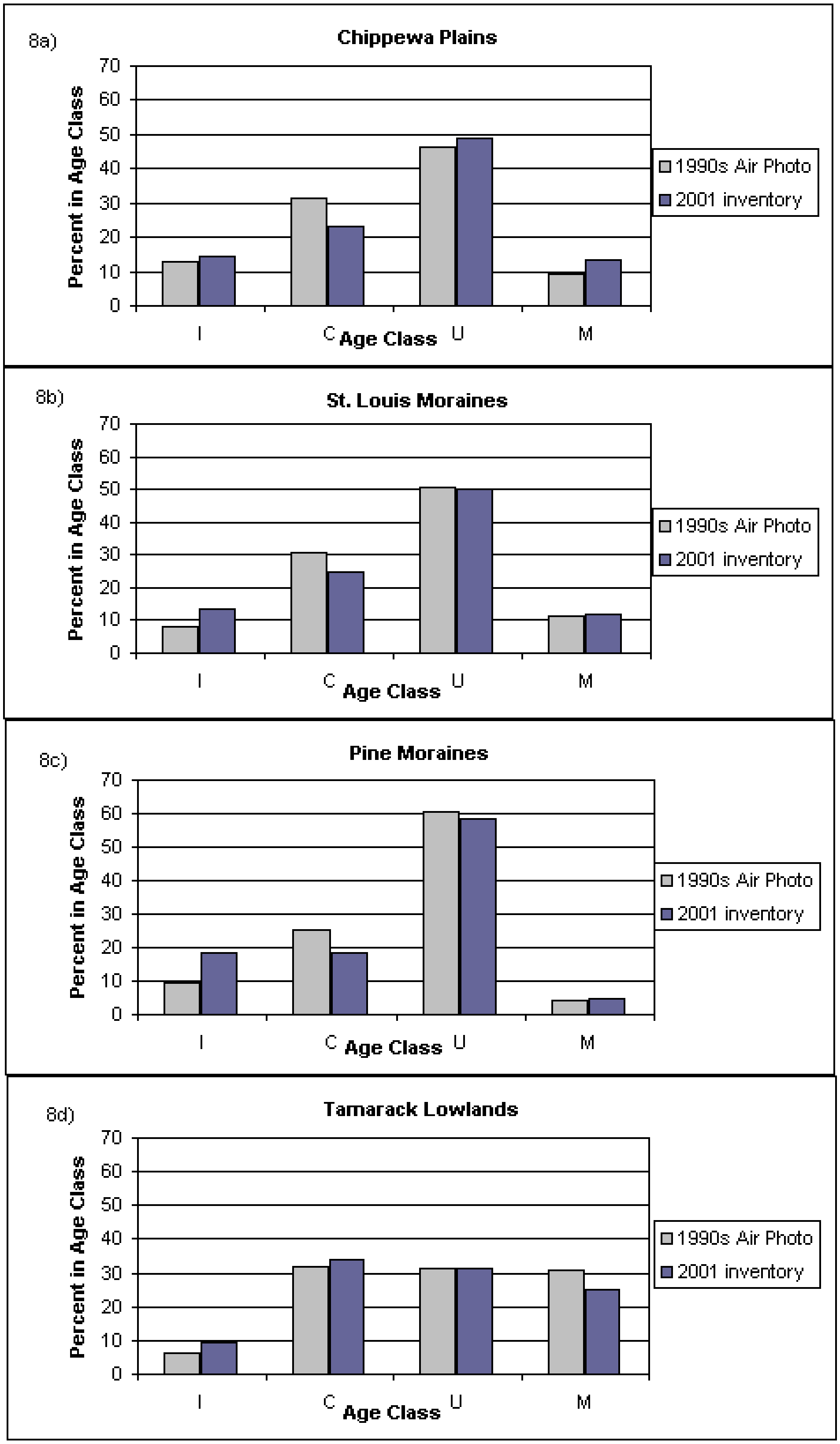
I = Initiation, C = Closed canopy, U = Understory re-initiation, M = Mature-multi-aged

Figure 7. Age distribution comparison with aerial photography and 2001 public land inventory data for Northern Superior Uplands subsections.



I = Initiation, C = Closed canopy, U = Understory re-initiation, M = Mature-multi-agec

Figure 8. Age distribution comparison with aerial photography and 2001 public land inventory data for Drift and Lake Plains subsections.



I = Initiation, C = Closed canopy, U = Understory re-initiation, M = Mature-multi-age

Figure 9. Estimated distribution of patch frequency and area for windthrow and fire in the Border Lakes and North Shore Highlands Subsections. Frequency values are patches per 5,000 km^2. Area values are km^2 per 5,000 km^2.

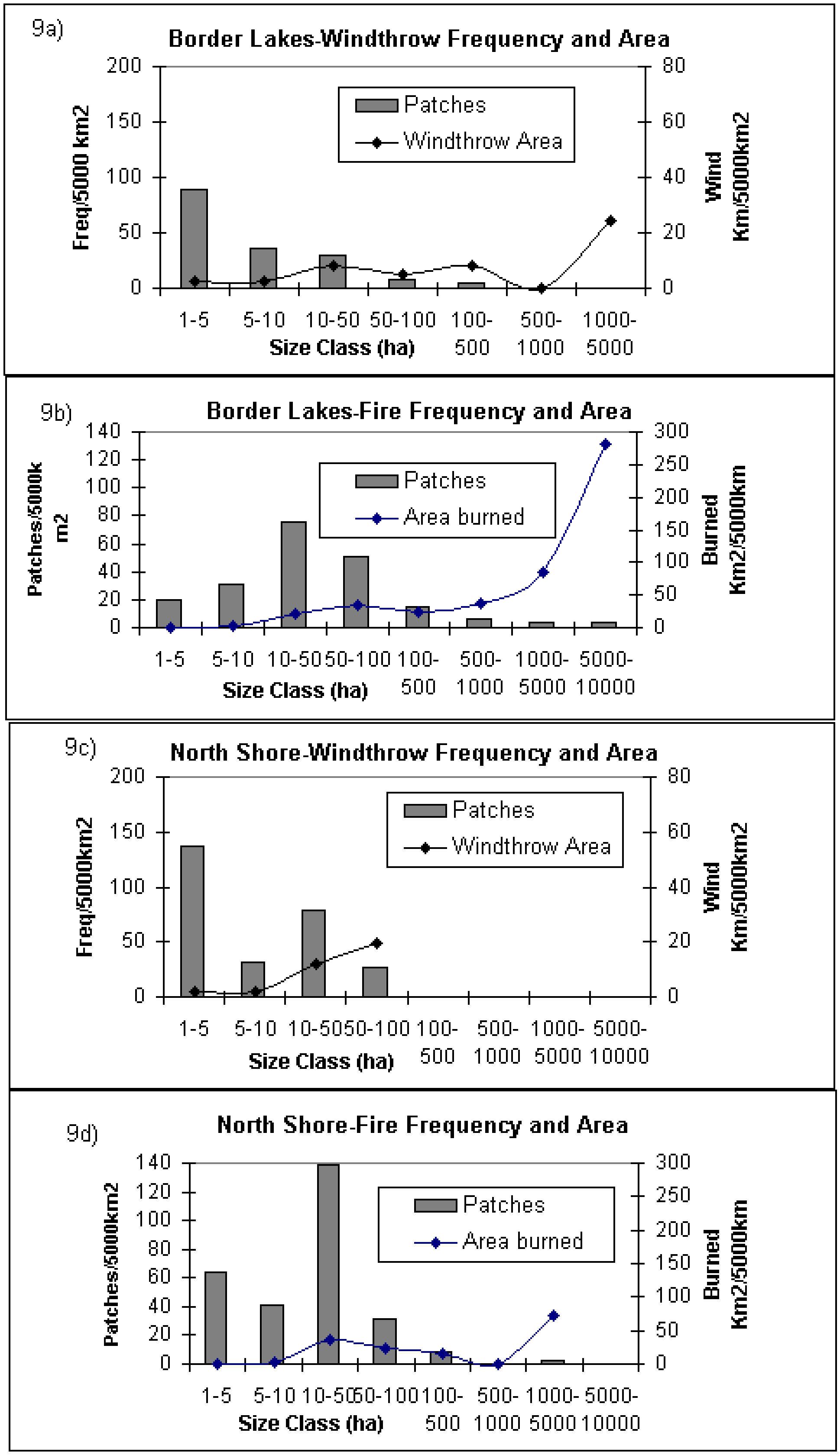


Figure 10. Estimated Distribution of patch frequency and area for windthrow and fire in the Nashwauk Upland and Laurentian/Toimi Subsections subsections. Frequency values are patches per 5,000 km^2. Area values are km^2 per 5,000 km^2.

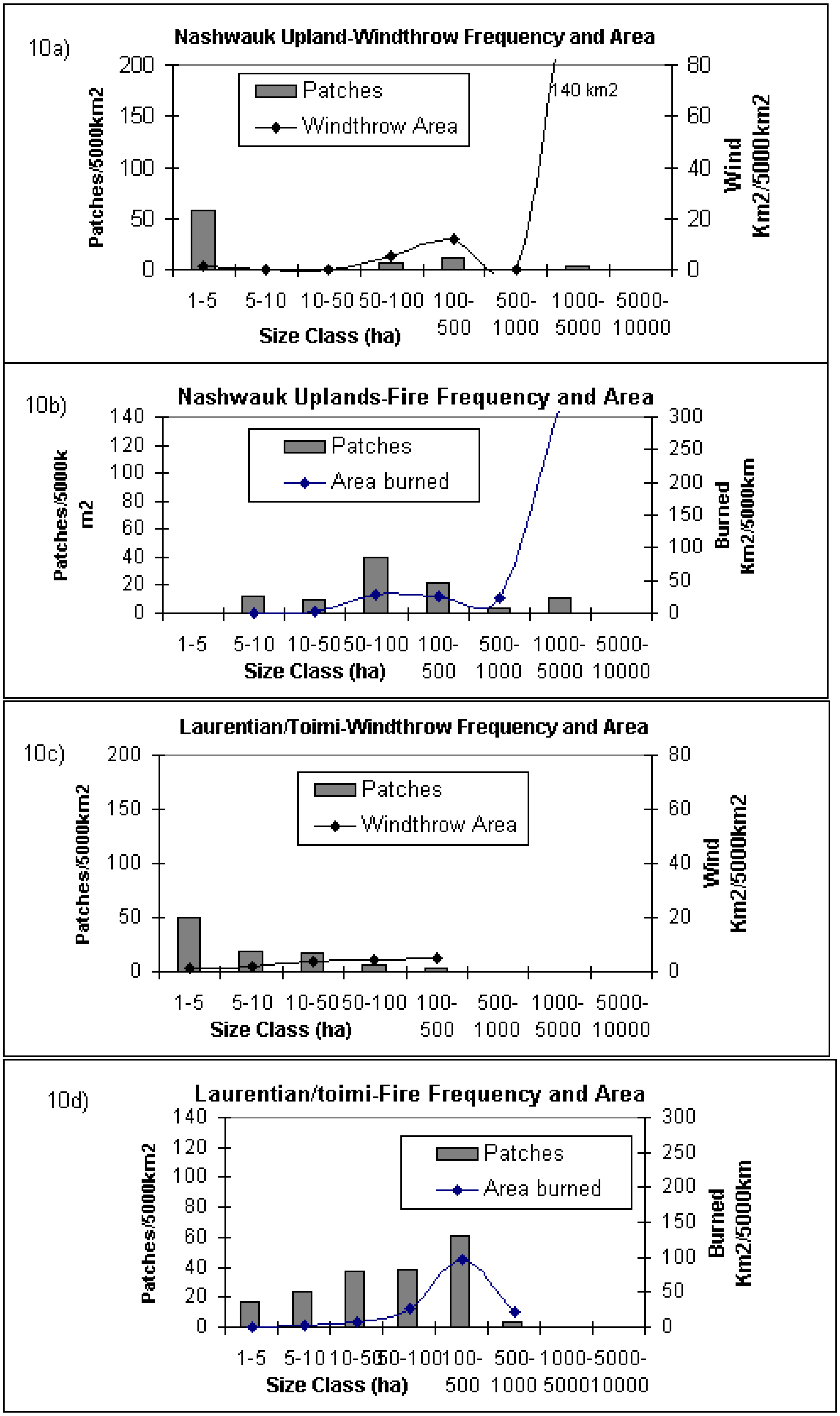


Figure 11. Estimated distribution of patch frequency and area for windthrow and fire in the Chippewa Plains and St. Louis Moraines subsections. Frequency values are patches per 5,000 km^2. Area values are km^2 per 5,000 km^2.

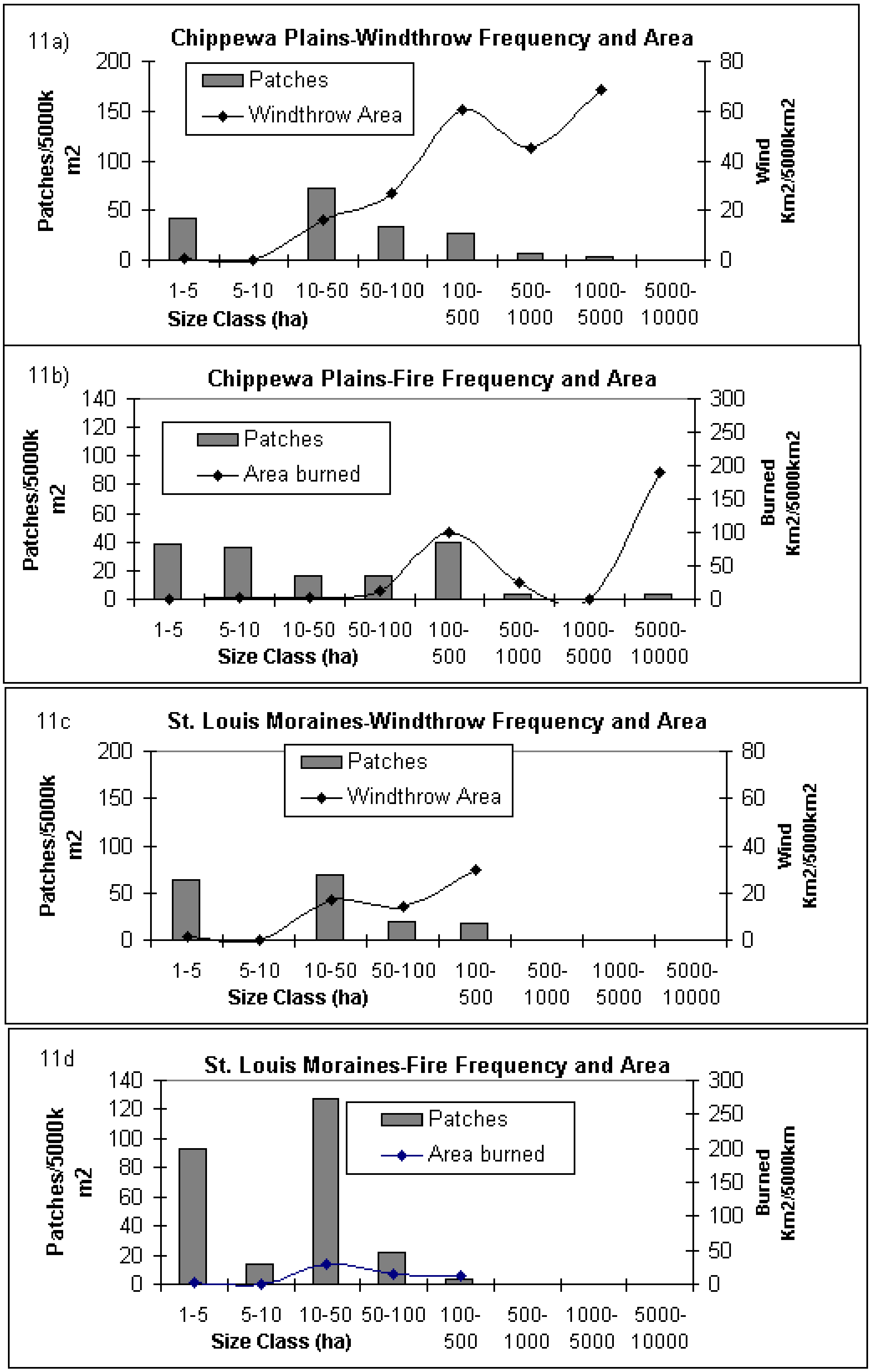


Figure 12. Estimated distribution of patch frequency and area for windthrow and fire in the Pine Moraines and Tamarack Lowlands subsections. Frequency values are patches per 5,000 km^2. Area values are km^2 per 5,000 km^2.

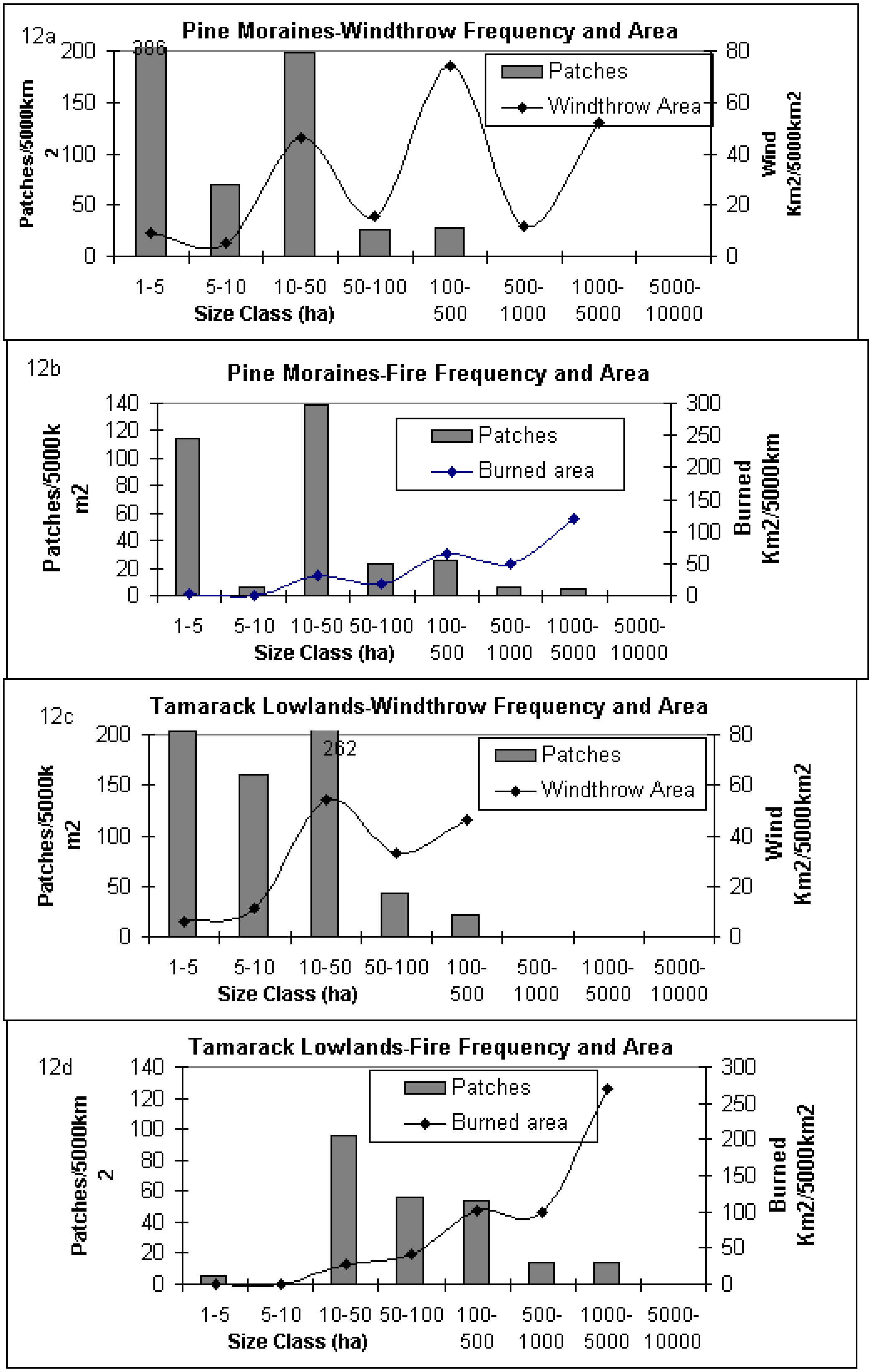


Figure 13. Percent fire patches and area burned for fire in the Border Lakes and North Shore Highlands subsections for 1850s and 1930s data. Values are percent of total patches and area respectively.

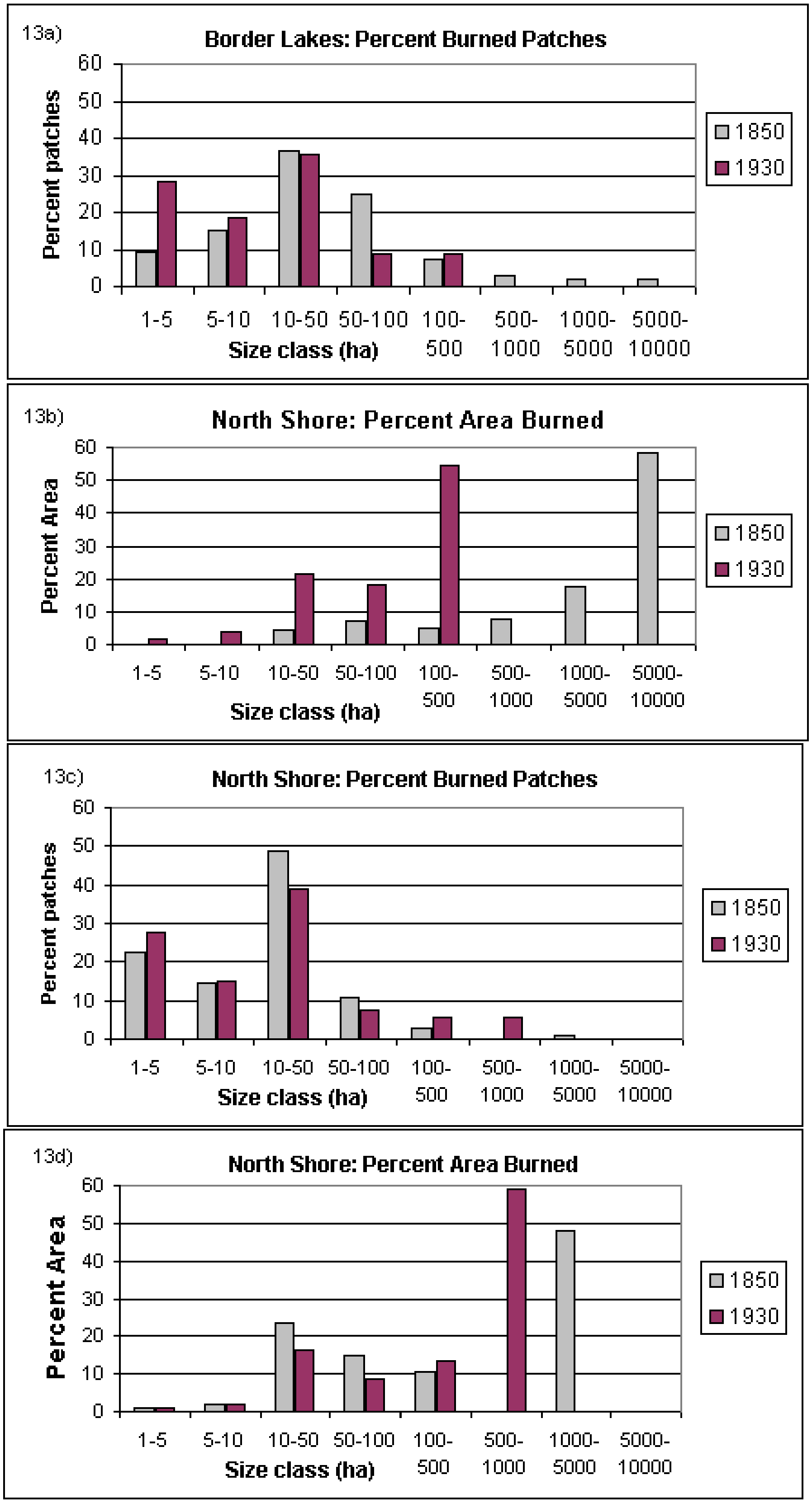


Figure 14. Percent fire patches and area burned for fire in the Chippewa Plains and Pine Moraines subsections for 1850s and 1930s data. Values are percent of total patches.