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CATASTROPHIC WINDTHROW IN THE PRESETTLEMENT FORESTS OF WISCONSIN[1]

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Abstract. Presettlement survey records for the state of Wisconsin (circa 1834–1873) reveal a widespread pattern of catastrophic windthrow. From these records, we have calculated that there were 51.8 separate patches (>1.0 ha) of complete canopy windthrow covering a total of 4828 ha annually within the region of the presettlement hemlock–northern hardwood forests, in the northeastern part of the state. The estimated return time for catastrophic windthrow at a site in this region is 1210 yr. Catastrophic windthrow was much less common in the forests of southern Wisconsin. Comparisons of the presettlement disturbance regime with contemporary climatological records suggest that catastrophic thunderstorms were the principal mechanism for large-scale windthrow in northern Wisconsin.

Key words: disturbance; disturbance patch size; hemlock–northern hardwood forests; presettlement forests; survey records; thunderstorms; tornadoes, windthrow; Wisconsin.

INTRODUCTION

There has been considerable debate about the significance of recurrent large-scale disturbances in mesic forests of the north central and northeastern United States (Loucks 1970, Lorimer 1977, Bormann and Likens 1979*a*). The mesic hemlock–northern hardwood forests of the western Great Lakes region lie north and east of a major climatic transition from fire-dependent forest, savanna, and prairie communities to the south and west (Curtis 1959, Heinselman 1973). These mesic forests, dominated in presettlement times by *Tsuga canadensis* L., *Acer saccharum* Marsh., and *Betula lutea* Michx. (Stearns 1949, Brown and Curtis 1952, Curtis 1959), represent the western extension of the complex of mesic, low-elevation forests classified by Nichols (1935) as hemlock–white pine–northern hardwood forests. The occurrence of charcoal fragments in forest soils and lake sediments of northern Wisconsin (Swain 1978) indicates that fires were common in the region, particularly on sites with sandy soils. However, the predominance of large individuals of late-successional species as witness trees in presettlement land surveys of the region (Stearns 1949, Goder 1955, Bourdo 1956) indicates that the average interval between catastrophic fires on more mesic sites was considerably longer than the lifespan of the major tree species of the region. Reports of large-scale disturbance of forests by catastrophic winds in many regions of the world (Spurr 1956, Webb 1958, Wilson 1976) suggest that severe winds provide an alternative mechanism for forest turnover in humid climates where natural fires are infrequent. However, with the exception of Lorimer's (1977) study in northeastern Maine, quantitative analyses of the regional significance of catastrophic windthrow in temperate climates have been lacking.

On 4 July 1977 a severe squall line thunderstorm crossed eastern Minnesota and north central Wisconsin. Within a 4-h period, forests and property were devastated by extreme winds in a path 266 km long and up to 27 km wide (Fujita 1978). Winds in excess of 50 m/s broke and uprooted trees on an estimated 344 000 ha of forest land. Approximately 7% of these forests were virtually leveled by catastrophic winds that have been identified as downbursts from the thunderstorm cells (Fujita 1978).

The scale and intensity of the 1977 storm came as a considerable surprise to state officials. Weather records and records of public forest lands describe instances of periodic, severe wind damage to forests of the region, but complete canopy windthrow has apparently been limited to relatively isolated patches of forest in the last two decades (National Oceanographic and Atmospheric Administration 1959–1977). While contemporary records are too sporadic and anecdotal to provide quantitative estimates of the frequency and extent of large-scale, wind-caused disturbance to forests in this region, frequent references to catastrophic windthrow in early land surveys of the northeastern and north central United States (Lutz 1930, Stearns 1949, Goodlett 1954, McIntosh 1962, Lorimer 1977) suggest that historical records can provide a more systematic description of regional patterns of large-scale

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windthrow. In this paper we report an analysis of the frequency and extent of catastrophic windthrow in presettlement forests of Wisconsin, and identify the probable mechanism for most catastrophic windthrow in this region.

Methods

The notes and maps of the original United States General Land Office survey of Wisconsin (circa 1834–1873) provide a systematic description of the landscape of Wisconsin prior to the extensive felling and clearing of forests that accompanied European settlement. By 1850, surveyors in the state were explicitly required to record "... the tracks of tornadoes and hurricanes, commonly called 'windfall' or 'fallen timber' ..." encountered along survey lines (Dodds et al. 1943). Detailed township maps at the scale 1:31 680 (3.2 cm to the kilometre) were produced by the Surveyor General's offices from the surveyors' field notes and sketch maps. The original maps for southern Wisconsin and photostats of the originals for northern Wisconsin were used in this study to record the locations, areas, and maximum lengths and widths of patches of large-scale windthrow for all of the townships in the state. Witness tree records and comments in the surveyors' field notebooks provided only limited additional information. In general, the surveyors recorded the bearing of a blowdown and its position along survey lines and mapped the outline of each blowdown on their sketch maps. Descriptions of the blowdowns were generally not included in the section and township descriptions unless blowdowns dominated a section line or township. Burley and Waite (1965) reported figures for the number of presettlement blowdowns by county, according to a compilation done by I. A. Lapham in 1872 (Lapham 1872). During the course of the present study, however, this compilation was found to be incomplete.

The presettlement land survey of Wisconsin provides a systematic line transect sample of the state along a 1.6 km (1 mile) square grid system. All blowdowns longer than 2.24 km would, of necessity, have intercepted at least one survey line. Because of the magnitude of such disturbances, and the considerable difficulty they must have presented for travel by the surveyors, we have assumed that the township maps provide an essentially complete record of large blowdowns (>2.24 km in length) in the state at the time of the surveys. It is conceivable that some large blowdowns were encountered by surveyors and not recorded for some reason, but for blowdowns that predated surveys by only a few years, this seems unlikely. However, as blowdowns aged and the logs decayed, there could well have been considerable latitude in the judgment of different surveyors in deciding whether to record blowdowns.

For smaller blowdowns, the survey records provide only a systematic sample, rather than a complete tally, of patches of complete canopy windthrow in the presettlement forests. We used line transect sampling theory to estimate the total number of smaller blowdowns present in the state at the time of the surveys. If a transect of length L is placed through a population of randomly distributed elements, then the number of elements in an area of size s is estimated by

$$x = \frac{\pi s}{2L} \sum_{i=1}^{n} \frac{1}{y_i}, \tag{1}$$

where n is the number of times elements intercept the transect, and y_i is the length of the i^{th} intercepted element ($i = 1, \ldots n$) (DeVries 1974). In the case of the presettlement survey of Wisconsin, the grid system of survey lines provides an average of 3.2 km of transects (survey lines) for each 2.59 km^2. Thus, $L = 1.24\ s$ for the grid system of survey lines. Substituting this into Eq. 1 simplifies Eq. 1 to

$$x = 1.24 \sum_{i=1}^{n} \frac{1}{y_i} \tag{2}$$

for blowdowns of length y_i (measured in kilometres). Eq. 2 has several useful features. Without having to determine either the total area or actual length of survey lines in a region, the total number of blowdowns can be estimated from knowledge of the number of times blowdowns intercepted survey lines, and their lengths. Eq. 2 also has the desirable feature that the recorded blowdowns can be subdivided into size-classes and the total number of blowdowns estimated for each size-class. In order to estimate the total area of these smaller blowdowns, the blowdowns recorded by the surveyors were first divided into size-classes. Then for the size-classes with mean patch lengths of <2.24 km, Eq. 2 was used to estimate the total number of blowdowns in each of those size-classes. The total number of blowdowns was then multiplied by the mean size of the recorded blowdowns in the size-class to estimate the total area of blowdowns for each size-class.

The estimation of both the annual frequency of catastrophic windthrow in this region and the average return time between successive disturbances at a given site depends largely on the lapse of time following a storm beyond which surveyors no longer recorded blowdowns. I. A. Lapham, a director of the state's geologic and natural history survey near the end of the period of the original land surveys, reported that blowdowns were recorded only if they had occurred within ≈10 yr prior to a survey (Lapham 1872). While some evidence of catastrophic windthrow may persist for much longer periods of time (Henry and Swan 1974), the rates of reestablishment of a closed canopy of saplings and small trees and the rate of decay of most of the tree species of the hemlock–northern hardwood forests are quite rapid. Within 25 yr following complete canopy windthrow in the Porcupine Mountains of northern Michigan, unsalvaged tracts were characterized by dense stands of trees 10–15 m tall with numerous well-rotted logs on the forest floor (C. D. Canham, *personal observation*). We feel that the assumption of a 15-yr recording interval is conservative with respect to estimates of large-scale windthrow frequency in this region. Any records of blowdowns that had occurred in a township >15 yr prior to the time of a survey would be offset by the absence of records of younger patches that were not recorded due to factors such as intervening fires.

Results and Discussion

Patterns of catastrophic windthrow in presettlement Wisconsin

The distribution of complete canopy windthrow in the presettlement forests of Wisconsin is shown in Fig. 1. Blowdowns were largely concentrated in the northern half of the state; 77% of the blowdowns were recorded within the presettlement boundary of the hemlock–northern hardwood forests of northern Wisconsin. The paucity of blowdowns in southern Wisconsin was, in part, simply a consequence of the considerable area of prairies and oak savannas in the presettlement landscape (Curtis 1959). However, blowdowns were rare even within the major areas of presettlement hardwood forests of southern Wisconsin. The long, narrow dimensions of most of the blowdowns recorded in these forests suggest that they were caused by tornadoes.

Blowdowns recorded by early land surveyors in northeastern Maine were almost entirely restricted to lowland conifer forests on stony flats and in swamps (Lorimer 1977). Lorimer (1977) suggests that most of the blowdowns in Maine may have resulted from one major storm in 1795. In contrast, blowdowns in the presettlement forests of northern Wisconsin occurred in all major forest types, and the orientation and distribution of the blowdowns suggest that several major and many smaller storms were responsible for the disturbance pattern.

Within the 6 560 000-ha region occupied by the presettlement hemlock–hardwood forests in Wisconsin, surveyors recorded 413 patches (>1.0 ha in size) of large-scale windthrow covering 67 775 ha. The largest contiguous area of windthrown forest was 3785 ha. Only three blowdowns smaller than 1.0 ha were recorded, suggesting that there was an implicit lower limit to the size of blowdowns actually recorded by surveyors. We have used 1.0 ha as the lower size limit for our analysis of catastrophic windthrow in the presettlement forests. Using the land survey as a line transect sample of catastrophic windthrow, we have estimated that there were at least an additional 364 blowdowns (>1.0 ha) in the region at the time of the surveys. However, these additional blowdowns are concentrated in the smaller size-classes (Fig. 2) and contribute only an additional 4649 ha to the total area recently disturbed by catastrophic winds at the time of the land surveys.

For the combined pattern of recorded and estimated additional blowdowns, the mean size of a patch of windthrown forest was 93.2 ha. The distribution of the sizes of blowdowns actually recorded by the surveyors was approximately lognormal (a Kolmogorov-Smirnov D statistic for departures from the expected lognormal frequencies was not significant at $P = .05$). Adding the additional blowdowns estimated using line transect sampling theory shifts the modal size into a smaller size-class, but still results in a size-class distribution that is approximately lognormal. However, it is likely that bias by the surveyors against mapping blowdowns in the smallest size-class (1.0–2.5 ha) has affected the estimated size-class distribution. Failure by the surveyors to record 30 blowdowns in the smallest size-class would produce a monotonically decreasing size-class distribution. However, the 158 blowdowns that would be estimated for the region from the recording of 30 more small blowdowns along survey lines would contribute <254 ha to the estimated total area of forest recently disturbed by catastrophic winds at the time of the surveys.

There is potentially a continuous spectrum of windthrow from small treefall gaps of one or a few trees to the large, contiguous patches of several thousand hectares of catastrophic windthrow recorded by the surveyors and observed in the 1977 storm in northern

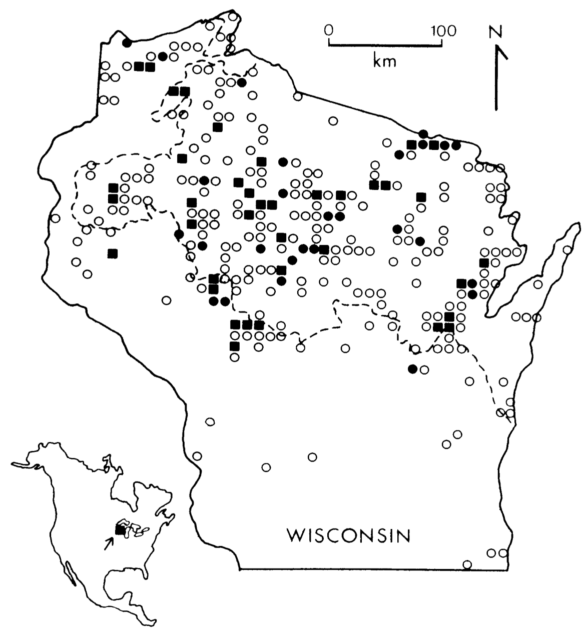

Fig. 1. The distribution of blowdowns in presettlement Wisconsin (circa 1834–1873). The dashed line is the southern and western limit of the mesic, hemlock–northern hardwood forest in the state, taken from the map "Presettlement Vegetation of Wisconsin" (Wisconsin Geological and Natural History Survey 1965) based on work by the University of Wisconsin Plant Ecology Laboratory. The symbols represent the total area of blowdowns in 9328-ha townships: ○ = 1–324 ha; ● = 325–649 ha; ■ = >649 ha.

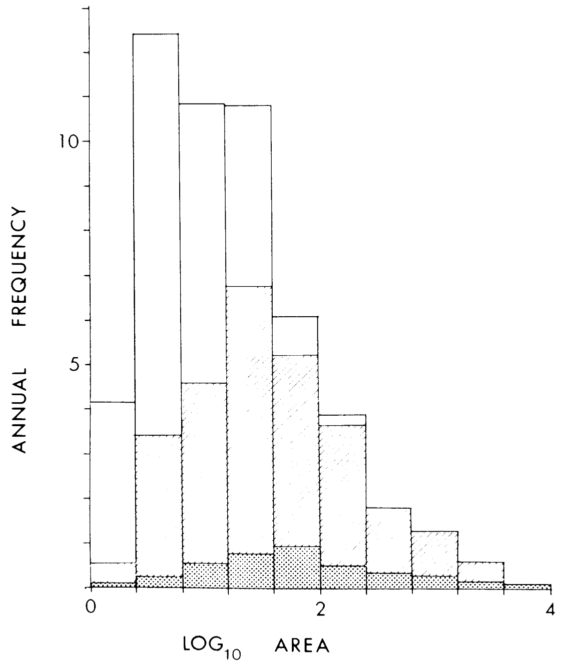

FIG. 2. Annual frequencies of presettlement blowdowns and contemporary tornadoes (1953–1977) by logarithmic size-classes (size measured in hectares) within the 6 560 000-ha region occupied by the presettlement hemlock–hardwood forests of northern Wisconsin. The stippled portions of bars are contemporary tornadoes. Blowdowns actually recorded by surveyors are shown with hatching, while the estimated regional totals for smaller size-classes are indicated by the open portions of the bars.

Wisconsin. While it is likely that surveyor bias may have affected our estimate of the actual size distribution of presettlement blowdowns, there are several factors that argue against considering the distribution of blowdown sizes determined from the survey records as simply the right-hand tail of a single continuous distribution from small canopy gaps to large catastrophic blowdowns. The process of complete canopy windthrow is ecologically and climatologically distinct from the process of within-canopy windthrow of small patches of trees. Both the sources of the winds and the local factors affecting the scale of the disturbance differ in the two processes.

The susceptibility of an individual tree to windthrow is a function of characteristics of the tree, its site, surrounding forest structure, and the nature of prevailing storm systems. Widespread storms with moderately severe winds can cause numerous canopy gaps by toppling the more susceptible individuals and through a domino effect in these initial canopy openings. While the area of forest affected by such storms is a function of the horizontal dimensions of the severe winds associated with a storm, the size distribution of windfall gaps resulting from moderate storms is likely to be more strongly affected by features of the forest and its site.

Successively higher wind speeds will cause successively higher damage as the more resistant trees are toppled, until some level of wind speed and turbulence is reached that is sufficient to open up the canopy and topple most of the trees. At this extreme, the size of a blowdown will reflect both the local factors affecting susceptibility to windthrow and the dimensions of catastrophic winds near the ground. The physical dimensions of catastrophic winds are principally determined by the nature of specific storm systems, although patterns of local turbulence are strongly affected by ground conditions. The horizontal extent of catastrophic winds from a particular storm will set limits for blowdown patch size, while the actual boundaries of a blowdown will be affected by local variation in forest and site conditions. Small stands of old-growth forests, locally exposed forests on knolls and ridges, or small patches of exposed, poorly drained land with shallow soils would all contribute to the formation of small blowdowns. However, our reconstruction of the size distribution of presettlement blowdowns and our discussion of the climatology of severe wind storms in this region later in this paper both suggest that winds severe enough for complete canopy windthrow normally affect areas considerably larger than 1 ha.

The frequency of catastrophic windthrow in the presettlement hemlock–hardwood forests of Wisconsin

Within the 6 560 000-ha region occupied by the presettlement hemlock–hardwood forests of Wisconsin, we have calculated that ≈11% of the region was not forested at the time of the surveys due to the occurrence of wetlands and lakes (Wisconsin Conservation Department 1955–1959), pine barrens (Curtis 1959), and the area of recent blowdowns estimated from the survey records. For the remaining 5 840 000 ha of potentially forested land, the estimation of both the annual

TABLE 1. Estimated cumulative areas of blowdowns in patches larger than 1, 10, 100, and 1000 ha in northern Wisconsin at the time of the presettlement land surveys, and the calculated time for the disturbance of an area equal to the size of the entire region (the blowdown cycle) by blowdowns larger than 1, 10, 100, and 1000 ha, assuming that the survey records reflect the cumulative effects of blowdowns for 10, 15, or 20 yr prior to the surveys.

Blowdown size (ha)	Cumulative area (ha)	Recording interval (yr)		
		10	15	20
		Blowdown cycle (yr)		
>1.0	72 424	806	1210	1612
>10.0	70 749	825	1238	1650
>100.0	59 605	980	1470	1960
>1000.0	30 179	1935	2903	3870

frequency of catastrophic windthrow and the regional windthrow disturbance cycle (calculated as the time necessary for the disturbance of an area equal to the size of the region) depends largely on the length of time following a storm beyond which surveyors no longer recorded blowdowns. This interval undoubtedly varied for different surveyors and for blowdowns with different rates of recovery, but for the reasons we outlined earlier (see Methods), we feel that an interval of 15 yr is reasonable, and probably conservative with respect to estimates of windthrow frequency in this region.

On this basis, we have calculated that the annual frequency of catastrophic windthrow in this region was 51.8 patches (>1.0 ha), covering 4828 ha annually. At this rate, it would take 1210 yr for an area equal to the size of the entire region to be disturbed by catastrophic winds affecting patches of forest larger than 1.0 ha. Table 1 illustrates the sensitivity of these calculations to different estimates of the interval for which blowdowns were recorded. Table 1 also presents calculated blowdown cycles for patches of forest larger than 10, 100, and 1000 ha. The blowdown cycle for disturbance by patches larger than 10 ha is only slightly longer than the cycle for all patches larger than 1 ha, illustrating the significance of the larger blowdowns to the overall extent of catastrophic windthrow in the region.

The actual average return time for catastrophic windthrow at any given site within this region probably varied considerably. Despite the fairly moderate amount of topographic relief in northern Wisconsin, patterns of wind damage following the 1977 storm suggest that both local topography and stand composition and structure have significant effects on the susceptibility of forests to catastrophic windthrow.

There are currently no comparable, quantitative estimates of the presettlement frequency or extent of stand-initiating fires in northern Wisconsin. Recent burns were recorded on only a few of the township maps. The personal notes and memoirs of the field surveyors do provide descriptions of major forest fires, particularly in the extensive areas of windthrown forests in the central sand plains of Jackson and Clark counties. However, the survey records do not appear to provide a quantitative record of the presettlement fire regime. The reconstruction of historical patterns of charcoal deposition in lake sediments of northern Wisconsin (Swain 1978) certainly demonstrates that fires occurred in the region, but the interpretation and extrapolation of these results are complicated by the occurrence of sandy soils within the region, which supported extensive pine forests that were presumably more fire-prone than surrounding, more mesic sites. If quantitative regional estimates of presettlement fire regimes were available, our estimate of the effect of windthrow on the presettlement landscape would be altered in several ways. Significant areas of land lacking a forest canopy because of previous fires would substantially reduce the calculated return time for catastrophic windthrow on the remaining forested land. In addition, fires that burned through recent windthrows could have significantly lengthened the successional development of old-growth stands, thereby increasing the percentage of the landscape occupied by successional forests.

While patterns of succession following windthrow in this region have not been studied, we assume that the development of all-sized stands of late-successional species requires at least 200–300 yr. Our results thus indicate that catastrophic windthrow maintained at least 17–25% of the presettlement landscape in forests of successional composition and structure. Such stands are characterized by both a net accumulation of biomass and nutrients (Vitousek and Reiners 1975, Bormann and Likens 1979*b*) and an increase in species diversity due to the temporal overlap of successionally related species (Loucks 1970). While the calculated return time for catastrophic windthrow is long compared to return times for fires in conifer forests of drier climates of North America (e.g., Habeck and Mutch 1973, Heinselman 1973), the return time for catastrophic windthrow in mesic forests of Wisconsin indicates that, on average, four to five generations of late-successional trees historically occupied a given site before the successional process was initiated again by catastrophic winds.

Sources of catastrophic winds

The three principal sources of extreme winds in Wisconsin are thunderstorms, tornadoes, and the general circulation around severe low-pressure systems (extratropical cyclones). Severe low-pressure systems have periodically caused widespread damage to forests of the region. The most severe and widespread of these storms occurred on 10 October 1949. Wind damage to property and forests was extensive throughout northern Iowa, eastern Minnesota, and northwestern Wisconsin. Peak wind speeds at stations within this region ranged from 35 m/s to over 44 m/s. While it is likely that the most severe gusts resulted from downbursts from unreported thunderstorms, weather records indicate that widespread locations sustained winds >27 m/s for periods of up to several hours. Stoeckeler and Arbogast (1955) have summarized the extent of forest damage associated with this storm in northern Wisconsin and upper peninsula Michigan. While the cumulative lumber losses over the entire region were estimated at >484 000 m^3 (Stoeckeler and Arbogast 1955), disturbance of individual stands was largely limited to the windthrow of individual trees or small patches of trees. No significant areas of complete canopy windthrow were reported within the region. Thus, while severe low-pressure systems are a significant source of small-scale canopy gaps, there is currently no evidence that they are a significant mechanism for catastrophic windthrow in this region.

Tornadoes, however, are an obvious mechanism for catastrophic windthrow. Records of tornadoes in

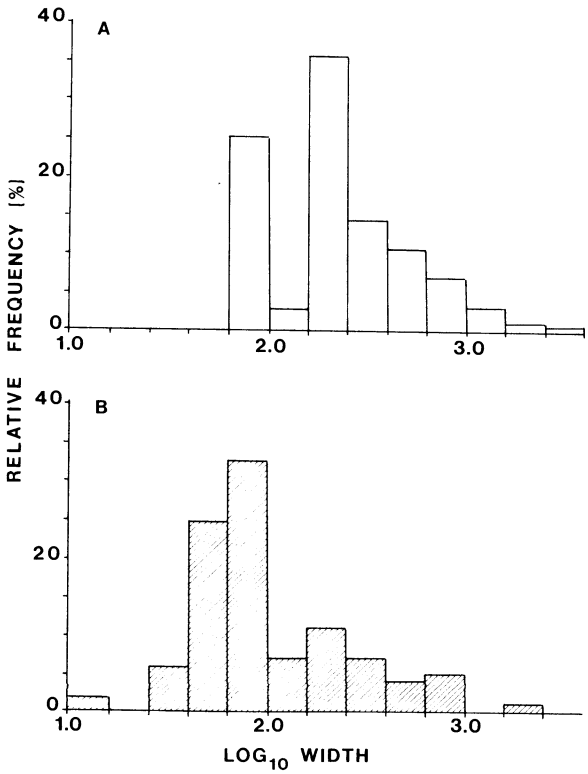

FIG. 3. Relative frequencies of patch widths (measured in metres) for (A) presettlement blowdowns (open bars) and (B) contemporary tornadoes (hatched bars). The distributions are standardized separately for comparison. The smallest width class of presettlement blowdowns represents the smallest width depicted on the original survey maps.

northern Wisconsin during the 25-yr period from 1953 to 1977 (Kelly et al. 1978) were used for comparisons with the pattern of windthrow recorded by early land surveyors. Using this 25-yr period as a representative interval, the expected frequency of tornado-caused windthrow in the region is 5.0 patches/yr covering 2062.2 ha/yr, with an expected return time of 2832 yr. Thus, it would be necessary to postulate greater than a 10-fold increase in tornado frequency and greater than a 2-fold increase in annual tornado path area in presettlement times to produce a pattern similar in frequency and extent to the presettlement pattern of windthrown forests.

Comparisons of tornado path dimensions with dimensions of presettlement blowdowns further indicate that tornadoes were not the principal mechanism for catastrophic windthrow in this region. The distributions of patch sizes for presettlement blowdowns and contemporary tornado paths are given in Fig. 2. The median area of the tornado paths is significantly larger than the median windthrown area (median test: $t = 6.45$, $P < .01$). Moreover, the median width of the tornado tracks is significantly smaller than the median width of the blowdowns (median test: $t = -4.82$, $P < .01$). The distributions of patch widths (Fig. 3) indicate that the presettlement windthrow pattern was a composite produced by tornadoes and a more frequent mechanism that produced characteristically wider patches of disturbance. A recent survey of thunderstorm downburst paths indicates that they are usually substantially wider than tornado tracks (Fujita 1978). This result, coupled with the comparatively low frequency of tornadoes in this region, supports the hypothesis that thunderstorm downbursts were the principal mechanism for catastrophic windthrow in the presettlement forests of northern Wisconsin.

CONCLUSIONS

Bormann and Likens (1979*a*) have argued that natural disturbances in northern hardwood forests were infrequent enough that steady-state communities dominated the presettlement landscape of the northeastern United States. Our results indicate that the presettlement landscape of northern Wisconsin reflected a level of catastrophic disturbance that was intermediate to fire-dependent coniferous forests further west, and the very low levels of disturbance proposed by Bormann and Likens (1979*a*) for the mesic forests of northern New England. On mesic upland sites in northern Wisconsin, local communities often may have reached the structural and compositional characteristics of old-growth forests. However, even on these sites, late-successional forests were inevitably transient, subject to catastrophic windstorms within four to five generations on average. The extensive pine forests and the paleological record of charcoal deposition within northern Wisconsin (Curtis 1959, Swain 1978) suggest that on more xeric sites old-growth forests were even more ephemeral.

Prior to the 4 July 1977 storm in Wisconsin, the potentially catastrophic effects of thunderstorms on forests of temperate regions were generally not recognized. Nevertheless, presettlement records summarized in this study indicate that thunderstorms were a major source of catastrophic disturbance to forests of the western Great Lakes region of North America. The apparent differences between presettlement and postsettlement disturbances regimes appear to be due to the extensive conversion of presettlement forests to early-successional stands that in many cases have lower susceptibility to windthrow (C. D. Canham, *personal observation*). The presettlement disturbance regime has been replaced, in effect, by short-rotation, even-aged management of the forests of northern Wisconsin.

The frequency of thunderstorms in the western Great Lakes region of North America is not high in comparison with many tropical and subtropical regions (Court 1974). Very little is known, however, of the nature of regional variation in the severity of thunderstorms or of the frequency with which thunderstorms produce catastrophic downbursts in different regions. However, in humid climates where natural fires may be infrequent, extreme winds provide an alternative mechanism for catastrophic disturbance of forest ecosystems. For temperate mesic forests, thunderstorm downbursts appear to be a previously unrecognized but potentially significant natural mechanism for the maintenance of a diversity of succesional forest communities in forested landscapes.

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