EFFECTS OF FROST ON HARDWOOD REGENERATION IN NORTHERN WISCONSIN

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Abstract—In northern Wisconsin, frosts often occur during the early growing season when shoot and leaf development are beginning and trees are most susceptible to freezing temperatures. We measured the intensity and duration of frosts in late May and early June 1994 in a vertical, 10 meter temperature profile in a clearcut, a stand with 50 percent crown cover, and a control. In addition, we monitored shoot development of northern red oak (*Quercus rubra* L), white ash (*Fraxinus americana* L.), ironwood (*Carpinus caroliniana* Walt.), sugar maple (*Acer saccharum* Marsh.), and aspen—both trembling (*Populus tremuloides* Michx.) and big tooth (*Populus grandidentata* Michx.) in these stands and in a stand with 75 percent crown cover. We also assessed frost damage on a broader scale as it was related to overstory condition, distance from clearcut edge, and topographic position in two areas with clearcut and partially cut hardwood forests. The frost damage was more severe in the clearcut, less in the 50 percent crown cover, and did not occur in the 75 percent crown cover and control. Northern red oak and white ash shoots were severely affected by frost with death of all new growth in the clearcut; ironwood was slightly damaged; and sugar maple and aspen were apparently unaffected by frost. All trees with frost damage produced new shoots; the location of the buds that flushed depended on the severity of frost damage. In addition to differences among overstory treatments, frost damage differed with topographic positions and with depth-of-edge between areas with different temperature environments. Silvicultural implications of our observations are discussed.

INTRODUCTION

Forest succession patterns are determined by many interrelated factors acting at different spatial and temporal scales. The most obvious factors, such as site productivity, herbivory, plant species growth rates, vegetative reproduction, and seed availability, are commonly used to explain the variation in composition and development of forest ecosystems. Other physical and biological factors may also be important, but we know little about their occurrence in space and time. Late spring frosts are one factor that may be more important than expected for some species and sites. Frost has long been implicated as a factor in hardwood regeneration and growth, particularly for oaks (Buckley 1994, Crow 1992, Emerson 1846, Gordon and others 1995, Johnson 1979, McGee 1975, Ward 1964). However, there is little documentation of the frequency and severity of frost damage to oaks at varying scales of resolution, e.g., within and among individuals, stands, and landscapes, although Geiger (1965) described general spatial and temporal variation of frost in forests. Early growing season frosts result from the interaction between cold air masses that generally affect a region (advective frost), radiative heat loss, and pooling of cold air in areas with restricted air flow. The duration and severity of sub-freezing temperatures are related to the local topography, amount and type of forest cover, and weather conditions. The inability of vegetation to return to some northern Wisconsin sites after forest clearing in the early 1900s was due, in part, to the presence of frost pockets. Plant response to frost can vary significantly depending on the inherent ability of species to withstand frost, the stage of plant development when frost occurs, the severity of frost, and the ability to recover after frost damage (Kramer and Kozlowski 1979).

This paper describes frost damage in 2 regenerating hardwood stands in northern Wisconsin. The purpose of these observations is to better understand the short term effects of frost and determine if different forest structures resulting from silvicultural treatments reduced damage.

METHODS

Willow Springs

The Willow Springs site is located on the Chequamegon National Forest near Park Falls, WI (T38N R3E, Sections 13-14). Our most detailed observations were made at this site, which has a habitat type of *Acer/Viola - Osmorhiza* (Kotar and others 1988). The topography is level to gently sloping (0 to 5 percent) and the soil is a moderately well-drained, sandy loam. Early results of an artificial oak regeneration study on this site are available (Teclaw and Isebrands 1991).

The study area consists of 4, 8 hectare overstory blocks—0 (clearcut), 50 percent, and 75 percent canopy cover and an uncut control. Basal area was 17.0, 20.7, and 32.4 square meters/hectare, respectively in the 50 percent, 75 percent, and control blocks. Temperature was measured in the clearcut, 50 percent, and control blocks at the surface and 0.25, 0.50, 1.0, and 2.0 meters above ground every 10 minutes. Hourly average and daily maximum and minimum values were recorded with Campbell CR10 data loggers. Weather stations were located in the center of each overstory treatment and temperature measurements were replicated three times within each block.

Shoot elongation was measured on sugar maple (*Acer saccharum* Marsh.), white ash (*Fraxinus americana* L.),

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ironwood (*Carpinus caroliniana* Walt.), red oak (*Quercus rubra* L), aspen—both trembling (*Populus tremuloides* Michx.) and big tooth (*Populus grandidentata* Michx.), and raspberry (*Rubus idaeus* L.) in the overstory blocks in which they were present. The terminal shoot was measured on each of six plants for each species. Plants were located near the center of the block, as close to the weather stations as possible, and at least 150 meters from the edge of the block. Moreover, red oak acorn germination was observed on six artificially seeded plots in each overstory treatment block. Shoot elongation and germination observations were made every 7 to 14 days from May 1 through early July and in early August and September.

Two weeks after the temperature in the clearcut was recorded at -9.2 °C on Julian days 146-147 (May 26-27), we established three transects in all overstory treatments to determine the spatial variation in frost damage. Sample points were located at 10 meter intervals beginning at the edge of the clearcut block and going into the adjacent 50 percent and untreated blocks. The transects in the 50 percent block spanned the block and ended in the adjacent uncut forest. Transects were 150 and 300 meters long in the control and 50 percent blocks, respectively.

White ash and red oak were the only tree species severely affected by the frost. Because of the small number of red oak and the large number of uniformly distributed white ash seedlings that regenerated naturally, sample trees were only white ash. When oak seedlings were encountered, they were evaluated and the degree of damage was compared to adjacent white ash. Based on these observations, red oak and white ash were similarly affected by the frost. At each sample point, up to 20 white ash seedlings ranging in height from 0.25 to 1.5 meters were evaluated. Stump sprouts were also sampled in the clearcut because seedlings in that block were rare. In the control, most seedlings were 0.25 meter tall or less due to poor performance of seedlings in full shade. Frost damage was classified according to the following scale: class 1—no damage; 2—up to 20 percent of leaves damaged; 3—21 to 40 percent damage; 4—41 to 60 percent damage; 5—61 to 80 percent damage; 6—81 to 99 percent damage; 7—all leaves killed. In classes 2 to 5, there was little obvious damage to the current year's shoot. In class 6, the current year shoot was frost-pruned to varying lengths; in class 7, the entire current year shoot and all leaves were killed.

Bird Lake

The Bird Lake site is located near Lake Tomahawk, WI, on the American Legion State Forest (T38N R7E, Section 18) and has a habitat type of *Acer/Vaccinium - Viburnum* (Kotar and others 1988). The topography is typical of ground moraine deposits in the region with irregular slopes varying from 0 to as much as 60 percent over short distances (fig. 1). The mesoscale topography at this site was much more complex than at Willow Springs. The Bird Lake site consists of three replications of three overstory treatments—clearcut, and 25 percent and 50 percent crown cover (fig. 1). Residual basal area in the 25 percent and 50 percent plots was 7 and 14 square meters/hectare, respectively. Each overstory plot is 0.56 hectare. Teclaw and Isebrands (1993) have reported the early results of red oak artificial regeneration studies on this site.

Three weeks after the frost on Julian days 146-47, we made frost damage observations in all nine overstory treatment plots. Within each plot, 12 sample points were established. At each sample point, up to five red oak seedlings and three red oak sprout clumps were evaluated using the damage classes described above. In addition, we measured total plant height and height of frost damage.

The contour map of the site was developed using a hand-held abney level. All elevations in figure 1 are referenced from the starting point of the survey, which was designated as the 100 isoline. The total relief for the area is approximately 28 meters (relative height of 88 to 116).

RESULTS

Willow Springs

In 1994, sub-freezing temperatures were recorded on Julian days 131-133 (May 11-13), 136 (May 16), 146-147 (May 26-27), 152-154 (June 1-3), and 159 (June 8). The growing degree days (dd) for the clearcut based on 5 °C for the frost dates above were 97 to 111, 128, 243, 310 to 329, and 380, respectively. Degree days in the 50 percent and control blocks were slightly less. Bud break occurred between May 7 and 11, and there was measurable shoot elongation on May 22. Neither red oak nor white ash showed signs of frost damage on May 21; thus, frosts before this did not appear to affect development.

The sub-freezing temperatures on days 146-147 caused an immediate wilted appearance and green tissues turned black within a few days. Temperature regimes differed considerably among the three overstory treatments. Minimum temperatures in the clearcut, 50 percent crown cover, and 100 percent crown cover blocks were -9.2 °C, -2.5 °C, and -0.6 °C, respectively. The duration of the freezing conditions was 10 hours in the clearcut, 8 hours in the 50 percent crown cover block, and only 1 hour in the 100 percent crown cover block. The depth of freezing temperatures in the inversion layer was up to 10 meters above the ground in the clearcut and 50 percent crown cover blocks and only up to 0.5 meter in the 100 percent crown cover block (fig. 2).

Species differed in their ability to withstand frost. In the clearcut, red oak and white ash were equally susceptible. The current year shoot and associated leaves were killed on every seedling and sprout clump throughout the 8 hectare block (figs. 3A, 3B, 4A, and 5A). Frost damage did not differ between plants in open areas and those present in the understory of stands of dense young aspen suckers. About 20 percent of the red oak acorns on artificially seeded plots in the clearcut had germinated at the time of the frost. They were subjected to the coldest temperatures, and their above ground stems were killed. Red oak germinants on the artificially seeded plots in the 50 percent and 75 percent blocks were not damaged. Of the other common tree and shrub species present, ironwood and

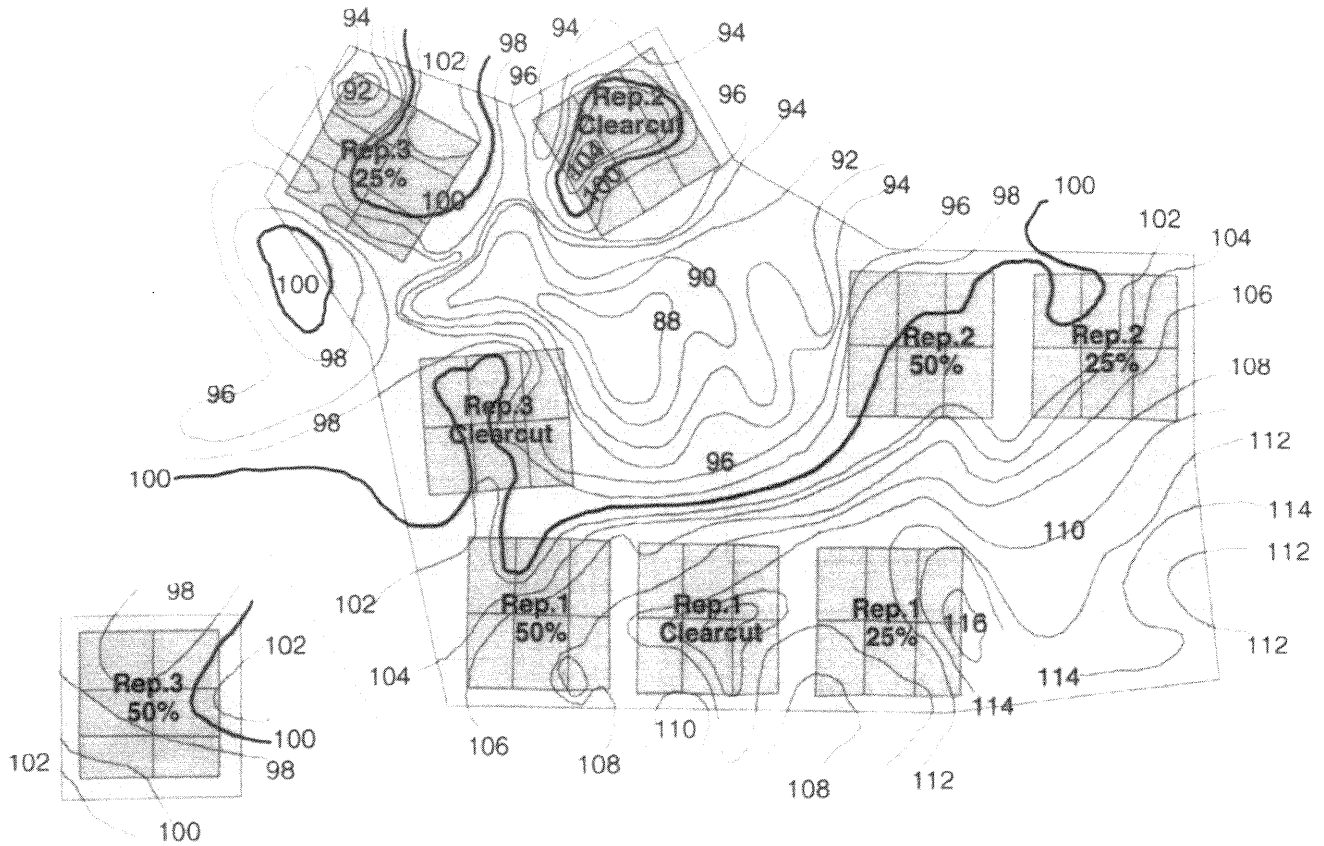

Figure 1—Contour map of the Bird Lake site with locations of clearcut, 25 percent crown cover and 50 percent crown cover plots. The elevations shown are in meters and relative to the 100 line (e.g., 88 indicates 12 meters lower than 100 and 116 indicates 16 meters higher). The total relief in the area is approximately 28 meters. Isolines in the Rep 3 - 50 percent plot are not continuous with other isolines in the figure as the plot is located several hundred meters away. See table 3 for estimates of frost damage in each treatment unit.

raspberry had some leaf and shoot damage. The damage to ironwood was not as immediately noticeable as in red oak and white ash. The most susceptible parts of the current growth of ironwood were killed by the frost, and there was a measurable reduction in shoot length (data not shown). In contrast, sugar maple and aspen did not exhibit signs of frost damage. Shoot growth patterns observed here were similar to those reported by Buech (1976) at another site in northern Wisconsin.

Severity of frost damage to white ash and red oak varied in the 50 percent and control blocks depending, in part, on the distance to the edge of the clearcut block. In the control, class 7 damage occurred to a minor degree up to 20 meters from the edge of the clearcut. From 30 to 150 meters from the edge, no damage was observed (table 1). In the 50 percent block, class 6 and 7 damage was common near the edge of the clearcut, but gradually declined with distance from the edge of the clearcut. Beyond 80 meters, class 7 damage did not occur and undamaged seedlings were most common, although class 2 damage occurred up to 210 meters from the clearcut (table 2). The damage from 80 to 190 meters from the edge of the clearcut block may be representative of that

Table 1—Percentage of frost damaged seedlings in the control block as related to distance from the edge of the clearcut

Distance from edge	Frost damage class						
	1	2	3	4	5	6	7
m							
0-10	24	-	6	-	9	1	60
11-20	88	2	-	7	-	-	3
21-30	96	-	2	-	2	-	-
31-150	100	-	-	-	-	-	-

Class 1 = no damage, 2 = up to 20 percent of leaves damaged, 3 = 21 to 40 percent damage, 4 = 41 to 60 percent damage, 5 = 61 to 80 percent damage, 6 = 81 to 99 percent damage, 7 = all leaves killed.

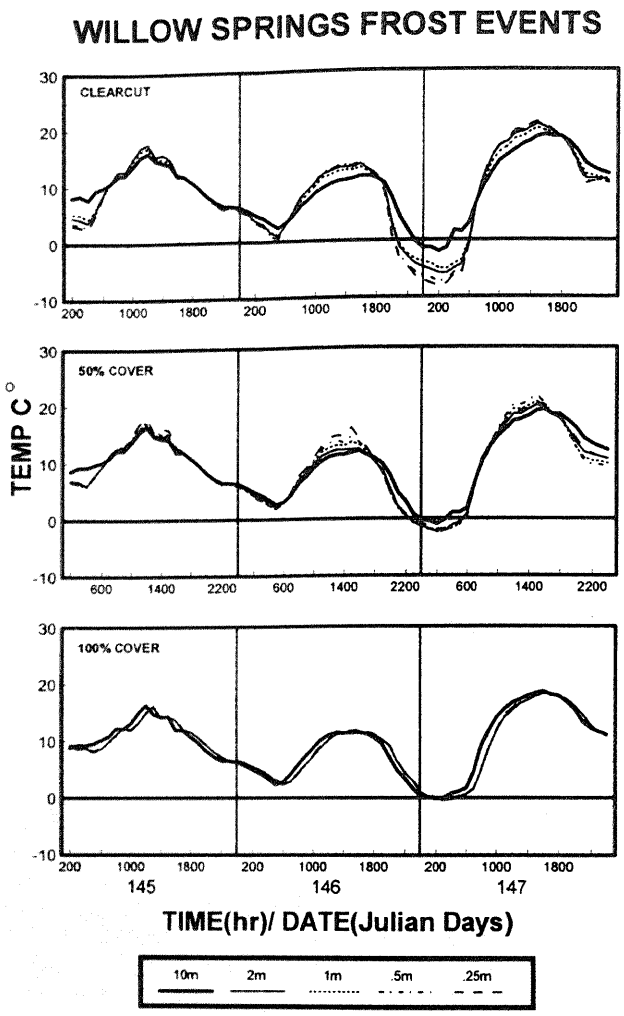

Figure 2—Temperature profiles in clearcut, 50 percent crown cover, and control blocks at the Willow Springs site on days 146 to 147.

Table 2—Percentage of frost damaged seedlings in the control block as related to distance from the edge of the clearcut

Distance from edge	Frost damage class 1	2	3	4	5	6	7
m							
0-10	-	-	-	-	-	-	100
11-20	-	-	-	-	-	-	100
21-30	-	-	-	-	10	-	90
31-40	-	-	-	-	8	-	92
41-50	2	-	6	2	6	10	74
51-60	25	14	7	4	10	14	25
61-70	29	19	12	9	12	12	7
71-80	61	19	5	5	4	5	2
81-90	74	18	4	4	-	-	-
91-100	93	6	-	1	-	-	-
101-110	78	19	-	3	-	-	-
111-120	93	6	-	1	-	-	-
121-130	82	18	-	-	-	-	-
131-140	100	-	-	-	-	-	-
141-150	87	13	-	-	-	-	-
151-160	78	22	-	-	-	-	-
161-170	80	20	-	-	-	-	-
171-180	89	11	-	-	-	-	-
181-190	73	27	-	-	-	-	-
191-200	87	13	-	-	-	-	-
201-210	96	4	-	-	-	-	-
211-280	100	-	-	-	-	-	-

Class 1 = no damage, 2 = up to 20 percent of leaves damaged, 3 = 21 to 40 percent damage, 4 = 41 to 60 percent damage, 5 = 61 to 80 percent damage, 6 = 81 to 99 percent damage, 7 = all leaves killed.

expected with a frost of this intensity (fig. 2) in larger blocks of continuous forest with these overstory conditions. Beyond 190 meters from the edge of the clearcut, the transect approached the uncut area and this may have affected microclimate (table 2). None of the other tree species or raspberry exhibited any evidence of frost damage in any part of the 50 percent block. The 75 percent block was surrounded by untreated forest and no damage to red oak, white ash or other species occurred.

The type of flushing after frost damage varied with the severity of damage. All plants with class 7 damage produced new flushes. Most commonly, the new shoot originated from dormant buds in the terminal bud cluster on the previous year's growth (fig. 3B) or from a dormant axillary bud on the previous year's growth or an axillary bud near the base of the seedling. Flushing in seedlings and stump sprouts was similar. Flushing began 1 to 2 weeks after the frost and was completed within about 2 weeks of budbreak. The post-frost flush was longer than the original flush in some trees (figs. 4 and 5).

Undamaged buds on the current year's shoot flushed (fig. 3C and 3D) on seedlings that sustained partial frost damage to leaves or shoots (e.g., red oak in the 50 percent block and ironwood in the clearcut block). Flushing occurred on stems with only damaged leaves and on those with damaged leaves and shoots pruned to varying lengths by the frost. For example, most of the leaves on the terminal shoot of tree 3 (fig. 4B) were killed and subsequently shed, but the shoot was not damaged. Following this damage, several axillary buds flushed, resulting in additional net shoot elongation for the year. Also, the tip of the shoot of tree 4 (fig. 4B) was killed and shoot length was reduced in the short-term; however, flushing of a bud on this shoot recovered the lost length and added an additional 10 centimeters.

Bird Lake

Red oak was the only species damaged by frost at Bird Lake. Other species present, but not damaged, were paper birch (*Betula papyrifera* Marsh.), red maple (*Acer rubrum*),

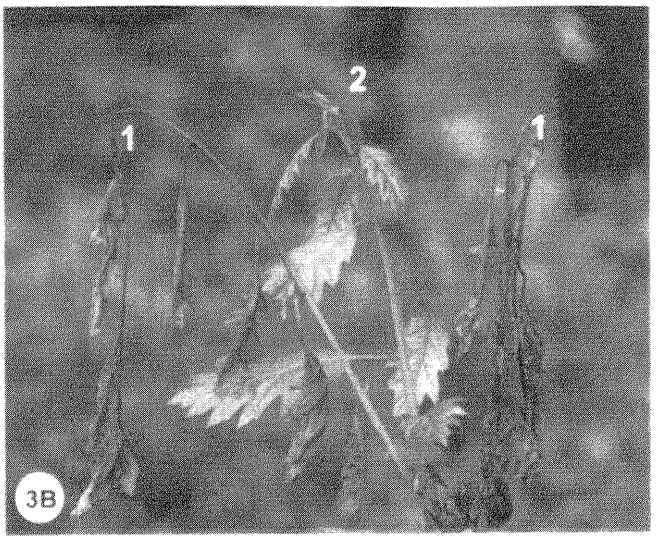

Figure 3—Examples of frost damage to northern red oak where (A) entire shoot and all leaves were killed, (B) close-up of frost killed shoot showing: (1) frost killed original flush and (2) new shoot formed by flush of dormant bud, (C) undamaged shoot with nodes where frost-damaged leaves have been shed and axillary buds flushing, (D) shoot with frost pruned tip and various degrees of leaf damage.

raspberry, and blackberry (*Rubus allegheniensis* Porter). Frost damage was not closely associated with any of the three overstory conditions in this area as it was at Willow Springs, but appeared associated with topographic position. However, seedlings and sprouts in 50 percent plots had the least damage (class 2-3), followed by the 25 percent plots and clearcuts, respectively. Although the number and size of plots in our study were not large enough to establish a definitive relationship between overstory condition and topographic position, frost damage

and topographic position seem related. For example, in the clearcut plots, the least damage occurred in the plot with the highest relative elevation (clearcut plot 2, fig. 1, table 3). Seedlings and sprouts in the 25 percent and 50 percent plots tended to have more class 6 and 7 damage where the elevation was below 100 than in those with elevations greater than 100 (fig. 1, table 3).

The height on the plant to which frost damage occurred differed among the plots. Affected seedlings always exhibited damage over the entire plant, suggesting that they were completely within the portion of the inversion layer with temperatures low enough to freeze stem and leaf tissues. However, stump sprouts in 25 percent plot 2 and 50 percent plot 2 were of sufficient height so that their tops were above the freezing conditions of the inversion layer, while their lower branches were damaged by freezing conditions. Red oak trees along roads with the lower part of their crowns damaged and the upper part undamaged were common in this area. The oak stump sprouts in clearcut plot 2 and 25 percent plot 3 showed damage over their entire vertical structure.

We did not follow the post-frost flushing on this site. However, measurements made at the end of the growing season indicated that all seedlings had produced new shoots and no mortality was observed as a result of the frost damage.

DISCUSSION

In northern Wisconsin, frosts often occur during the early growing season when trees are most susceptible to freezing temperatures. Frost damage should be viewed at different scales of resolution and as variable in space and time. At Willow Springs and Bird Lake, frost damage differed among shoots on the same plant, among species and populations of the same species in an area, and among stands within a landscape. We also observed variation in frost damage related to a significant depth-of-edge (Chen and others 1995) between areas differing in temperature regimes as, for example, between the clearcut block and the adjacent 50 percent and control blocks at our Willow Springs site. The observed penetration of frost damage into the control and 50 percent blocks from the clearcut at Willow Springs may have important implications for silvicultural practices such as strip or group selection cuts. The patterns of frost damage that we observed substantiate the work of Geiger (1965) on the spatial variation in frost damage in forests, and they provide examples of how hardwood forests of the northern Great Lakes region are affected by frost.

Understanding the role of frost in determining the composition and structure of these forests requires long term observations. Several things do stand out, however, from short-term observations. First, there are great differences in susceptibility to frost among species, and the most susceptible species, e.g., oak and ash, are at a disadvantage on sites where growing season frosts are common. For example, at Willow Springs, red oak was affected by frost in each of the past 6 years in the clearcut. Stump sprouts appear to have an advantage over seedlings in that they grow faster and attain heights that are above the damaging inversion layer during frost events and may be the best way to maintain oak as a component of the forest where frost is a concern. Oak sprouts in lower Michigan recovered quickly from frost damage and there was little effect on net shoot elongation (Johnson 1979).

Frost is probably not a critical factor by itself in terms of seedling survival. Rather, it is one of a host of biotic and abiotic factors affecting survival and growth. Buckley (1994, 1998) found that frost damaged seedlings often died, but that a combination of frost and repeated browsing of the new shoots (produced after the frost) likely caused most of

Table 3—Percentage of frost damaged seedlings at the Bird Lake site relative to canopy cover and elevation

Frost damage class	Clearcut			25 percent crown cover			50 percent crown cover		
	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3
	----------Elevation (m) ---------			----------Elevation (m)----------			----------Elevation (m)----------		
	108-114	94-104	96-100	110-116	100-108	92-102	102-110	96-102	98-102
1	25	-	2	31	28	-	25	14	45
2	34	-	19	27	23	-	41	12	10
3	29	-	17	22	11	-	26	8	3
4	4	-	17	11	3	-	2	11	-
5	5	-	8	4	2	-	-	14	5
6	2	-	21	-	20	-	-	15	8
7	2	100	17	5	12	100	7	26	28

Class 1 = no damage, 2 = up to 20 percent of leaves damaged, 3 = 21 to 40 percent damage, 4 = 41 to 60 percent damage, 5 = 61 to 80 percent damage, 7 = all leaves killed.

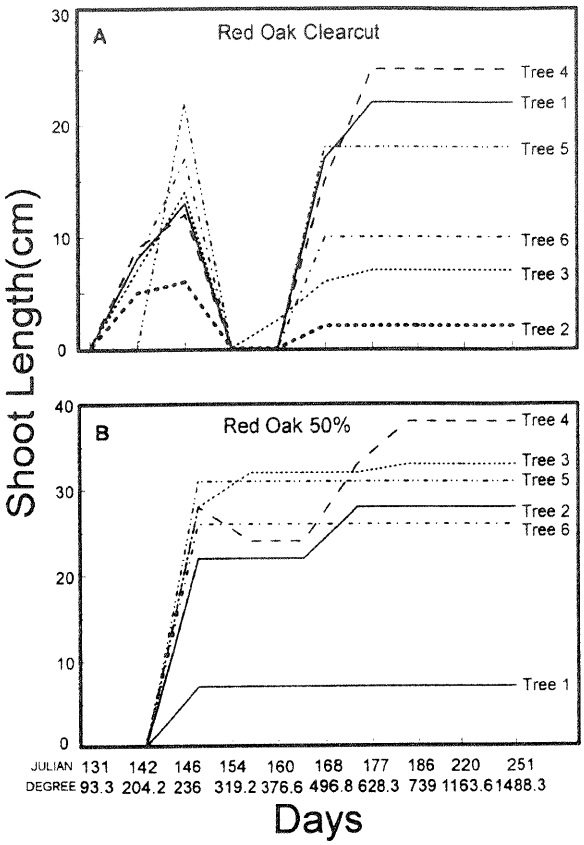

Figure 4—Shoot elongation of red oak in (A) clearcut, and (B) 50 percent crown cover block at the Willow Springs site. The frost on Julian days 146 and 147 killed all new shoot growth in the clearcut (fig. 3A), but affected only less mature tips of shoots in 50 percent crown cover (fig. 3C and 3D). Shoot growth of individual trees is shown for clearcut and 50 percent crown cover areas to better illustrate some of the variation within the seedling population. Note the effect of frost pruning on shoot length of tree 4 and on shoot elongation resulting from flushing in trees 2 and 4 in 50 percent crown cover.

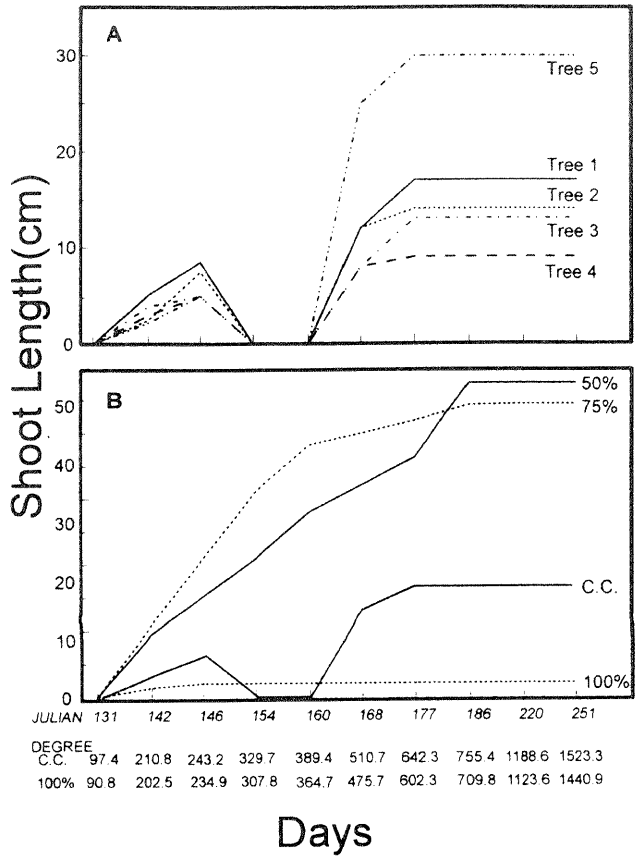

Figure 5—Shoot elongation of white ash (A) 5 individual trees in the clearcut, and (B) average of 5 trees in clearcut, 50 percent and 75 percent crown cover, and control blocks at Willow Springs.

the mortality. Where portions of terminal leaders are severely frost-pruned, reductions in height and photosynthate production may decrease growth rate and increase the period when a large proportion of the photosynthetic tissues of a seedling are susceptible to additional frosts, herbivory, and competition with understory vegetation.

Our work confirms the studies of Ringger (1972) on microclimate of forest gaps in northern hardwoods, as well as the broader experience of Geiger (1965) who found that silvicultural treatments significantly influence microclimate and more specifically the distribution, severity and effect of frost in the landscape. The importance of creating or maintaining an overstory to reduce frost damage to oak regeneration was recognized 150 years ago by Emerson (1846), Crow (1992), Buckley (1994, 1998), and Gordon and others (1995). The appropriate level of overstory cover and composition will depend on the local topography of the area and the frequency and severity of frosts in an area. For areas with relatively little relief, such as our Willow Springs site, it appears that a 50 percent canopy cover is at the lower end of a threshold for total prevention of frost. This agrees with observations from lower Michigan (Buckley 1994, 1998) of a significant decrease in frost damage as crown cover increased from 25 to 75 percent. However, on sites with more irregular topography, such as Bird Lake, there is a relationship between overstory condition, topographic position, and potential for frost. Small gaps or clearcuts in areas with highly irregular topography might best be situated on relatively higher areas where cold air drainage does not result in frost pockets. Because of the depth-of-edge between areas with substantially different microclimates, there could be considerable damage to susceptible species in stands that are not large enough to have a true interior (Chen and others 1995).

In summary, these two case studies provide insight into some aspects of how frost affects the development of hardwood forests and how silvicultural treatments can be used to ameliorate frost in northern hardwood forests. In areas subject to frequent late spring frosts, managers would benefit from increased information about the relationship of frost damage to canopy cover, canopy

composition, and the size of canopy openings. Certainly more work is needed to characterize interactions between these factors and frost, and to understand the long-term impacts of frost on species in these forests.

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