NOTE / NOTE

Patterns of damage and mortality in red pine plantations following a major ice storm

K.L. Ryall and S.M. Smith

Abstract: The impact of a major ice storm in eastern Ontario on 28 pine plantations (red pine, *Pinus resinosa* Ait.; Scots pine, *Pinus sylvestris* L.; white pine, *Pinus strobus* L.; and jack pine, *Pinus banksiana* Lamb.) was examined for 4 years after the event. Degree of crown loss and tree mortality were quantified in relation to tree and stand characteristics (e.g., tree species, diameter at breast height (DBH), stand density, stand edge versus interior). We also tested whether salvaging damaged material reduced subsequent tree mortality. Jack and Scots pine were 2.5 times more likely to be damaged by the ice storm than were red pine and white pine. Overstocked stands, and stands with lower mean DBH, were most susceptible to storm damage. Trees were five times more likely to be damaged in the interior versus the edge of a stand, in contrast with previous findings in hardwood stands. In unsalvaged stands, ca. 75% tree mortality was observed in severely damaged trees (>50% crown loss) compared with ca. 45% tree mortality in salvaged stands. Properly timed thinnings to increase diameter growth and the removal of dead and dying wood from heavily damaged stands are recommended to reduce the long-term effects of ice storms.

Résumé : Pendant les 4 années qui ont suivi une importante tempête de verglas survenue dans l'est de l'Ontario, les auteurs ont étudié l'impact de cette tempête dans 28 plantations de pins (pin rouge, *Pinus resinosa* Ait.; pin sylvestre, *Pinus sylvestris* L.; pin blanc, *Pinus strobus* L. et pin gris, *Pinus banksiana* Lamb.). Le degré de perte de cime et la mortalité des arbres ont été quantifiés en relation avec les caractéristiques des arbres et du peuplement (p. ex., espèce d'arbres, diamètre à hauteur de poitrine (DHP), densité du peuplement, bordure versus intérieur du peuplement). Ils ont aussi vérifié si le fait de récupérer les arbres endommagés réduirait la mortalité par la suite. Le pin gris et le pin sylvestre avaient 2,5 fois plus de chances d'être endommagés par le verglas que le pin rouge et le pin blanc. Les peuplements avec une densité relative excessive et les peuplements avec un plus faible DHP moyen étaient les plus susceptibles d'être endommagés par le verglas. Les arbres avaient cinq fois plus de chances d'être endommagés à l'intérieur qu'en bordure d'un peuplement contrairement à ce qui a été rapporté précédemment dans le cas des peuplements feuillus. Dans les peuplements où il n'y avait pas eu de récupération, la mortalité atteignait environ 75 % chez les arbres sévèrement endommagés (>50 % de perte de cime) comparativement à environ 45 % dans les peuplements où des travaux de récupération avaient été effectués. Des éclaircies effectuées au moment opportun pour augmenter la croissance en diamètre et enlever les tiges mortes ou mourantes dans les peuplements sévèrement endommagés sont recommandées pour réduire les effets à long terme des tempêtes de verglas.

[Traduit par la Rédaction]

Introduction

Ice or glaze storms are common in forests of the eastern United States and Canada. Tree damage from ice storms includes snapped stems, broken branches, and uprooted and bent trees (Stroempl 1971). In January 1998, an unusually severe ice storm occurred across eastern Canada and the northeastern United States. In the Maritimes, New England, Quebec, and eastern Ontario, approximately 10×10^6 ha of forested land were damaged by the storm (Meating et al. 2000), including more than 100 red pine (*Pinus resinosa* Ait.) plantations in eastern Ontario. The economic impact of this storm was enormous; total losses for red pine plantations have been estimated to be between \$21 million and \$32 million across the region (Heigh et al. 2003).

The ecology of ice-storm disturbances has been the subject of much research (reviewed by Van Dyke 1999; Bragg et al. 2003); however, the majority of studies have focused on hardwoods and on tree-level damage. Less is known about effects on conifers, although Lemon (1961), Whitney and Johnson (1984), and Boerner et al. (1988) all found pine

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Table 1. Classification system used to measure the level of damage to pine trees following the January 1998 ice storm across eastern Ontario.

Type of damage	Description of damage
Damage category	
0	No visible damage to crown
1	<25% crown loss, typically only leader lost
2	25%–50% crown loss
3	50%–75% crown loss but with some green branches
4	Complete stem breakage below the crown
Damage descriptor	
Snag	Standing portion of bole with no live crown remaining
Snap-top	Crown portion broken completely from bole, fallen to ground
Bent	Considerable arc in bole, often with crown touching ground
Uproot	Root system pulled out of soil and visible, tree lying on ground
Blowdown	Tree laying on ground but root system not visible above soil

species to be vulnerable to periodic storm events. Although the likelihood of mortality following disturbance is related to the amount of injury (Whitney and Johnson 1984; Boerner et al. 1988), the long-term prognosis for damaged pine trees is uncertain because previous studies have only addressed short-term (often only 1 to 2 years) effects. Pine plantations were salvaged immediately following the 1998 ice storm; however, information on the efficacy of such operations in preventing further damage and improving the future health of the forest is needed.

Our research was initiated to quantify (1) the relationship between levels of damage and forest and tree characteristics and (2) longer term patterns of mortality in damaged trees from salvaged or unsalvaged stands. Based on the literature, we hypothesized that (1) ice-storm damage would be greatest in poorly managed, overstocked stands; (2) longer term mortality would be greatest in trees with significant crown losses; and (3) salvaging operations would significantly reduce longer term mortality.

Methods

Field observations were conducted across eastern Ontario, from south of Pembroke and east to the Ontario–Quebec border. In the summer of 1998, data were collected from stands containing red pine across the affected region to characterize patterns of storm damage. Damaged plantations were identified and located from aerial surveys taken from January to March after the storm (Scarr et al. 2003). Twenty-eight stands were selected to represent varying levels of damage across the study region. Because stand-level values for ice accumulation were not available, information on ice deposition levels was obtained from an isocline map provided by the Ontario Ministry of Natural Resources (OMNR). Five additional stands, with one or more other species of pine (e.g., red pine, *Pinus resinosa*; Scots pine, *Pinus sylvestris* L.; jack pine, *Pinus banksiana* Lamb.; or white pine, *Pinus strobus* L.), were also sampled to compare damage among tree species. Three stands contained three of the pine species (red, Scots, and jack pine) and the remaining two stands contained two species (red pine and white pine only). All sites were plantations that were originally established on abandoned agricultural land. Little hardwood understorey was present in any of the sites (15% ± 4% (mean ± SE) ground cover by saplings). Stand age ranged from ca. 30 to 60 years old and canopy heights, from 15 to 20 m. Detailed information on the density, age, and diameter at breast height (DBH at 1.3 m) is provided by Ryall (2003).

Within each stand, one transect (200 m × 2 m) was sampled, recorded as 10 consecutive 20-m sections. Transects started at a random point at the edge of each plantation and extended along a random compass bearing into the interior of the plantation. Transect size and length were chosen to provide an adequate representation of each stand, yielding results similar to those based on initial visual assessments of the stand overall. For each tree within the transect, tree DBH and species were recorded. The level of damage to an individual tree was measured by assigning a subjective damage category (Table 1). Visual assessments of crown loss were made independently by two field workers and then compared for consistency. Despite difficulties with crown loss assessments on hardwood trees (e.g., Rhoads et al. 2004), visual assessments of conifers are considerably simpler and more accurate, because of their simple crown growth form. The diameter of each piece of coarse woody debris (CWD) that crossed the centre line of the 200-m transect was also recorded.

Stand density was calculated as the number of stems per hectare. Percent stand damage was calculated as the percentage of stems within a given stand having >25% crown loss. The volume of CWD was calculated using the sampling method commonly employed to measure fuel for forest fires (CWD volume = $(\pi^2(\Sigma\,(\text{CWD diam}^2 \times 10\,000))\ /\ 8(200))$ (Van Wagner 1968).

Linear regression analysis was used to examine the relationship between stand density and percent damage (percentage of stems with >25% crown loss) as well as the relationship between mean stand DBH and percent stand damage (percentage of stems with >25% crown loss). Initially, the intention was to perform a regression between the percent stand damage and ice accumulation; however, there was insufficient variation in the amount of ice accumulation based on these area-level data. For all statistics, parametric tests were used when the normality and variance assumptions were met; the equivalent nonparametric tests were used in those cases where assumptions were violated. All data analyses were conducted in SYSTAT® version 5.0 (Systat Software Inc., Point Richmond, Calif.).

Differences in the mean damage rating (0–4 for each species) among the four pine species were assessed using covariate analyses. Two separate analyses were conducted: one on the three sites containing three pine species (red, Scots, and jack pine) and one on the two sites containing two pine species (red pine and white pine). Independent variables included species and site, with DBH as a covariate. Post-hoc comparisons between pine species were made using Tukey's tests.

Given that each transect ran from near the edge of a stand towards its interior, damage levels could be compared between the edge and the interior of each stand. To do this, mean percent damage was calculated for the first section (on the edge) and compared with that of the fourth or fifth section (near the interior). Percent damage was defined as the number of trees with >25% crown loss in that segment of the transect. Data on the relative damage were analyzed using a Wilcoxon signed ranks test in 19 of the 28 stands. The remaining stands were not considered, because they did not have a transect running directly from the edge to the interior of the plantation.

Tree mortality was monitored for 4 years after the ice storm over a range of damage classes (Table 1) using permanent sample trees in four red pine stands. Ten trees from each of the four classes of crown damage were tagged in each stand (e.g., 40 trees per stand, for a total of 160 trees) and assessed annually from 1998 to 2001. At each sample date, all tagged trees were recorded as either alive (with some green branches) or dead. A two-way ANOVA was used to test for significant relationships between the percentage of mortality with increasing damage rating (e.g., percentage of 10 trees dead in each of the four damage categories with four stand replicates) and with stand type (unsalvaged stands compared with salvaged stands, see below).

Four stands that had dead and dying wood removed (salvaged) were sampled in 1999 to assess whether salvage operations reduced subsequent tree mortality among damaged trees that were left standing following the salvaging operation. One transect (200 m × 2 m) was placed in each stand to measure the volume of CWD left onsite after salvaging operations. In 2001, the stands were revisited and a minimum of 20 damaged trees (minimum of five trees per damage category) were located randomly within each site and the number of alive or dead trees was again recorded. Levels of mortality in standing damaged trees were compared between the two stand types (salvaged stands and unsalvaged stands) using a two-way ANOVA including stand type (salvaged versus unsalvaged) and damage class (categories 1 to 3 only, see Table 1). Damage category 0 was not included in the analysis as this would be examining natural levels of mortality, which are extremely low, and their inclusion violates the assumptions of homogeneity of variances and artificially increases the probability of finding a significant damage class effect. There was no significant interaction between damage class and stand type; hence, this was not included in the analysis.

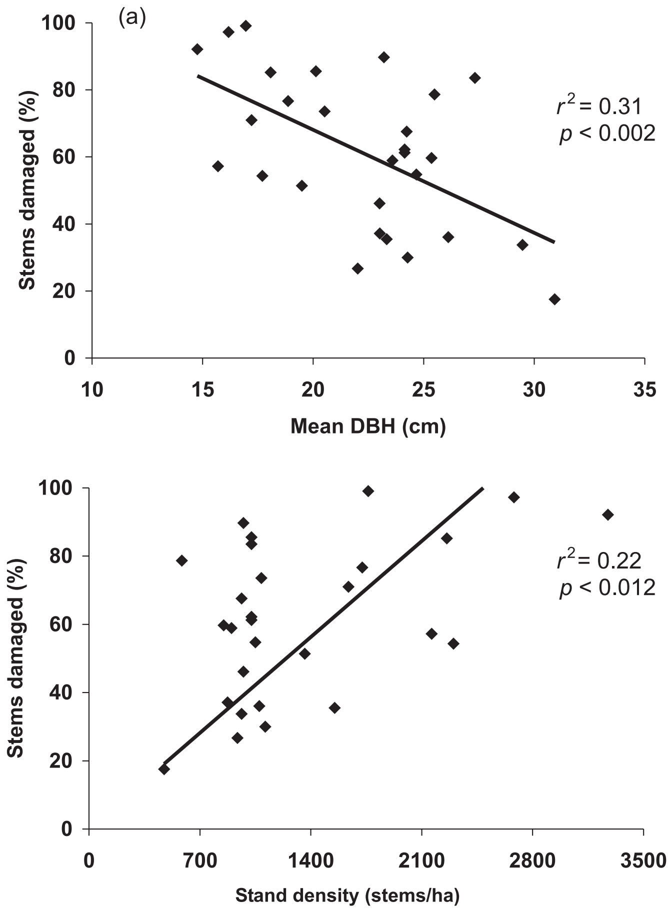
Results

The 1998 ice storm caused varying levels of tree and stand damage, including crown loss, and uprooting and bending of whole trees. Damage was highly variable (ranging from 4% to 81% of trees with >25% crown loss) across the 28 damaged stands. Ice accumulation ranged from 40 to 80 mm based on the isocline map, with 21 of 28 stands located within the 60-mm ice deposition range. Damage levels in those 21 stands ranged from 0% to 71%. Stand density prior to the ice storm (sum of the number of damaged and undamaged trees in each transect) averaged 1344.1 (±124.9) stems/ha (mean ± SE), and an average of 385.2 (±96.5) trees/ha were killed outright by the storm (i.e., complete stem breakage or uprooting). In addition, the storm damaged, but left standing, an average of 89.8 ± 17.1 trees/ha with >25% crown loss and left 38.8 (±7.7) highly susceptible trees/ha with severe crown damage of >50% crown loss. Over six times as much recently created CWD was found in highly damaged stands compared with that in undamaged stands (134.4 (±30.2) versus 23.3 (±11.7) m^3).

The ice storm caused varying amounts of crown damage among the different pine species. White pine (mean damage index rating: 0.64 (±0.11)) exhibited less damage than red pine (0.99 (±0.04) ($F_{[1, 250]} = 10.4$; $r^2 = 0.4$; $p = 0.001$) with a significant difference in mean damage levels between the two sites containing both species ($F_{[1, 250]} = 62.7$; $r^2 = 0.4$; $p < 0.001$). A significant interaction between site and species ($F_{[2, 250]} = 4.4$; $r^2 = 0.4$; $p = 0.04$) indicated that red pine had a higher mean damage rating than white pine only in the site with higher overall mean damage. Mean damage ratings declined significantly with increasing tree DBH ($F_{[1, 250]} = 55.4$; $r^2 = 0.32$; $p < 0.001$) for red pine and white pine. There was also a significant difference in mean damage ratings among the three-species comparisons ($F_{[2, 457]} = 8.5$; $r^2 = 0.3$; $p < 0.001$); red pine had significantly lower mean damage ratings (1.09 (±0.06) than either Scots pine (2.18 (±0.13), $p < 0.05$) or jack pine (2.36 (±0.13), $p < 0.05$). There was no significant difference in mean damage rating among the three sites ($F_{[2, 457]} = 2.3$; $r^2 = 0.3$; $p = 0.09$) and no significant interaction between species and site ($F_{[4, 457]} = 0.7$; $r^2 = 0.3$; $p = 0.6$). Mean damage ratings declined similarly with increasing tree diameter ($F_{[1, 457]} = 62.8$; $p < 0.001$). These differences in mean damage ratings were found after controlling for the effects of varying DBH among the pine species, where red pine (mean DBH = 20.2 ±0.6 cm) was significantly larger than white pine (18.7 ± 5.3 cm) ($F_{[1, 253]} = 31.9$; $r^2 = 0.2$; $p = 0.001$) and also jack pine (11.9 ± 3.4 cm) and Scots pine (16.6 ± 5.8 cm) ($F_{[1, 253]} = 58.6$; $r^2 = 0.2$; $p = 0.001$).

Crown damage in red pine stands declined with increasing mean stand DBH ($F_{[1, 26]} = 11.9$; $r^2 = 0.3$; $p = 0.002$; $n = 28$ stands) (Fig. 1*a*) and increased with mean stand density ($F_{[1, 26]} = 7.3$; $r^2 = 0.2$; $p = 0.01$; $n = 28$ stands) in these pure stands (Fig. 1*b*). The same relationships are found when only the 21 stands with 60-mm ice deposition are included in the analysis (DBH and damage: $F_{[1, 19]} = 7.1$; $r^2 = 0.3$; $p = 0.02$; density and damage: $F_{[1, 19]} = 9.4$; $r^2 = 0.3$; $p = 0.006$). These findings are probably related to the natural inverse relationship between stand DBH and stand density in younger pine plantations ($F_{[1, 26]} = 55.9$; $r^2 = 0.7$; $p < 0.001$; $n = 28$ stands). Similarly, there was a natural positive relationship between stand age and mean stand DBH ($F_{[1, 26]} = 6.26$; $r^2 = 0.23$; $p = 0.02$) and a significant negative relationship between stand age and mean stand density ($F_{[1, 26]} = 8.2$; $r^2 =$

Fig. 1. Relationship between percentage of total stems damaged (any level of damage) and (*a*) mean stem diameter at breast height (DBH) and (*b*) stem density for red pine (*Pinus resinosa*) plantations in eastern Ontario damaged by the 1998 ice storm (n = 28 stands).



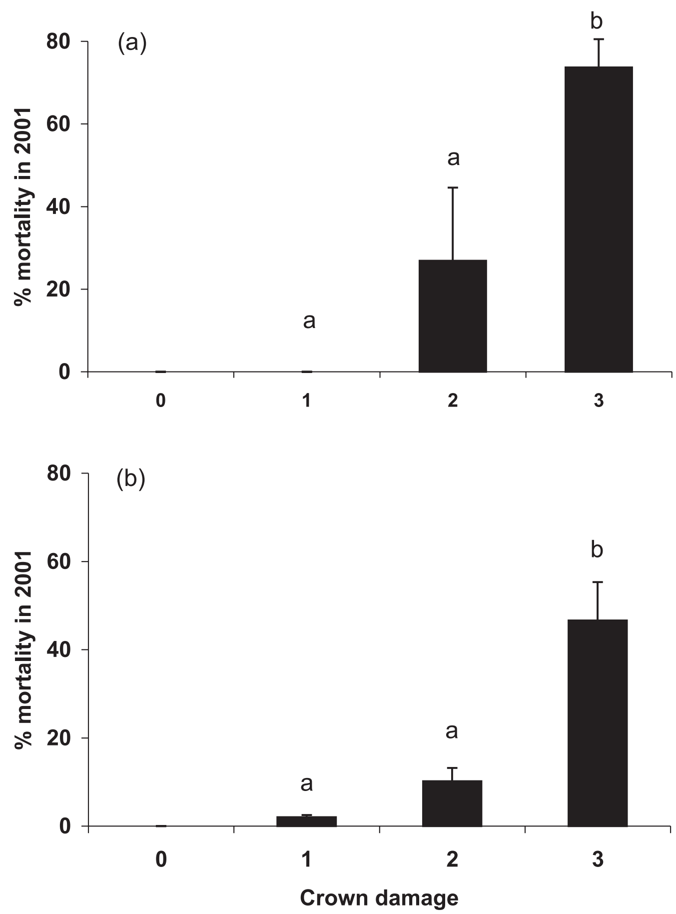
0.29; p = 0.01). However, stand age was itself not related to storm damage levels ($F_{[1, 26]}$ = 0.554; r^2 = 0.17; p = 0.78).

Extent of damage to trees in the red pine plantations varied with distance from the stand edge. Significantly more trees were damaged (higher percentage of trees with >25% crown loss) in the interior of a plantation than at the edge of a plantation, based on the relative storm damage index (edge: 0.3 (±0.1); interior: 1.5 (±0.1); Wilcoxon signed ranks test, Z = 3.1, n = 19, p < 0.002). Mean DBH of trees located at the edge as compared with mean DBH of trees in the interior was not significantly different (edge: 21.1 (±1.2) cm; interior: 19.9 (±0.9) cm; t-test, t = 1.25, n = 19, p = 0.2).

At least 75% of those trees that had high levels of crown damage (>50% crown loss, category 3) in 1998 were dead by the end of 2001 (Fig. 2). On average, 41.3% of the damaged trees (>25% crown loss, categories 2 and 3) in the four unsalvaged stands died after 4 years, whereas essentially no mortality was observed in the undamaged trees (categories 0 and 1) (Table 1). Higher levels of mortality were observed in trees with greater amounts of crown loss ($F_{[2,24]}$ = 25.7; p = 0.0001), when comparing unsalvaged and salvaged stands for categories 1–3 (see below).

Salvaging took place during 1998 and typically involved removing mostly damaged standing trees (>50% crown loss) and large CWD located on the ground. As expected, salvaged stands had significant reductions in both the volume of CWD and tree density compared with that of unsalvaged stands. CWD averaged 85.9 (±22.3) m^3/ha in salvaged stands compared with 134.4 (±32.2) m^3/ha in unsalvaged stands. Stand density was also reduced following salvaging, as only 512.9 (±36.6) trees/ha were left, which was fewer than in the damaged, but unsalvaged stands (1344.1 (±124.9) trees/ha). Slightly fewer damaged trees per hectare (62.9 (±15.2) trees/ha with >25% crown loss) were found in the salvaged stands compared with that of the damaged unsalvaged stands (89.8 (±17.1) trees/ha). Mortality in damaged trees that remained following salvage operations in the four salvaged stands was not reduced significantly compared with mortality of damaged trees in four of the unsalvaged stands ($F_{[1,24]}$ = 2.3; p = 0.14) (Figs. 2*a*, 2*b*); overall mortality levels remained relatively high in damaged trees (24.6% mortality in trees with >25% crown loss, categories 2 and 3 combined, p = 0.0001) (Fig. 2*b*).

Fig. 2. Tree mortality 4 years after the 1998 ice storm according to crown damage in either (*a*) unsalvaged (n = 4 stands with 40 trees per stand (10 trees per class)) or (*b*) salvaged (n = 4 stands with a minimum of five trees per class) red pine (*Pinus resinosa*) plantations, in 2001, across eastern Ontario. Vertical bars indicate standard errors. Letters indicate significant differences between means of damage categories within figures. (Two-way ANOVA was used for differences between salvaged and unsalvaged stands and between damage categories 1, 2, and 3.) (See Table 1 for crown damage classification.)



Discussion

Mortality caused directly by the ice storm in 1998 (i.e., up to 72% of trees with >50% crown loss) was higher than reported in the majority of previous studies. Whitney and Johnson (1984) reported 50%–75% mortality in pine species following a similar storm in southwestern Virginia, whereas Webb (1989) found only 0.6%–0.7% mortality in red pine and 0.9%–2.6% in white pine following a windstorm in Minnesota. Similar events left ca. 7% of the trees severely damaged (>1/3 crown loss) in old-growth oak–hickory forests (Rebertus et al. 1997), 46% of trees in mixed hardwood stands in Virginia (Whitney and Johnson 1984), and >30% of stems in pine plantations in Georgia (McKeller 1942).

Differential susceptibility to damage from ice accumulation was also reported by Stroempl (1971), who found that white pine was the most windfirm of all pine species, with increasing susceptibility in red, Scots, and jack pine. Other studies have shown pines in general, particularly red pine and white pine, to be highly susceptible to ice damage compared with hardwood tree species (Boerner et al. 1988; Foster 1988), although Hopkin et al. (2003) found conifers to be less damaged by the 1998 ice storm than were hardwoods.

In our study, large diameter trees were less damaged by ice accumulation than small diameter trees. This contrasts Belanger et al. (1996), who found no difference in damage to loblolly pines (*Pinus taeda* L.) of different size classes (DBH) following an ice storm. Other studies report more damage to larger trees (Van Dyke 1999), although often in hardwood forests (Rhoads et al. 2002; Nielsen et al. 2003) or following other types of disturbances (Webb 1989; Platt et al. 2000). Generally, past work has recommended that pine stands be thinned with the specific intent of producing thick, heavily boled trees resistant to ice-storm damage (Williston 1974). Our results on pine tree diameter support the strategy of thinning to manage for tree resistance.

With respect to damage levels, it is difficult to separate the effects of stem diameter from those of stand density and stand age. We found a strong positive relationship between tree damage and stand density, which further enhances the benefits of thinning to prevent damage from ice accumulation. In addition, the lack of a relationship between stand age and damage levels supports our conclusions that the size and density of conifer stems are important determinants of storm damage levels. Other studies on plantations have shown that thinned, or less dense, stands are more resistant to ice-storm damage than unthinned stands (Mulloy 1946; Cayford and Haig 1961; Stroempl 1971; Van Dyke 1999), but that stands thinned just prior to the event were more vulnerable than adjacent unmanaged stands (Foster 1988; Van Dyke 1999; Bragg et al. 2003). Unfortunately, because of the unpredictability of such catastrophic events, it is nearly impossible to correctly time thinnings to minimize the potential impact of ice storms (Belanger et al. 1996). The best that managers can hope to achieve is to follow standard silvicultural practices and employ a few light thinnings during the early stages of stand growth. Stand density may also partially explain why we saw extensive damage in red pine stands with no apparent relationship to stand age in areas throughout eastern Ontario following the 1998 ice storm. Mixed management objectives over the past several decades in these stands meant they did not have sufficient noncommercial thinning, and this may have left them relatively dense as they matured compared with stands in other studies, and, thus, with a greater vulnerability to ice accumulation.

Red pines along the edge of plantations were less susceptible to ice-storm damage than red pines in the interior of plantations. This observation supports initial observations following the storm on pine plantations (Meating et al. 2000) and one previous study on jack pine (Kienholz 1941). In contrast, other studies report higher amounts of damage to hardwood trees located on the forest edge as compared with damage in the interior (Seischab et al. 1993; Meating et al. 2000) or no difference (Proulx and Greene 2001). Finally, when simulating windstorm damage adjacent to clear-cut areas, Peltola (1996) predicted that trees growing near the edge of a forest were more susceptible to uprooting than trees in the interior; however, trees on the newly formed edge would not be accustomed to growing on an edge.

Volumes of CWD averaged 134 m^3/ha in the damaged red pine plantations but were virtually absent in undamaged plantations. Previous studies have reported much lower values for CWD input; for example, Rebertus et al. (1997) found that CWD input averaged 5.1 m^3/ha following an ice storm in old-growth oak–hickory forests, while Bruederle and Stearns (1985) found 19.3 m^3/ha CWD was created following an ice storm in Wisconsin. CWD included various types of pine material, from snapped, severed tops to standing snags, uprooted and blowndown trees, and trees with varying levels of crown damage and loss. This CWD is problematic in that it can be utilized by bark beetles and wood-boring beetles (Coleoptera: Scolytidae and Cerambycidae), whose populations can build up following such a disturbance event (Hopkin et al. 2001) and lead to additional tree mortality.

The likelihood of mortality in trees with significant crown damage was high in our study. In contrast, other studies have concluded that conifer trees with at least two to five living branches will survive after such a large-scale storm event (Gardiner 1975; Schroeder and Eidmann 1993; Barry et al. 1993); indeed, in our study, red pine trees with only 5–10 live branches were able to survive the first two growing seasons following the 1998 ice storm (Ryall, personal observation). However, almost 40% of trees that had crown damage were dead or dying four growing seasons after the storm. The greater mortality we observed may be due to red pine's relatively susceptible to ice-storm damage (Stroempl 1971; Lemon 1961), and those species that are highly susceptible to ice damage have been predicted to die at higher rates (Lemon 1961; Whitney and Johnson 1984). All plantations examined in this study were on abandoned agricultural land; hence, depleted soil nutrients may also be a factor. In addition, weather conditions during the growing seasons following a disturbance (e.g., drought) may exacerbate levels of tree mortality. Finally, the majority of previous studies stopped monitoring trees after only two or three growing seasons and thus would not report delayed tree mortality. Longer studies are needed to ascertain whether the lightly damaged trees in these stands will continue to have higher rates of mortality.

Effects of salvaging operations were also highly variable. Compared with unsalvaged stands, salvaged stands had only slightly reduced volume of CWD, possibly because salvage operators may have focussed on merchantable material (standing trees with variable amounts of crown loss). Schroeder and Lindelöw (2002) found that significantly more spruce trees, *Picea abies* L., died in unsalvaged stands following a stormfelling. However, in our study, while there were fewer heavily damaged trees per hectare in the salvaged areas, a large proportion of them were dying in subsequent years. The salvaging operations failed to prevent further tree mortality in damaged trees left onsite, so we recommend the removal of heavily damaged trees by salvaging.

In conclusion, our results supported two of our hypotheses: (1) storm damage was greatest in poorly managed, overstocked stands and (2) trees with significant crown losses experienced high rates of subsequent mortality. However, our third hypothesis that salvaging operations would significantly reduce longer term tree mortality was not supported. Salvaging operations may help foresters recover damaged material that retains some economic value, but these operations do not necessarily improve longer term stand health. Our study points strongly to the need for regular thinnings in young red pine stands to maintain high rates of growth and tree vigour, increase stem DBH, and reduce stand density. In so doing, forest managers will produce trees that are better able to withstand such unpredictable, yet highly damaging, events as the 1998 ice storm.

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