Effects of Ice Storm Damage on Hardwood Survival and Growth in Ohio

Richard M. Turcotte, Thomas R. Elliott, Mary Ann Fajvan, Yong-Lak Park, Daniel A. Snider, and Patrick C. Tobin

ABSTRACT

In 2003, an ice storm occurred across four Mid-Atlantic states. This study investigated the effects of the ice-storm damage on growth and mortality of five tree species (*Acer rubrum, Acer saccharum, Quercus alba, Quercus prinus*, and *Quercus rubra*) from three forest stands in the Wayne National Forest in Ohio. We remeasured the same trees five times between 2003 and 2009. Logistic regression analysis of mortality revealed significant ($P < 0.05$) effects of tree species, crown damage, and size class. We detected a significant effect of crown class on epicormic branching ($P < 0.01$), and saplings and poles as a group had significantly less dieback than sawtimber ($P < 0.01$). Dieback also varied according to crown class, with codominant and dominant trees having significantly ($P < 0.05$) more dieback than both intermediate and overtopped trees. We detected a significant ($P < 0.01$) reduction in diameter growth when >33% of a tree's crown was damaged. The results of this study will help forest managers to make decisions about salvage, sanitation, and forest rehabilitation efforts following ice storm damage.

Keywords: ice storm, crown damage, epicormic sprouts

Ice or glaze storms are among the most frequent climatic disturbance events (Smith 2000), but they are generally considered partial disturbances (Oliver and Larson 1996) because not all of the existing trees are killed, and some predisturbance trees survive (Oliver 1981). Forest development after such storms is determined by the extent of physical damage, residual density, species, vigor and spatial arrangement of the surviving trees, and whether or not a new cohort develops in the understory (Oliver and Larson 1996). A typical ice storm event lasts for 5–15 days, with an occurrence rate of 2–8 storms per decade in the northern United States (Van Dyke 1999, Lafon and Speer 2002, Takahashi et al. 2007). Although these storms can develop from a number of different weather patterns, they typically form when a winter warm front passes over lower level air masses with a temperature at or below freezing. Under these conditions, rain falling through the layers of cooler air becomes supercooled and then freezes on tree limbs, foliage, and other surfaces to form glaze ice (Lemon 1961, Melancon and Lechowitz 1986). The ice thickness can range from a thin film to as much as 9 cm (Downs 1938, Brommit et al. 2004).

Tree susceptibility to ice storm damage is influenced by biotic factors (e.g., species, age, crown shape, wood tensile strength, crown position, and density) (Croxton 1939, Smith and Shortle 2003, Brommit et al. 2004) and abiotic factors (e.g., physiographic, climatic, and edaphic factors) (Whitney and Johnson 1984, Boerner et al. 1988, Hopkin et al. 2003). Generally, the decurrent growth form of some deciduous species (e.g., *Quercus rubra*; Zimmerman and Brown 1971) makes them more susceptible to branch and stem breakage than trees with excurrent growth forms, such as spruces. Damage can be especially severe if leaves are still present, trees are supporting vines (Siccama et al. 1976), and/or heavy winds are associated with the ice storm event (Lemon 1961, Warrillow and Mou 1999, Rhoads et al. 2002). Tree survival and subsequent growth rates are directly influenced by the extent of physical damage and indirectly by climatic site variables and insect and disease invasion into wounds. Tree wounds can provide favorable sites for attack by insects and decay fungi (Rogers 1923, Campbell 1937).

Reduction of the forest canopy by stem and branch breakage increases the amount of sun exposure on residual stems, favoring the development of epicormic branches (Blum 1963, Meadows 1995). The probability of epicormic branching is also related to species/genetics (Smith 1966, Ward 1966, Van Dyke 1999), aspect, site productivity, crown position, stand density (Miller 1995), and history of forest management (Smith et al. 1997). A decline in tree vigor from stem damage may also initiate growth of epicormic branches (Meadows 1995). Epicormic branches can reduce tree quality through the formation of knots, wood blemishes, and other defects (Smith 1966, Miller 1995).

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; hectares (ha): 1 ha = 2.47 ac.

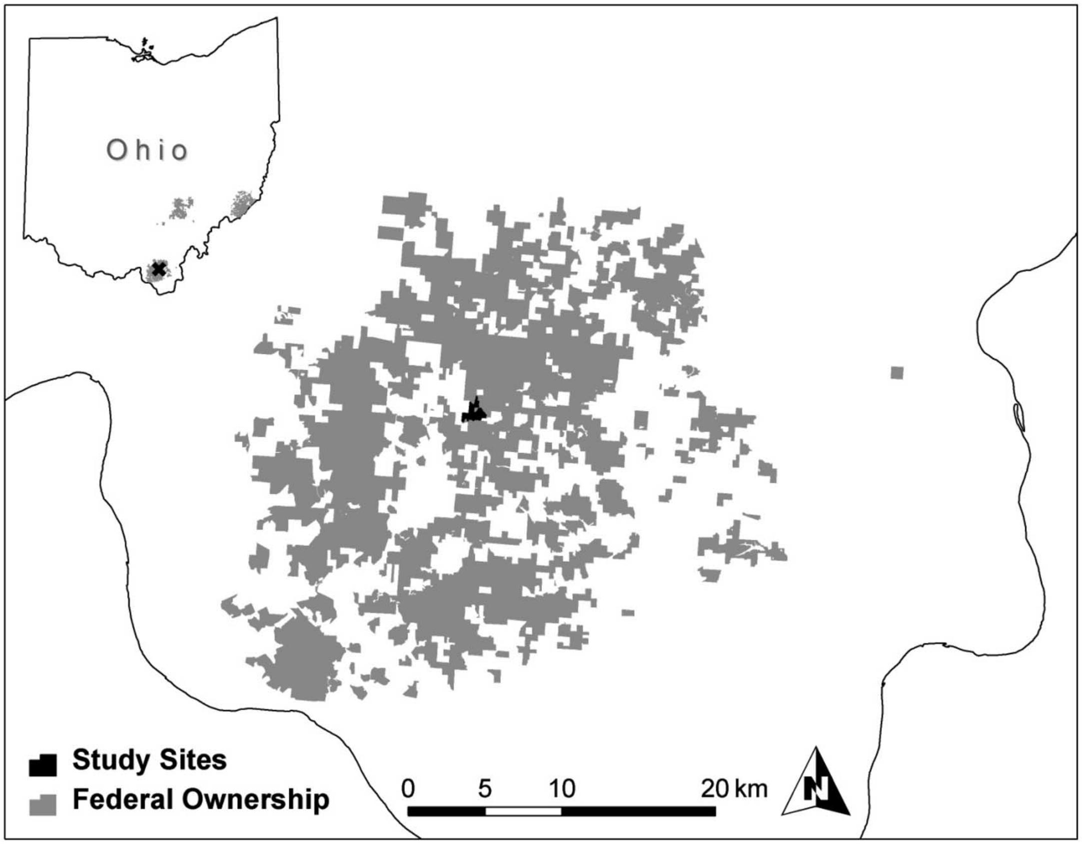

Figure 1. Location of the Ironton Ranger District on the Wayne National Forest in southeastern Ohio.

On Feb. 15–17, 2003, a widespread ice storm occurred across four Mid-Atlantic states: Ohio, West Virginia, northeastern Kentucky and southwestern Virginia. Rainfall amounts ranged from 5 to 13 cm, causing small stream flooding across many counties. During this storm event, 0.3–0.6 m of snow and ice accumulated in southeast Ohio and central West Virginia. In spring 2003, this area including our study sites experienced outbreaks of native spring defoliators: the common oak moth (*Phoberia atomaris*), forest tent caterpillar (*Malacosoma disstria*), Linden looper (*Erranis tiliaria*), and half-wing geometer (*Phigalia titea*) (US Forest Service 2003). In 2004 and 2005, a series of cool wet springs and above-average rainfall created ideal conditions for foliage diseases, and the area was consequently subjected to an outbreak of anthracnose fungi (US Forest Service 2004, 2006).

Our goal was to quantify the effects of an ice storm on forest structure and development on the Wayne National Forest in southeastern Ohio. Knowledge about the fate and impact of ice storms on residual trees can assist forest managers in making decisions about salvage and sanitation and forest rehabilitation efforts to restore stand integrity and sustainability. Specifically, our objectives were to (1) correlate the degree of ice damage, with tree species, size and growth, dieback, epicormic branching, and mortality; (2) determine species-specific relationships of ice damage with subsequent injury from insect defoliation and diseases; and (3) examine the 6-year trends in tree recovery by modeling species-specific diameter growth rates.

Materials and Methods

Study Area

This study was conducted from 2003 to 2009 in the Ironton Ranger District (IRD), Wayne National Forest, in Lawrence County, Ohio (38° 43′ 57.056″ N, 82° 35′ 57.561″ W; Figure 1). We selected study sites using multiple data sources, including aerial sketch mapping surveys (Turcotte 2003), forest stand inventory data for the IRD, and local knowledge of damaged areas. The distribution of ice storm-damaged areas was identified from aerial surveys conducted to develop a preliminary map of damage locations throughout the district. From this map, we randomly selected three stands that would not be affected by future management activities. These stands covered 65 ha, representing three different forest types: black oak/scarlet oak/hickory, yellow popular/white oak/northern red oak, and mixed oaks (US Forest Service 2001). Stands ranged in age from 60 to 109 years, basal area from 16 to 30 m^2/ha, and elevation from 227 to 290 m above sea level.

Data collection

In the summer of 2003, a "tag and track" project (Shortle et al. 2003) was initiated to determine the effects of the ice storm on trees in the IRD. We selected five tree species for this study: red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), chestnut oak (*Quercus prinus*), white oak (*Quercus alba*), and northern red oak (*Quercus rubra*), which are all considered intermediate in resistance to ice storm damage (Abell 1934, Downs 1938, Lemon 1961). We surveyed the three stands for each of the five species and randomly selected trees that corresponded to one of three size classes: sapling (5–10 cm), pole (>10–25 cm) and sawtimber (>25 cm) (Perkey and Wilkins 2001) and one of four damage classes based on the amount of crown that was damaged or lost following the storm (none; light, 1–33%; moderate, 34–66%; and heavy, >66%; Table 1). All categorical data values (crown damage, crown class, dieback,

Table 1. Number of trees selected by species, size, and crown damage class.

Species	Size class	Crown damage class[a] None	Light	Moderate	Heavy
Chestnut oak	Sapling	13	10	10	8
	Poles	10	12	10	11
	Sawtimber	8	10	10	8
Red maple	Sapling	12	10	12	9
	Poles	10	12	8	9
	Sawtimber	2	4	1	0
Red oak	Sapling	8	8	8	10
	Poles	9	11	10	11
	Sawtimber	6	13	12	9
Sugar maple	Sapling	10	9	5	10
	Poles	6	5	3	3
White oak	Sapling	8	9	11	9
	Poles	12	12	8	9
	Sawtimber	8	16	15	9

[a] Light, 1–33%; moderate, 34–66%; heavy, >67%.

and defoliation) were assigned on the basis of the consensus of three independent observers.

After determining the damage category for each tree, we flipped a coin to decide whether it would be tagged for future measurements or excluded from sampling. We proceeded to inventory the stand in this manner until 10–12 trees were assigned to each species, size class, and damage class grouping. Because of the structure of the stands, no sawtimber-sized sugar maple trees and few sawtimber-sized red maple trees were found. In total, 501 trees were selected for this study. For each tree, we recorded dbh (diameter at 1.37 m above the ground), crown class (i.e., dominant, codominant, intermediate, or overtopped; US Forest Service 2001), dieback (none; light, 1–5%; moderate, 6–10%; and heavy, >10%), defoliation (none; light, 1–25%; moderate, 26–50%; and heavy, >50%), and number of epicormic branches ≥15.2 cm in length (none; light, 1–10; moderate, 11–20; and heavy, >20 per tree) on the bole. All field measurements were made during July or August of 2003–2006 and 2009; no dbh measurements were taken in 2004 or 2005.

Trees that died during the first 3 years of the study were felled, dissected, and sampled for insect and disease activity. We peeled a 60.9-cm section of bole from the lower, middle, and upper thirds of the tree. We measured insect damage based on the percentage of the bole that was girdled (none; light, 1–25%; moderate, 26–50%; and heavy, >50%) and disease activity according to the presence, location (inner bark, sapwood, and heartwood), and percentage (none; light, 1–25%; moderate, 26–50%; and heavy, >50%) of bole cross-section showing signs of rot, staining, advanced decay, fungal mats, and rhizomorphs.

Data Analysis

We first compiled the observations on dieback, defoliation, and epicormic branching across the 6 years by considering the highest class level (e.g., heavy dieback) observed in any year. We opted for a more parsimonious statistical model by considering defoliation, epicormic branching, and dieback as binary response variables, along with mortality. We tested the significance of the effect of species, damage class, crown class, size class, and each interaction on each binary response variable using stepwise logistic regression (PROC CATMOD, SAS Institute 2002) on the basis of the likelihood-ratio chi-squared, G^2 (Stokes et al. 1995). Because of the low number of trees in the dominant crown class category, dominant and codominant crown classes were combined for this response variable. If a significant association was detected at $\alpha = 0.05$, we conducted post hoc tests by partitioning G^2 into nonsignificant components and calculating odds ratios between significant components (Agresti 1996). We also conducted our analyses by grouping species on the basis of genus (i.e., red and sugar maples combined) when possible.

Trends in diameter growth measured in three years (i.e., 2003, 2006, and 2009) were analyzed using a repeated measures mixed model with fixed terms for the main effects of crown damage, species, crown class, size class, and each interaction (PROC MIXED, SAS Institute 2002). Year was considered as the repeated measure factor, with dbh at each year as the response variable. Individual trees were considered random, and error terms were included for the effects of trees nested within crown damage classes. Diameter data were not normally distributed and consequently were transformed using $\log_{10}$. An unstructured variance/covariance structure was chosen by using the best fit information criterion and likelihood ratio (Littell et al. 1998, 2000, 2006).

Results

Tree Mortality

Over the 6 years of this study, 80 trees died; 58 of these during the first 3 years. Forty-three of the 58 were felled; 33 of these had some level of preexisting disease (e.g., Hypoxylon cankers, galls, conks, or signs of advanced decay), and 26 had complete insect girdling in at least one of the sections examined. No significant relationship was found between defoliation and mortality, dieback, crown class, or dbh. Logistic regression analysis of mortality revealed significant effects of tree species ($P < 0.01$), crown damage ($P < 0.01$), and size class ($P = 0.04$). We did not observe a significant difference in mortality by crown class or year, and no interaction terms were significant ($P > 0.05$). Across all tree species, the predicted probability of mortality increased with increasing crown damage (Table 2). There was no significant difference in the probability of mortality between undamaged and lightly damaged trees. Moderately damaged trees had lower mortality than heavily damaged trees ($P < 0.01$; Table 2). Odds ratios indicated that moderately and heavily damaged trees were 4.1 (95% confidence interval [CI] = 2.0–8.3) and 10.6 (95% CI = 5.5–20.5) times more likely to die, respectively, than undamaged and lightly damaged trees. No significant difference in mortality was detected among red maple, sugar maple, and chestnut oak or between red and white oak. When red maple, sugar maple, and chestnut oak were compared with the red and white oak, these two groups were significantly different from each other ($P < 0.01$), and odds ratios indicated that red and white oak were 4.0 (95% CI = 2.3–6.8) times more likely to die than the combined group of red maple, sugar maple, and chestnut oak. There was no significant difference between the pole and sapling trees, and when combined this group had lower probability of mortality than sawtimber trees ($P = 0.01$; Table 2). Sawtimber trees were 1.9 times (95% CI = 1.1–3.1) more likely to die than saplings and poles (Table 2).

Epicormic Branching

Only one red maple sapling (of a total of 501 trees) had epicormic branches at the beginning of this study. By the end of 2003, almost 60% of all trees had produced epicormic branches, and by 2009, 95% of all trees had epicormic branches. We detected a significant effect of crown class on epicormic branching ($P < 0.01$),

Table 2. The probability (±SE) of mortality predicted by logistic regressions for species, size class, and crown damage.

		Crown damage class[a]			
Species	Size class	None	Light	Moderate	Heavy
Red maple	Sapling	0.03 ± 0.017	0.04 ± 0.020	0.12 ± 0.049	0.32 ± 0.096
	Pole	0.01 ± 0.009	0.02 ± 0.011	0.06 ± 0.029	0.19 ± 0.071
	Sawtimber	0.03 ± 0.021	0.04 ± 0.025	0.14 ± 0.061	NA
Sugar maple	Sapling	0.01 ± 0.008	0.01 ± 0.010	0.04 ± 0.031	0.13 ± 0.084
	Pole	0.01 ± 0.004	0.01 ± 0.005	0.02 ± 0.017	0.07 ± 0.049
	Sawtimber[b]	NA	NA	NA	NA
Chestnut oak	Sapling	0.02 ± 0.013	0.03 ± 0.016	0.10 ± 0.039	0.26 ± 0.081
	Pole	0.01 ± 0.007	0.02 ± 0.008	0.05 ± 0.022	0.15 ± 0.054
	Sawtimber	0.03 ± 0.021	0.03 ± 0.017	0.11 ± 0.042	0.29 ± 0.088
Red oak	Sapling	0.07 ± 0.04	0.10 ± 0.040	0.26 ± 0.073	0.55 ± 0.088
	Pole	0.04 ± 0.02	0.05 ± 0.022	0.15 ± 0.051	0.37 ± 0.083
	Sawtimber	0.08 ± 0.04	0.11 ± 0.042	0.29 ± 0.074	0.58 ± 0.088
White oak	Sapling	0.10 ± 0.048	0.14 ± 0.052	0.35 ± 0.081	0.64 ± 0.082
	Pole	0.05 ± 0.027	0.07 ± 0.030	0.20 ± 0.063	0.47 ± 0.091
	Sawtimber	0.11 ± 0.053	0.15 ± 0.053	0.38 ± 0.079	0.67 ± 0.079

[a] Light, 1–33%; moderate, 34–66%; heavy, >67%. NA, not applicable.
[b] Few saw-timber-sized sugar maple trees were present in the stands sampled.

Table 3. The probability (±SE) of epicormic branching predicted by logistic regressions for crown class.

		Epicormic branching[a]			
Species	Crown class	None	Light	Moderate	Heavy
Red maple	Dominant/codominant	0.03 ± 0.026	0.26 ± 0.064	0.28 ± 0.064	0.42 ± 0.076
	Intermediate	0.12 ± 0.048	0.37 ± 0.068	0.28 ± 0.061	0.23 ± 0.055
	Overtopped	0.15 ± 0.056	0.44 ± 0.072	0.26 ± 0.059	0.15 ± 0.043
Sugar maple	Dominant/codominant	0.02 ± 0.017	0.14 ± 0.056	0.22 ± 0.073	0.61 ± 0.094
	Intermediate	0.08 ± 0.046	0.25 ± 0.076	0.27 ± 0.078	0.40 ± 0.091
	Overtopped	0.11 ± 0.049	0.33 ± 0.071	0.27 ± 0.065	0.29 ± 0.066
Chestnut oak	Dominant/codominant	0.01 ± 0.009	0.09 ± 0.028	0.31 ± 0.051	0.58 ± 0.055
	Intermediate	0.05 ± 0.029	0.16 ± 0.049	0.39 ± 0.068	0.39 ± 0.068
	Overtopped	0.07 ± 0.037	0.23 ± 0.057	0.41 ± 0.067	0.30 ± 0.060
Red oak	Dominant/codominant	0.01 ± 0.011	0.13 ± 0.036	0.23 ± 0.046	0.62 ± 0.053
	Intermediate	0.05 ± 0.041	0.24 ± 0.068	0.30 ± 0.069	0.42 ± 0.075
	Overtopped	0.08 ± 0.060	0.32 ± 0.091	0.30 ± 0.079	0.31 ± 0.076
White oak	Dominant/codominant	0.01 ± 0.008	0.11 ± 0.032	0.28 ± 0.049	0.60 ± 0.055
	Intermediate	0.04 ± 0.029	0.20 ± 0.058	0.35 ± 0.071	0.41 ± 0.072
	Overtopped	0.07 ± 0.042	0.27 ± 0.074	0.37 ± 0.076	0.31 ± 0.069

[a] Number of epicormic branches ≥15.2 cm in length (light, 1–10; moderate, 11–20; and heavy, >20 per tree).

whereas the main effects of species, crown damage, and size class, and their interactions, were not significant ($P > 0.05$). The predicted probability of heavy epicormic branching was highest for the dominant and codominant crown classes (Table 3), which as a group were significantly higher than the intermediate and overtopped crown classes ($P \leq 0.01$). Dominant and codominant trees were 6.8 (95% CI = 2.0–23.4) times more likely to have epicormic branches than the intermediate and overtopped tree group.

Dieback, Defoliation, and Growth

No significant relationship was found between dieback and damage class ($P > 0.05$). A significant difference in dieback was detected between the maple and oak species ($P \leq 0.01$). Oaks were 6.2 (95% CI = 3.8–9.9) times more likely to show dieback than maples. Within the oak group, there was no significant difference in dieback among species. In the maple group, red maple was 3.7 (95% CI = 1.3–10.5) times more likely to show dieback than sugar maple. Regardless of species, size class was a significant predictor ($P \leq 0.01$) of dieback. Saplings and poles as a group had significantly less dieback than sawtimber ($P \leq 0.01$). Dieback also varied according to crown class, with codominant and dominant trees having significantly more dieback than both intermediate ($P = 0.03$) and overtopped ($P \leq 0.01$) trees. Codominant and dominant trees were 1.7 (95% CI = 1.0–2.75) and 3.1 (95% CI = 1.9–4.93) times more likely to show dieback then intermediate and overtopped trees, respectively.

There was no difference in defoliation among the oaks, but red maples were 2.5 times (95% CI = 1.2–5.0) more likely to be defoliated than sugar maples ($P = 0.01$). Defoliation by crown class was not significantly different in either the oak and maple groups. Defoliation by crown damage category was significantly different only for the oak group ($P < 0.01$). Undamaged oaks and those with light and moderate damage were 1.5 (95% CI = 1.1–1.9) times more likely to be defoliated than heavily damaged trees. No trees refoliated during any of the years we sampled.

We detected a significant effect of species ($P < 0.01$) and crown damage ($P < 0.01$) on diameter growth (Table 4). No interaction terms were significant ($P > 0.05$). For all five species, trees with no or light crown damage showed significant linear or quadratic growth rates (Figure 2). Additionally, undamaged and lightly damaged trees generally grew faster than moderately or heavily damaged trees, especially for chestnut oak, red maple, and white oak.

Discussion

In this study, damage severity, tree species, and crown class were the best predictors of mortality following an ice storm. Although

Table 4. Mean diameter, SE, and the number (*n*) of trees by species and crown damage class over time.

Species	Crown damage[a]	Mean diameter ± SE; *n*		
		2003	2006	2009
		.(cm).		
Red maple	None	15.4 ± 1.34; 66	16.7 ± 1.49; 60	17.2 ± 1.42; 66
	Light	19.4 ± 1.12; 72	20.8 ± 1.12; 72	21.7 ± 1.16; 72
	Moderate	17.3 ± 0.94; 57	17.9 ± 0.96; 57	18.2 ± 0.96; 57
	Heavy	16.5 ± 1.12; 45	16.8 ± 1.09; 45	17.3 ± 1.14; 45
Sugar maple	None	11.8 ± 0.64; 48	13.9 ± 0.66; 48	15.7 ± 0.69; 48
	Light	11.3 ± 0.91; 42	12.5 ± 1.02; 39	14.6 ± 1.09; 42
	Moderate	12.4 ± 1.17; 30	14.4 ± 1.24; 24	15.6 ± 1.37; 24
	Heavy	11.6 ± 0.91; 30	11.2 ± 0.81; 24	12.5 ± 0.94; 30
Chestnut oak	None	20.8 ± 1.19; 93	21.8 ± 1.19; 93	22.5 ± 1.24; 93
	Light	25.9 ± 1.24; 93	26.5 ± 1.32; 87	27.5 ± 1.24; 93
	Moderate	23.6 ± 1.60; 81	24.3 ± 1.63; 81	25.1 ± 1.62; 81
	Heavy	22.4 ± 1.49; 54	22.8 ± 1.52; 54	23.1 ± 1.52; 54
Red oak	None	19.5 ± 1.91; 63	23.1 ± 2.01; 63	21.3 ± 1.91; 54
	Light	28.4 ± 1.60; 84	30.1 ± 1.67; 78	30.2 ± 1.62; 84
	Moderate	29.3 ± 2.13; 63	28.1 ± 1.85; 60	31.2 ± 2.11; 63
	Heavy	22.4 ± 1.45; 51	23.2 ± 1.44; 51	23.6 ± 1.45; 51
White oak	None	24.3 ± 1.22; 75	25.4 ± 1.22; 75	26.1 ± 1.22; 75
	Light	28.9 ± 1.14; 96	29.9 ± 1.17; 96	30.4 ± 1.19; 96
	Moderate	29.6 ± 1.68; 69	30.4 ± 1.70; 69	31.1 ± 1.73; 69
	Heavy	24.7 ± 1.93; 30	25.5 ± 2.03; 30	25.7 ± 2.06; 30

[a] Light, 1–33%; moderate, 34–66%; heavy, >67%.

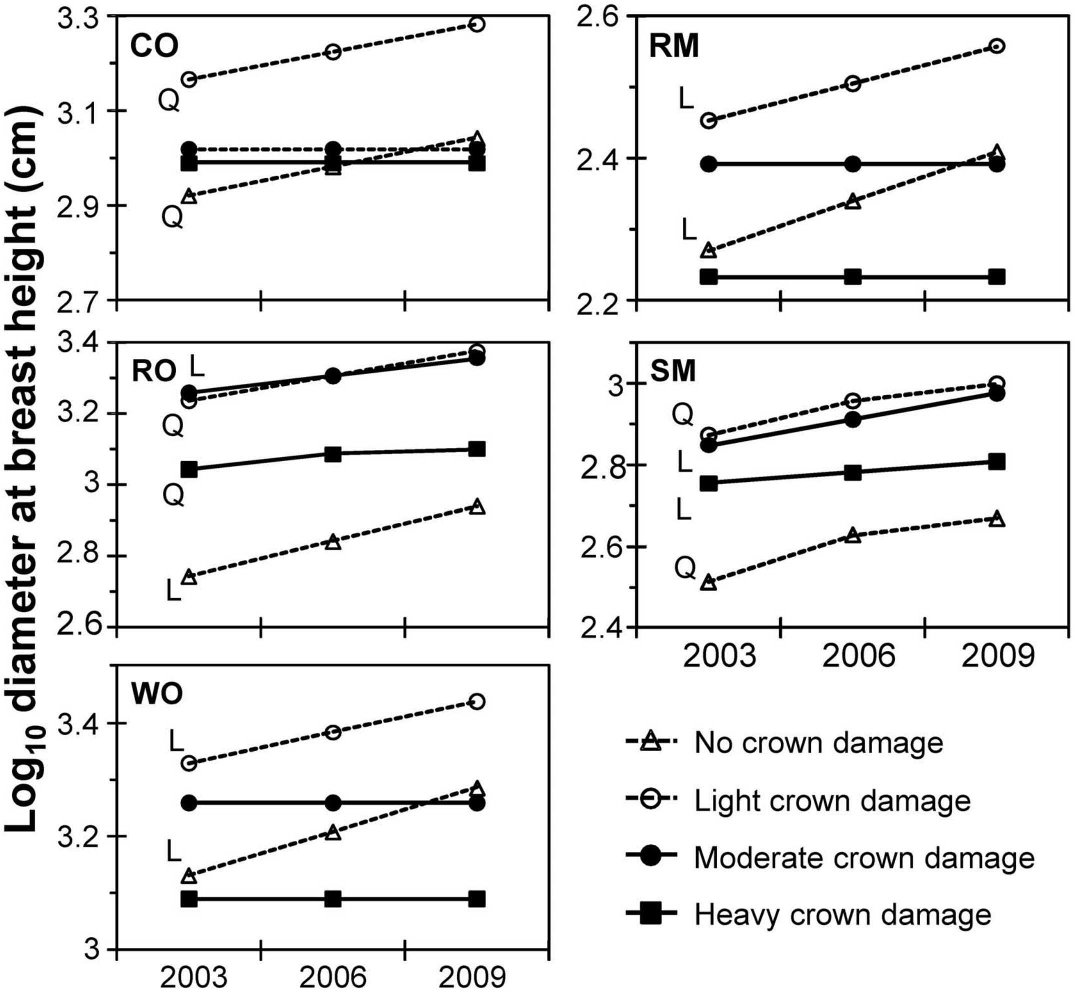

Figure 2. Predicted diameter growth response for logistic regression by species (CO, chestnut oak; RO, red oak; WO, white oak; RM, red maple; SM, sugar maple) and crown damage class, 2003–2009. Trees with no or light (1–33%) crown damage tended to grow over the course of the study, whereas trees with moderate (34–66%) and heavy (>67%) crown damage often showed little or no diameter increase. For chestnut oak, the predicted growth response was the same for trees with moderate and heavy crown damage. Lines denoted with L and Q are significant ($P < 0.05$) at the linear and quadratic levels, respectively.

many studies have used the poststorm susceptibility of different species as an indicator of ice storm impact and mortality (e.g., Whitney and Johnson 1984, Boerner et al. 1988, Reberus et al. 1997), fewer studies have investigated long-term, species-specific mortality rates of ice storm-damaged trees (Shortle et al. 2003, Lafon 2006, Luley and Bond 2006). Long-term mortality rates appear to be highly species-specific and affect larger size classes the most. The mortality rates in this study were consistent with prior observations (Shortle and Smith 1998, Lafon 2006). Lightly to moderately damaged trees (i.e., those with <67% crown loss) had a ≥ 60% chance of surviving after 6 years, whereas heavily damaged trees (>67% crown loss) had only a 30% chance of survival (Table 2).

Red and white oaks had the highest mortality rates, which is consistent with damage in similar forest types (Dance and Lynn 1963, Whitney and Johnson 1984, Rebertus et al. 1997). The differential mortality of sawtimber red and white oaks (Table 1) on the IRD could have important consequences for future stand structure and development. Because many of the stands on the IRD have an oak overstory and maple understory, the loss of any overstory oak will likely affect mast production and accelerate the successional progress of maple dominance occurring in these stands (Tift and Fajvan 1999).

Branch breakage and stem snap are the most common injuries to residual trees in an ice- damaged forest (Lemon 1961, Hopkin et al. 2001). Such damage changes site microclimate, reduces tree vigor, and creates favorable conditions for disease and insect invasion (Shortle and Smith 1998). Ice storms also create a large temporal pulse of woody debris (Rebertus et al. 1997) available for colonization by insects and diseases. In most undisturbed hardwood forests, subcortical, wood-dependent, and wood-boring insects are believed to occur at low (endemic) levels (Olivier and Larson 1996, Gandhi et al. 2007). This assessment may be attributed to the cryptic habit (Solomon 1995) and lack of efficient monitoring tools for many of these wood-boring insects. Native wood-boring insects have a functional role in maintaining forest ecosystems. However, when a disturbance alters environmental conditions and suitable host resources are more available, these vectors have the potential to increase to epidemic levels (Bragg et al. 2003). Numerous ice storms have occurred in the eastern United States in the past century (Van Dyke 1999, Hopkin et al. 2001) but no wide-scale post-storm insect outbreaks have occurred (Gandhi et al. 2007). In our study, many subcortical, wood-dependent, and wood-boring insects were present. Even though no subsequent outbreak of wood-boring insects was observed, their normal densities likely contributed to loss of vigor and mortality of damaged trees. Such insects can introduce fungal pathogens associated with wood decay and staining. Most trees survive by compartmentalizing the wound (Shigo 1982, Smith et al. 2001), resulting in a further decrease in stem quality.

General trends in ice storm-initiated damage observed in this study are typical of similar eastern hardwood forest types. However, because of differences in stand structure, ice loads, and measurement criteria, a direct comparison with other studies is difficult. Epicormic branching can occur regardless of the level of crown damage sustained (Brommit et al. 2004). Meadows (1995) proposed three major factors affecting the production of epicormic branches in hardwoods: species, stress and sunlight. In our study, the ice storm stressed many trees by breaking branches and creating canopy openings. Of the species we monitored, white and red oaks had the highest propensity for disturbance-induced epicormic branching, followed by chestnut oak, with sugar and red maple demonstrating a low tendency for epicormic branches (Smith 1966, Trimble and Seegrist 1973, Meadows 1995). Unlike the observation made by Smith (1966), we observed more epicormic branching on codominant and dominant trees than on intermediate and overtopped trees. This difference is likely related to the size of the canopy openings created by this storm and/or to the prestorm vigor of the intermediate or overtopped trees. Epicormic branches sprouted in the first growing season after the storm and continued to sprout for the duration of this study. The impact of the development of these branches on the bole will be a degrading of lumber quality (Stubbs 1986, Oliver and Larson 1996). This pattern will likely continue until the growing space created by the storm is refilled by expanding crowns.

Because we measured tree diameters over 6 years following the ice storm, we interpret the growth trends to be a reflection of tree recovery from damage. In three of the four ice damage classes, sugar maple showed the fastest diameter growth rate, followed by red oak, chestnut oak, white oak, and red maple (Figure 2). For all species, a crown loss of more than one-third (i.e., damage classes 2 and 3) reduced radial growth by an average of 0.07 cm/year, or 52% per year. Our findings indicated that all species examined showed positive diameter growth after light crown damage. Sugar maple and red oak trees survived and demonstrated growth increases even after moderate levels of branch breakage and crown loss. Moderately to heavily damaged red maple showed significantly more dieback and defoliation than sugar maple and were probably still recovering and unable to capitalize on the available growing space. Other studies have shown that understory red maple can have an increased growth rate after canopy disturbance events, assuming that they do not suffer significant crown damage (Orwig and Abrams 1995, Tift and Fajvan 1999).

Ice storms are a reoccurring disturbance event for many hardwood forests. Our ability to predict forest damage and mortality caused by ice storms is limited to generalizations on impact and tree survival (Bragg et al. 2003). A tree's response to disturbance is based on the individual characteristics of the species (Oliver and Larson 1996), the type of disturbance, and predisturbance condition of the tree. Thinnings and other timber stand improvement operations could be used to maintain tree vigor and reduce the number of trees of a susceptible species in a stand. However, regardless of species, our findings indicated that diameter growth is significantly reduced when more than one-third of the crown is damaged.

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