Species-specific effects of a 1994 ice storm on radial tree growth in Delaware[1]

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Smolnik, M., (James City County Planning Division, 101 Mounts Bay Road, Williamsburg, VA 23185), A. Hessl (Department of Geology and Geography, West Virginia University, Morgantown, WV 26506), and J. J. Colbert (USDA-Forest Service, NE Research Station, Morgantown, WV 26506). Species-specific effects of 1994 ice storm on radial tree growth in Delaware. J. Torrey Bot. Soc. 133: 577–584. 2006.—Ice storms are recurrent disturbances that alter forest succession and forest structure throughout North America. However, long-term effects of ice storms on tree growth are largely unknown. Following a 1994 ice storm in Delaware, the Delaware Forest Service established seventy-five study plots to sample four species of trees (southern red oak [*Quercus falcata* Michx.], white oak [*Quercus alba* L.], loblolly pine [*Pinus taeda* L.], and yellow poplar [*Liriodendron tulipifera* L.]) affected by the ice storm. The objective of this study is to identify multi-year species-specific responses to the 1994 Delaware ice storm using tree ring data collected statewide four years following the disturbance. A ground survey classified affected trees into damage class categories based on the percentage of crown limbs broken. Dendrochronology was used to identify the radial growth response of the four species studied across four damage classes (control, light damage, moderate damage, and severe damage). Yellow poplar was most susceptible to ice storm damage followed by loblolly pine, red oak, and white oak. In general, severely damaged trees experienced the greatest reduction in annual radial growth. Yellow poplar had the fastest recovery rate following the storm, followed by white oak, red oak, and loblolly pine. The results of this study suggest that species have differential growth responses to ice storms that is in part attributable to the species' ability to produce epicormic branches.

Key words: dendrochronology, disturbance, ice storms, tree rings.

Ice storms affect forests throughout North America (Irland 2000), though their recurrence in a particular area may be uncertain. Damage from ice storms can affect community structure and composition by creating canopy gaps and altering the microclimate near the ground (Wolfe *et al.* 1949) and accelerating forest succession (Downs 1938, Lemon 1961, Siccama *et al.* 1976, Whitney and Johnson 1984). The effects on forest structure, composition, and succession depend on the severity of the disturbance, the successional age of the forest stand (Glitzenstein *et al.* 1986), differential species susceptibility to ice damage (Lemon 1961, Bruederle and Stearns 1985), microsite soil and climate conditions (Whitney and Johnson 1984), and stochastic patterns of secondary damage (Boerner *et al.* 1988). Damage caused by ice storms can hinder timber production, reduce the value of forests as wildlife refuges or recreational areas, and exert tremendous economic effects on forest industries, forest landowners, and public forest agencies (Hauer *et al.* 1993, Rhoades 1995, Sisinni *et al.* 1995).

Though their frequency in a particular region is uncertain, ice storms occur throughout the United States and southern Canada with some regularity each year (Bruederle and Stearns 1985). Ice storms most commonly develop along a line stretching from northern Texas to Newfoundland associated with slow-moving low-pressure systems where a large temperature difference exists between warm Gulf air and cold Arctic air. Ice accretion ranges in thickness from a trace to approximately 2.5 cm or more. The degree of tree

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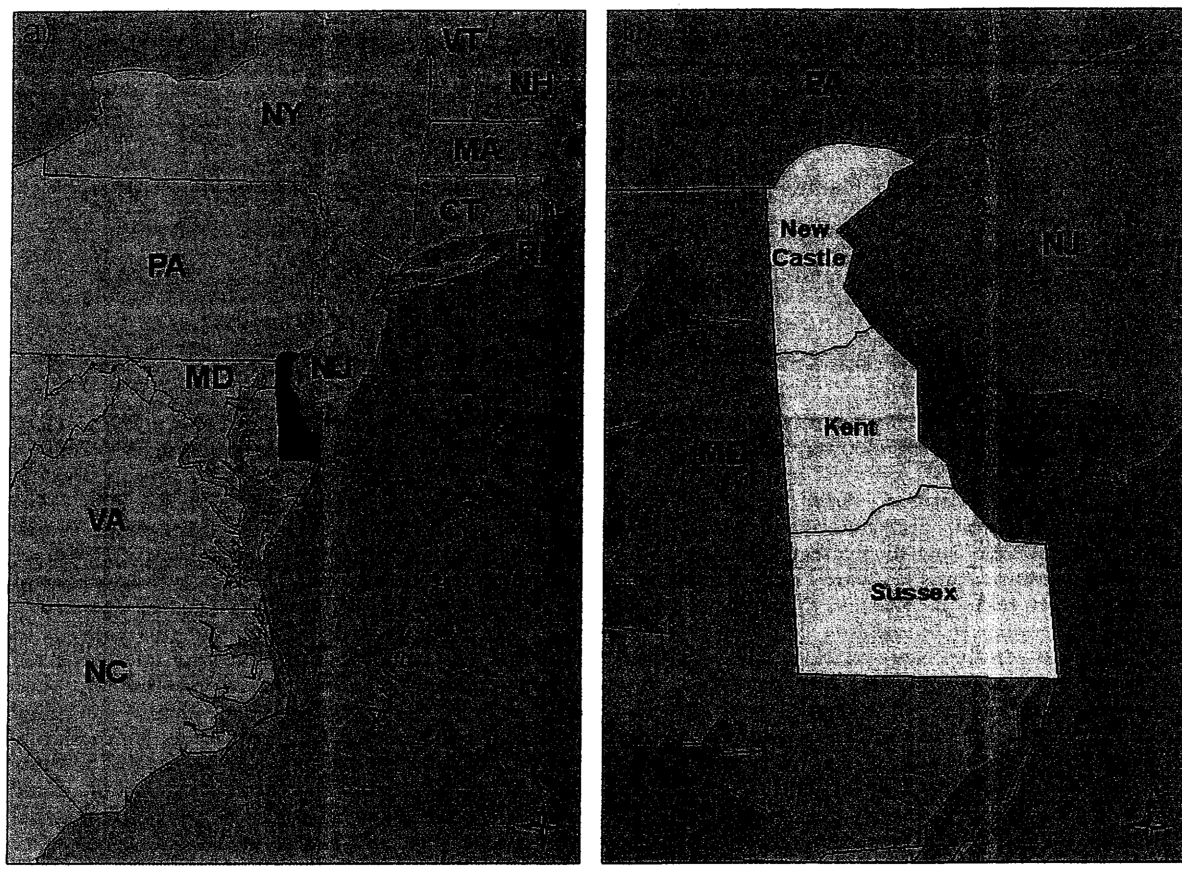

FIG. 1. Location of the study area in the eastern United States (a) and within Delaware (b).

injury is related to total physical loading, based both on the weight of the ice and wind speed (Bruederle and Stearns 1985), but may also be different among species. Previous studies of ice storm damage to trees have been conducted following large storms in New York (Seischab *et al.* 1993), Ohio (Boerner *et al.* 1988), Virginia (Mou and Warrillow 1999), and Wisconsin (Bruederle and Stearns 1985), however none of these studies used tree-ring methods to evaluate effects on tree growth. Lafon and Speer (2002) investigated ice storm damage via dendrochronological studies in oak forests of southwestern Virginia, but they focused on reconstructing previous events. Similarly, Travis and Meentemeyer (1991) explored the influence of winter versus early spring ice storms on radial growth of loblolly pine (*Pinus taeda* L.) and shortleaf pine (*Pinus echinata* Mill.). Other research suggests that two ice storm responses, one of suppression and one of release, may occur in the years following a storm (Lafon and Speer 2002, Smith and Shortle 2003). The pattern and duration of growth reduction after ice storms may be species and damage specific (Smith and Shortle 2003, Shortle *et al.* 2003), though few studies have examined radial growth for more than 1–2 years following a storm and no studies have compared growth of conifers and broadleaf deciduous tree species. The objective of this study is to identify long-term species-specific responses to a recent (1994) ice storm in Delaware using tree ring data collected statewide four years following the disturbance.

Materials and Methods. STUDY SITE. The study area is located in southern New Castle, Kent and northern Sussex Counties, Delaware and is primarily located on state lands managed for recreational activities (Fig. 1). The forest stands have not been thinned or actively managed. New Castle, Kent, and Sussex Counties have a moist continental climate characterized by seasonal fluctuations in temperature with warm moist summers and moderately cold winters. Mean annual temperature for the counties range from 13.1–

Table 1. Damage class (DC), number of trees, number of cores, and time span covered for each chronology of loblolly pine (*Pinus taeda*), southern red oak (*Quercus falcata*), white oak (*Q. alba*), and yellow polar (*Liriodendron tulipifera*).

Species chronology	DC	Trees	Cores	Time span	PDSI Coeff.	*P*	Adj. R^2 (%)
Loblolly Pine	0	45	90	1924–1998	0.047	0.005	21.8
	1	63	126	1912–1998	0.001	0.930	0.0
	2	51	102	1907–1998	−0.010	0.673	0.0
	3	58	116	1882–1998	−0.014	0.592	0.0
S. Red Oak	0	45	90	1901–1998	0.060	0.002	27.3
	1	42	84	1902–1998	0.030	0.072	7.7
	2	48	96	1897–1998	0.031	0.044	10.3
	3	52	104	1889–1998	0.030	0.018	14.9
White Oak	0	44	88	1859–1998	0.044	0.010	18.3
	1	45	90	1842–1998	0.037	0.001	27.5
	2	41	82	1811–1998	0.035	0.004	23.1
	3	49	98	1828–1998	0.020	0.056	9.0
Yellow Poplar	0	45	90	1901–1998	0.062	0.013	16.9
	1	45	90	1915–1998	0.073	0.003	24.9
	2	45	90	1910–1998	0.066	0.004	22.1
	3	50	100	1911–1998	0.066	0.007	19.8

13.5 °C, and the average total annual precipitation range from 110–112 cm for the 31 year time period 1960–1990 (NCDC 2003).

New Castle, Kent, and Sussex Counties are part of the oak-pine forest region, a transitional region between the southeastern evergreen forest and the central deciduous forest (Braun 1950). Common tree species in the study area include: southern red oak (*Quercus falcata* Michx.), white oak (*Q. alba* L.), loblolly pine (*Pinus taeda* L.), yellow-poplar (*Liriodendron tulipifera* L.), red maple (*Acer rubrum* L.), dogwood (*Cornus florida* L.), and sweet gum (*Liquidambar styraciflua* L.). The natural northern limit of loblolly pine is located within Sussex County (Ireland and Matthews, 1974) and pure stands of loblolly pine are rare in Kent County due to the latitude of the area (Matthews and Ireland 1971). The soils of these three counties are most commonly ultisols, such as Typic Hapludults and Typic Umbraquults, depending in part on the depth of the water table (NRCS 2005). The study area is characterized by homogeneous topography, which greatly reduces the confounding influence of slope and aspect on ice storm severity and species susceptibility.

METHODS. An aerial survey was performed by the Delaware State Forestry Department in order to subjectively place damaged forest stands into four damage class categories. The resulting map was used to identify areas where varying degrees of damaged trees were located. The Delaware State Forestry Department also conducted ground surveys in 1994 to objectively assess individual tree damage in the damage classes defined by the aerial survey. Seventy-five plots were established to determine the damage to four major tree species: southern red oak, white oak, loblolly pine, and yellow poplar. The goal in establishing each study plot was to incorporate trees from the four species of interest in a variety of crown positions and diameter classes. A single tree was selected to serve as the center of the plot. From this single tree a 30-meter radius was established for selecting additional trees within the plot. Trees selected for the study had a DBH between 25.4 and 50.8 cm, were in the dominant or co-dominant strata, had a crown ratio between 20% and 50%, and damage (excluding ice storm related injuries) was below Forest Service Health Monitoring severity standards (Colbert and Onken 1999). Trees with damage caused by rot, conks, disease, and insect outbreaks were avoided to insure that the damage to the study trees was associated with the ice storm. All trees representing the four study species that met these criteria and were within the 30-meter radius were included in the study (Table 1).

The ground survey of the study plots revealed pockets of trees with various levels of damage within a single aerial damage class so sampled trees were individually assessed and placed into one of the four damage classes (0-no damage to very light, 1-light, 2-moderate, and 3-severe) based on the percentage of crown limbs broken (0–4%, 5–33%, 34–66%, and 67–100% respectively). Twenty of the 75 study plots were established as control plots, and were chosen because they were not affected by or received minimal damage from the ice storm; trees within these plots were all classified as damage class 0. USDA Forest Service and Delaware Forest Service employees extracted two increment cores at breast height from each of the 786 trees between December 1998 and April 1999.

Core samples were mounted and sanded with 320, 400, 800, and 1200 grit sandpaper. Samples were cross dated using marker years and ring widths were measured using a measuring stage (0.001 mm) and binocular microscope. COFECHA was used to evaluate cross-dating accuracy (Grissino-Mayer 2001).

The program ARSTANL (Cook and Holmes 1986) was used to standardize the individual tree ring series and remove significant temporal autocorrelation from the chronologies. We applied a 50-year cubic smoothing spline to each measured ring width series and then divided the ring width values by the value of the fitted curve to produce tree ring indices. A 50-yr smoothing spline retains 50% of the variance over a 50-yr period and 99% of the variance over a 16-yr period thus removing long-term trends while retaining annual to decadal-scale variation (Lafon and Speer 2002). To build chronologies, we grouped series by species (4) and damage class (4) yielding 16 different ring width chronologies.

Radial tree growth in the mid-Atlantic may be affected by drought (Baker and Langdon 1990, Orwig and Abrams 1997, Fekedulegn *et al.* 2003), so we used two methods to separate the ice storm response from the drought response: 1) graphical comparison; and 2) regression analysis. We used time series plots of standardized ring widths to compare the damage class zero trees (located in control plots) to the three other damage classes, by species. If unusual climatic conditions occurred in 1994, all of the plots, including control plots, would have been affected and would have exhibited a decline in radial growth for 1994.

In order to quantitatively maximize the pattern of growth produced by ice storms, the background noise associated with drought was removed using residual analysis (e.g., Lafon and Speer 2002). We regressed the standardized ring width index (1968–1998) (dependent variable) from each of the 16 chronologies on annual PDSI (Palmer Drought Severity Index) (independent variable). Annual PDSI values were calculated from average monthly data for the 12 months prior to September of the ring formation (Delaware, division 2, NCDC 1994). PDSI is strongly correlated with tree ring indices in eastern North America (Stahle *et al.* 1985, Jenkins and Pallardy 1995) and is a measure of meteorological drought that incorporates precipitation, runoff, soil moisture, and potential evapotranspiration (Oladipo 1985). This index is standardized to local climate and emphasizes relative moisture conditions, but has performed well except in the western United States due to its inability to calculate water supplies locked up in snow (Wells *et al.* 2004). Regression models were developed for all sixteen chronologies and the remaining "drought-free" residuals were used to identify the ice storm response in the years following the storm. To allow comparison with the ring width values (control plots) and reduce negative values, we added a value of one to all residuals (e.g., Lafon and Speer 2002).

To quantitatively identify growth suppression or release events, we compared the 1994 drought-free residual for each species in each damage class to the mean residual value from the previous five years. To quantify percentage change in radial growth in 1994, we divided the 1994 residual by the previous five-year mean, and then multiplied the quotient by 100.

Results. Species Specific Patterns of Ice Storm Damage. Damage class zero trees received no or minimal physical ice damage based on ground surveys, therefore if a drought or other unusual climate conditions affected the area during the 1994–1998 period, it would be most apparent in these chronologies (Fig. 2). For all species in damage class 0, radial growth in 1994 was close to the 31 year mean (1968–1998). However, white oak showed a slight increase and loblolly pine exhibited a slight decrease in radial growth (Fig. 2). The decrease in loblolly pine ring width index may be due to climatic conditions, but generally loblolly pine are not as susceptible to drought as yellow poplar (Baker and Langdon 1990).

All species except loblolly pine contained variation that was significantly related to PDSI (1968–1998) ($P < 0.075$) (Table 1). For all other species and damage classes, the

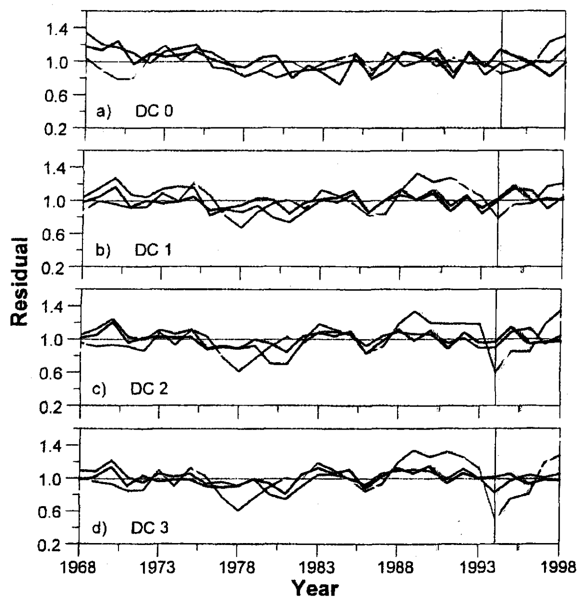

FIG. 2. Residual values from 1968–1998 by damage class (DC): damage class 0 (a); damage class 1 (b); damage class 2 (c); and damage class 3 (d). Black lines represent white oak, red lines represent southern red oak, yellow lines represent yellow poplar, and green lines represent loblolly pine (also plotted as standardized ring width). Dashed line indicates the 30-yr mean, solid black vertical line indicates the year of the ice storm (1994).

models removed the influence of PDSI from annual radial growth; from 9% to 27.5% of the annual variation could be attributed to annual climate as expressed by PDSI (Table 1). This is typical of closed canopy trees growing in moderate conditions where climate is not the primary limiting factor on growth (Fritts 2001). In subsequent analysis, growth for loblolly pine is expressed as a standardized ring width index while for all other species growth is expressed in terms of the drought free residuals.

Growth response during the year of the storm varied by species and by damage class (Fig. 2). Damage class 1 white oak and southern red oak experienced average radial growth in 1994 when compared to the reference period (1968–1998). In the four years after the storm, southern red oak and white oak annual growth hovered around the 31-yr mean. Damage class one yellow poplar showed the largest decrease in radial growth for 1994, but had recovered to approximately the 31-yr mean by 1995. Damage class one loblolly pine showed the second greatest reduction in radial growth in 1994, but by 1997 annual growth had exceeded the mean.

Among damage class 2 trees, only loblolly pine and yellow poplar show a clear reduction in radial growth in 1994 (Fig. 2). White oak and southern red oak growth during the year of the storm was approximately the same as the previous year, remaining slightly below the 30-yr mean. Loblolly pine had a large reduction in growth in 1994, but by 1998 loblolly pine growth was well above the 30-yr mean. Loblolly growth had been well above the mean for several years prior to the ice storm and this post storm release may have been a return to the short term normal. Similar to damage class 1 (Fig. 3), yellow poplar showed the greatest percent reduction in radial growth the year of the ice storm and by 1998 growth was above the 30-yr mean.

All damage class three chronologies had reduced growth the year of the storm except white oak. White oak continued to show little response during the year of the storm or in subsequent years (Fig. 2). Yellow poplar, loblolly pine, and southern red oak experienced their greatest relative growth reductions in the damage class three category. Southern red oak annual growth in 1994 and 1995 was below the 30-year mean, but growth returned to just above the mean in 1996–1998. Damage class 3 yellow poplar exhibited the largest relative reduction in annual radial growth for all species in 1994. However, yellow poplar growth rebounded and remained well above the mean between 1996–1998. Loblolly pine showed the second largest relative reduction in annual growth in 1994, and by 1998 the annual growth rate for loblolly pine was well above the 30-yr mean.

Discussion. SPECIES-SPECIFIC SUSCEPTABILITY. Susceptibility to physical ice damage appears to be strongly species-specific (Abell 1934, Lemon 1961, Whitney and Johnson 1984). The results of this study suggest that immediate (same year) effects of ice storms on radial growth are also species-specific (Fig. 2). Studies often disagree however on which species are the most susceptible to ice damage. Some research has shown that needle leaved species are more susceptible to ice damage (Whitney and Johnson 1984, Boerner *et al.* 1988) while other research has shown that broadleaf deciduous trees are more likely to be damaged by ice storms (Abell 1934, Downs 1938). This study indicates that both broadleaved and needle-leaved species sustain growth reduc-

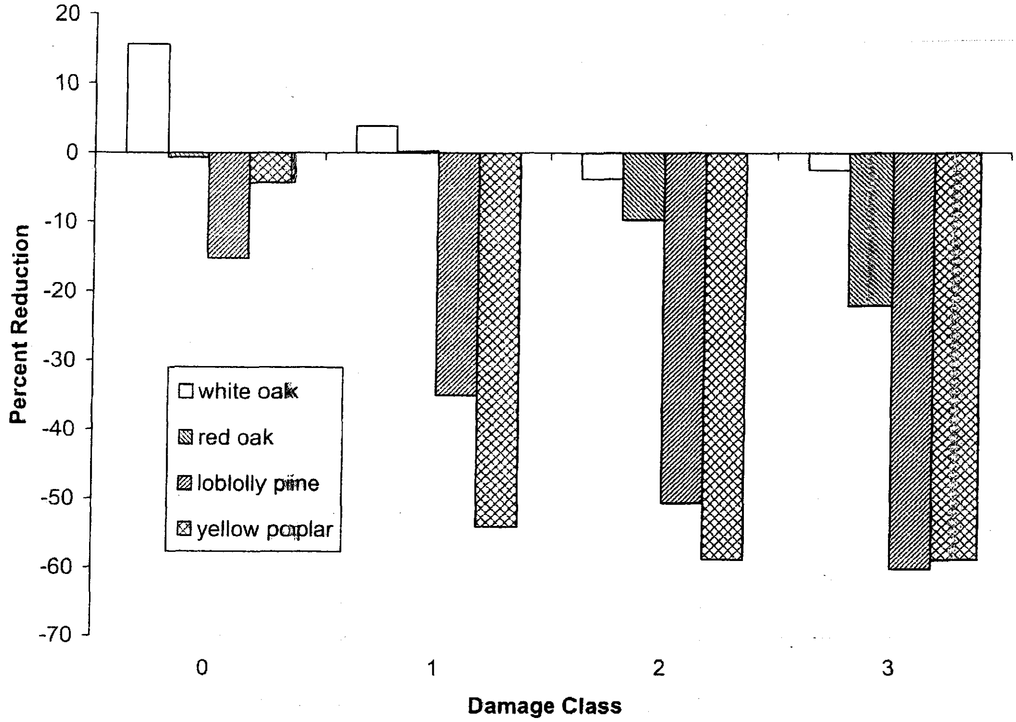

FIG. 3. 1994 percentage growth reductions for individual species in each damage class relative to the prior 5-yr average.

tions during the year of the storm and that for some tree species, growth reductions are a function of degree of physical damage (Fig. 2).

The results of this and other studies have demonstrated that ice storm effects on growth may be sustained for several years or may result in a growth release, depending on species (Smith and Shortle 2003). In all four of the damage class categories (Fig. 2), white oak showed the greatest resistance to the ice damage (in terms of radial growth) followed by southern red oak, loblolly pine, and yellow poplar. Results of previous studies involving susceptibility to ice storms also indicate that among eastern hardwood species, white oak is highly resistant to direct physical damage as well (Rogers 1923, Downs 1938, Whitney and Johnson 1984, Seischab *et al.* 1993). Initial physical damage to white oak may be less extensive because the wood of this species is resistant to breakage (Whitney and Johnson 1984, Rebertus *et al.* 1997) and their extensive root systems resist uprooting (Gale and Grigal 1987, Abrams 1990). In this study we compared growth of tree species given the same physical damage and our results suggest that white oak is also resistant to the effects of damage on growth. White oaks may maintain consistently high radial growth following disturbance because oaks have a determinate growth habit. After oaks have leafed-out, additional growth for the remainder of the growing season relies on currently produced photosynthates, rather than stored food reserves (Hinckley *et al.*, 1976). As a result, crown loss during the winter season, before leaf out, may not have as much of an effect on growth as for species with a determinate growth habit.

Differences in the physical structure of needle leaved versus broadleaved species may influence ice accumulation, physical damage and growth. For needle leaved species, the increased canopy area due to the presence of evergreen winter foliage coupled with low flexibility and low wood strength (Rogers 1923, Lemon 1961) has in some cases resulted in more extensive ice damage (Whitney and Johnson 1984, Boerner *et al.* 1988, Warrillow and Mou 1999). In this study, loblolly pine growth was affected by the ice storm, though differences depended on the degree of physical damage. Travis and Meentemeyer (1991) only observed decreased loblolly pine growth during the year of the ice storm and not in the two years following, however it is not known how severe the ice damage was for their sampled trees, just that they were within the influence of a storm. The difference in physical structure between broad-leaved deciduous species and evergreen needle leaved species plays an important role in ice accumulation and initial ice damage, but other factors likely influence the species' growth response in the years following an ice storm.

Tree physiology and competition for available resources can determine the growth patterns of trees following a major disturbance (Smith and Shortle 2003). Although yellow poplar experienced the greatest relative reduction in radial growth in 1994, this species recovered from the disturbance quickly (Fig. 2). This rapid recovery following the ice storm may be due to yellow poplar's ability to produce epicormic branches. Following a disturbance where many crown limbs are destroyed, there is a sudden change in hormonal balance, which causes this species to develop epicormic branches from dormant buds along the stem and branches (Oliver and Larson 1996). The addition of branches and leaves to the stem of yellow poplar may have then intercepted additional solar radiation that penetrated the porous canopy, resulting in a growth release. Epicormic branching varies by species and most needle leaved species do not have this characteristic (Oliver and Larson, 1996).

Conclusion. The four species studied here showed different susceptibilities and variable growth responses to ice damage in the years following the disturbance. White oaks showed the greatest resistance in terms of radial growth to ice damage regardless of the percentage of crown limbs broken. Both yellow poplar and loblolly pine had the greatest reductions in radial growth the year of the storm, but also recovered quickly to pre-storm growth rates. In the most severely damaged trees, growth rates four years after the storm exceeded the 30-year mean indicating a major growth recovery in the years following the storm.

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