COMPARISON OF WINDTHROW DAMAGE AMONG THINNED AND UNTHINNED HARDWOODS AND ADJACENT PINE STANDS FOLLOWING A LATE WINTER TORNADO ON THE CUMBERLAND PLATEAU NEAR SEWANEE, TN

Karen Kuers and Samuel C. Grinstead[1]

Abstract—In March, 2004, prior to spring leaf-out, an F0 tornado snapped or uprooted 672 trees across 25 ha of the western margin of the Cumberland Plateau near Sewanee, TN. A ridgeline separated the impacted area into two parts: westward-facing slopes of mature hardwoods and eastward-facing slopes with thinned and unthinned hardwoods, pine stands, and clearcuts. Greatest damage (29 to 30 percent of damaged stems and basal area) occurred in the pine stands. Among hardwood stands, damage was greater in the mature hardwoods west of the ridgeline than in either thinned or unthinned hardwoods east of the ridge. Damage was intensified on the windward shoulders of ridges and along the margins of clearcuts. Canopy trees were impacted more than lower crown positions, with scarlet oak damaged more severely and white oak less severely than other oak species. Overall, 84 percent of damaged trees were uprooted rather than broken, upturning approximately 0.5 percent of the ground surface.

INTRODUCTION

Prior to leaf-out in March 2004, an F0 tornado (Troutman 2004) snapped stems and uprooted trees across 25 ha of the western edge of the Cumberland Plateau near Sewanee, TN. Wind is a common disturbance factor on the Plateau, but tornadoes are quite rare, even on these western edges that are the first to receive the force of the westerlies-driven thunderstorm activity striking the Plateau.

The area impacted by the storm consisted of a variety of stand types and provided an opportunity to compare wind damage in adjacent stands representing different species, stand densities, and recent management activities. Approximately half of the area consisted of mature, upland hardwoods; the remainder consisted of recently thinned hardwoods, areas clearcut in response to southern pine beetle damage, hardwood buffer strips, and small remnant stands of eastern white pine (*Pinus strobes* L.) and loblolly pine (*Pinus taeda* L.).

The objectives of this study were to (1) compare wind damage in thinned and unthinned upland hardwoods and adjacent pine stands, (2) map wind damage with respect to Plateau topography and harvest edges, (3) identify species differences in response to the wind storm, and (4) quantify the degree of soil disturbance associated with the blowdown.

STUDY SITE

The blowdown area is located on a narrow southward-projecting ridge of the Cumberland Plateau, 2.5 km SSW of Sewanee, TN (35°12'30"N and 85°55'W) (fig. 1). This 1,400-m-wide ridge, which ranges in elevation from 545 to 575 m, constitutes the western-most part of the Plateau at this latitude. Tennessee Highway 56, which follows the top of the ridge, separates the study area into two zones, one west and the other east of the highway. While most of the area is typical of Landtype 1 (undulating sandstone ridges), the area is drained both to the east and the west by several intermittent first-order stream drainages classified as Landtype 14 (streambottoms with good drainage) (Smalley 1982, Smalley and others 2001). The moderately deep to deep soils developed in loamy residuum from sandstone and some shale and are classified

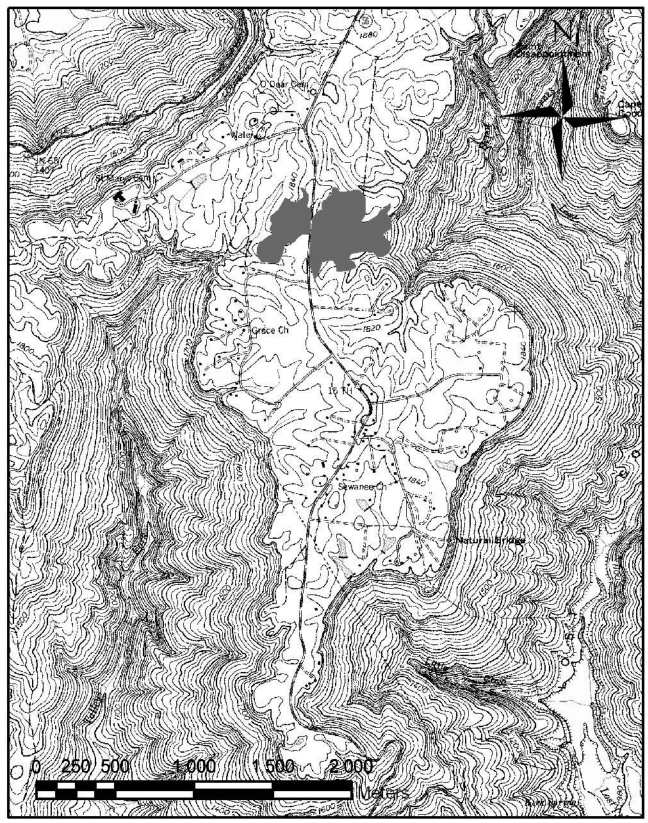

Figure 1—Location of the 25 ha March 2004 blowdown site (shaded area) within a portion of the Sewanee 7.5 minute topographic quadrangle. Note the site's location on a ridge of the western margin of the Cumberland Plateau, 2.5 km south of Sewanee, TN.

[1] Associate Professor of Forestry and Research Intern, respectively, Department of Forestry and Geology, Sewanee: The University of the South, Sewanee, TN 37383.

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as fine-loamy, siliceous (or mixed mineralogy), mesic, Typic Hapludults. Annual precipitation averages 155 cm and is evenly distributed, with lowest values typically recorded in September and October.

Stand Descriptions

Based upon stand structure, species composition, and recent management, the stands impacted by the storm were classified into five categories: mature hardwoods, thinned hardwoods, hardwood buffers, pine stands, and clearcuts with reserves. The mature hardwoods area was located west of Highway 56, while the four more-recently managed stand types were located east of the highway.

Mature hardwoods—The mature hardwoods consisted of 7.8 ha of mixed upland hardwoods dominated by oaks. Stem disks collected from 5 of the downed canopy trees indicated at least 2 age classes, a dominant canopy age of 110 to 130 years and an intermediate crown class consisting of trees approximately 65 years old. The canopy height averaged 22 to 25 m, and the pre-storm basal area averaged 34 m^2 ha^{-1}. Previous management included a selective harvest in 1970 and a white oak (*Quercus alba* L.) harvest in 1955.

Thinned hardwoods—The thinned hardwoods sites consisted of 6.4 ha of mostly mixed upland hardwoods with some loblolly and Virginia pine (*Pinus virginiana* P. Mill) that had been thinned in the 6 months just prior to the blowdown. The site had been marked to leave 100 high-quality hardwood crop trees/ha, with average diameters of 20 to 40 cm d.b.h. The residual basal area after thinning averaged 15 m^2 ha^{-1} but was highly variable (5 to 27 m^2).

Hardwoods buffers—The hardwood buffers totaled 4.4 ha and consisted of streamside management zones, visual buffers, and small areas of unthinned pine-hardwood mixtures. Selective removal of a few large trees occurred during the thinning of the adjacent hardwood stand. Pre-storm basal areas ranged from 20 to 34 m^2 ha^{-1}.

Pine stands—The six pine stands consisted of 1.9 ha of pine left in small groups (0.2 to 0.5 ha) or in rows along fire lanes after the harvest of adjacent loblolly and Virginia pine. The groups were composed of planted loblolly pine (40 to 45 years old), and the fire lanes were bordered by planted eastern white pine.

Clearcuts with reserves—The clearcuts with reserves totaled 4.8 ha. They were created from pine stands harvested in 2002, 2 years before the storm, in response to an infestation from southern pine beetle (*Dendroctonus frontalis* Zimmermann). The cleared areas ranged in size from 0.3 to 3.1 ha with 3-20 residual canopy hardwoods/ha left after harvest.

Storm Characteristics

The storm was classified as an F0 tornado by the Huntsville, AL, office of the National Weather Service, with maximum wind speeds of approximately 70 miles per hour (Troutman 2004). While there was no rainfall in the 24 hours immediately preceding the blowdown, 3.8 cm fell in the 48 hours preceding the tornado, and 20.6 cm (somewhat above average) fell during the preceding month. The storm approached the study area from the valley southwest of the Plateau. It proceeded northeasterly across the site, climbing in elevation as it traversed the western part of the study area (mature hardwood forest) and descending in elevation as it crossed the eastern part of the site (recently managed stands).

METHODS

The location of each damaged tree in the 25-ha blowdown area was mapped with a Garmin III+ GPS unit. The species, d.b.h., height, and azimuth of fall were recorded for each stem. The source of damage was classified as direct wind damage or indirect damage caused by an adjacent tree, and damage type was classified as uprooted or snapped for each stem. Length, width (now height), and thickness of each upturned rootball were measured and the area of disturbed soil in each rootball was calculated using the formula for one-half an ellipse:

$$\text{disturbed soil surface}(m^2) = 0.5 \times (0.5 \times \text{length} \times \text{width} \times \text{pi}) \quad (1)$$

The volume of disturbed soil was then estimated by multiplying the disturbed soil area by the thickness of the rootball.

Pre-storm inventory data was available for the mature hardwood stand to the west of the highway and was used to calculate basal area loss by species. Marking guidelines were available for the thinned areas to the east of the highway and were used to estimate stand structure at the time of the storm. Post-storm basal areas were obtained with a series of randomly located prism points in each stand type. Pre-storm basal areas were estimated in the recently managed stands from prism points located in areas that lacked damaged trees. All reserve trees in the clear-cut areas were counted to determine percent loss during the storm.

The proximity of damaged trees to the margins of clear-cuts was evaluated for the managed areas on the east side of Highway 56. ArcView 3.2 software was used to construct successive 10-m zones around the clearcut areas to a maximum distance of 100 m. The number of hardwoods and pines within each 10-m strip was tabulated and plotted relative to distance from the clearcut to determine the extent to which damage density was controlled by proximity to the forest edge.

The azimuth of tree fall for each stem was analyzed using RockWorks™ software. Mean tree fall azimuth was calculated separately for the east and west sides of the ridge, with the highway serving as the boundary.

RESULTS

A total of 672 stems and 64.8 m^2 of basal area were damaged across the 25.3-ha blowdown zone (table 1). Eighteen different species had uprooted or broken stems. The average diameter of the damaged stems (32 cm) did not differ among stand types but was almost 10 cm greater than the average pre-storm diameter for the mature hardwood stand (22.6 cm), indicating that proportionally more large than small diameter trees were felled by the storm. This relationship was true for most of the 11 species for which pre-storm diameters were available. However, hickory (*Carya* spp.), white oak, and red maple (*Acer rubrum* L.) showed an opposite relationship, with their storm-damaged stem diameter averages smaller than pre-storm diameter averages (fig. 2).

Among the hardwood-dominated stands, the western side of the ridgeline (Highway 56) received more damage than areas

Table 1—Number of damaged stems, basal area loss, and average d.b.h. of damaged stems by stand type from the March, 2004 tornado on the Cumberland Plateau near Sewanee, TN

Stand type	Total stem loss	Stem loss/ha	Damaged BA total	Damaged BA	Avg. d.b.h. of damaged stems
			m²	*m² ha⁻¹*	
Mature hardwoods	245	31.5	24.1	3.1	31.5
Hardwood buffers	90	20.6	8.5	2.0	32.0
Thinned hardwoods	130	20.5	13.0	2.0	32.8
Pine stands	204	107.2	18.9	10.0	32.5
Clear-cuts	4	0.8	0.4	0.1	32.0
Overall	672	26.7	64.8	2.6	32.0

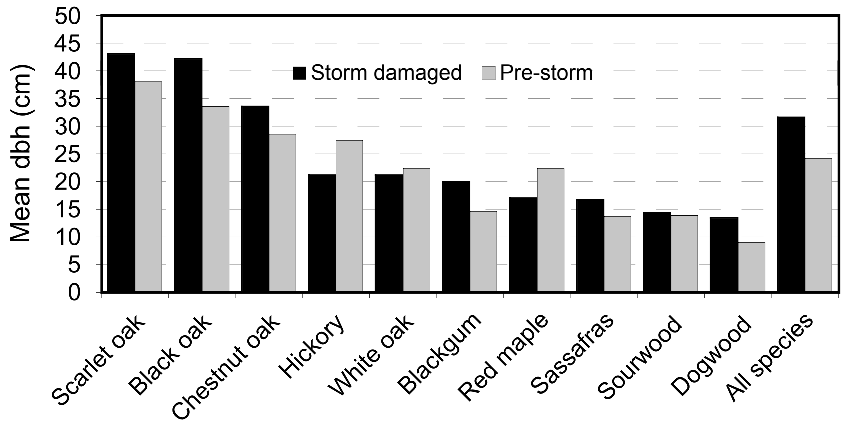

Figure 2—Comparison of pre-storm average diameters to damaged-stem diameters for the mature hardwood stand.

east of the ridgeline. The storm damaged 3.1 m^2 ha^{-1} (9 percent) of the basal area in the mature hardwood forest west of the highway but only 2.0 m^2 ha^{-1} in the thinned and unthinned hardwoods east of the highway. Very little damage occurred to the reserve trees in the clear-cut areas, with only 4 of approximately 86 stems damaged across the entire 1.9 ha of clearcuts.

By far the greatest basal area damage occurred in the pine stands, which sustained 3 to 5 times the basal area loss per unit area (10 m^2 ha^{-1}) of the hardwood stands (table 1). While pine areas constituted only 8 percent of the total damaged areas, pines made up 29 to 30 percent of both damaged stems and basal area.

Over 75 percent of the damaged stems belonged to 6 of the 18 species: scarlet oak (*Quercus coccinea* Muenchh., 21.2 percent of all stems); eastern white pine (16.4 percent); loblolly pine (10.7 percent); chestnut oak (*Quercus montana* Willd., 10.6 percent); sourwood [*Oxydendrum arboreum* (L.) DC., 9.4 percent]; and black oak (*Quercus velutina* Lam., 7.9 percent). Four of those species (scarlet oak, eastern white pine, black oak, and chestnut oak) received 75 percent of the basal area damage. Overall, damage to oak species was quite high. In the mature hardwoods, for example, 93 percent of the damaged basal area occurred among oak species, even though they only composed 66 percent of the pre-storm basal area. Among the oaks, damage was greatest to scarlet oak, intermediate to chestnut and black oak, and least to white oak (fig. 3). White oak, which represented 25.8 percent of the pre-storm basal area in the mature hardwoods, represented only 3.4 percent of the damaged basal area in the mature hardwoods and 3.7 percent of all damaged basal area.

With respect to damage type, the majority of the damaged stems were uprooted rather than broken (fig. 4). Only 15 percent of all damaged stems and 16 percent of all damaged basal area were due to stem breakage. The average diameter of the snapped stems was not significantly different from that of the uprooted trees (30.4 versus 32.4 cm). Among the oaks, the percentage loss of stems to breakage was highest for white oak (29 percent) and scarlet oak (27 percent), followed by black oak (23 percent) and chestnut oak (16 percent; fig. 4). The rankings by basal area were different, with white oak showing much lower percent loss than by stem counts. By basal area, damage due to breakage was highest in scarlet oak (29 percent) and black oak (21 percent), and lowest in chestnut oak (13 percent) and white oak (11 percent; fig. 5).

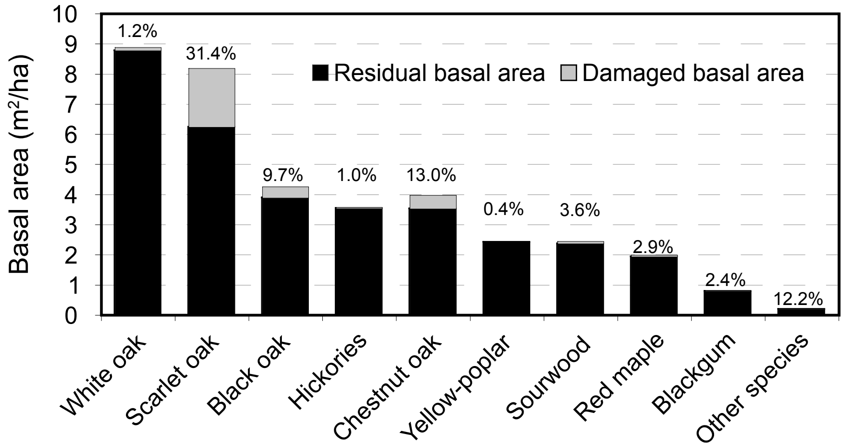

Figure 3—Percentage of pre-storm basal area damaged, by species, for the mature hardwood stand.

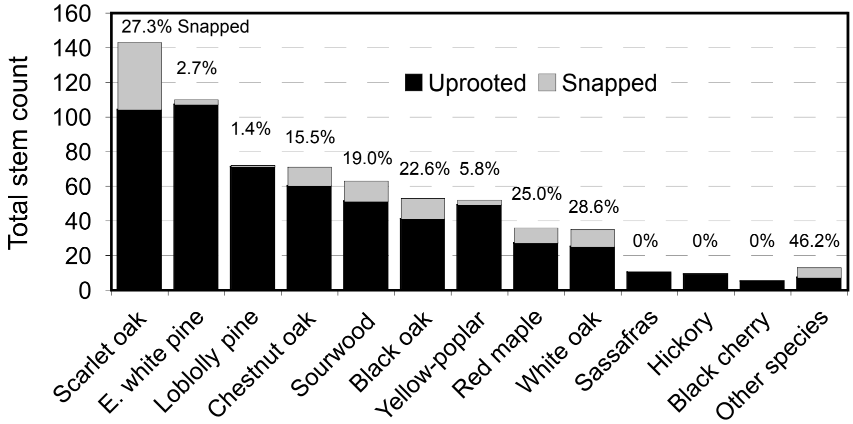

Figure 4—Number of stems uprooted or snapped, by species, across all stand types.

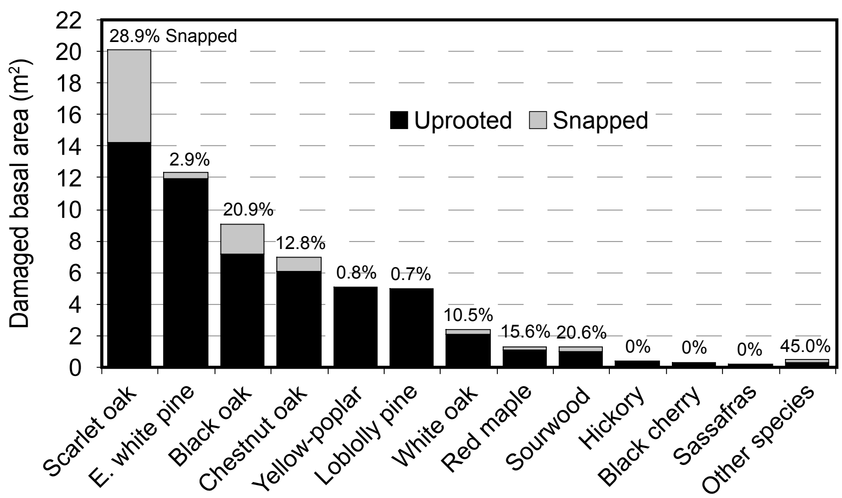

Figure 5—Basal area of stems uprooted or snapped, by species, across all stand types.

Direct wind effects accounted for 72 percent of stems damaged and 85 percent of the total basal area damage across the entire site (fig. 6). The diameter of trees directly damaged by the wind was greater than that of the trees indirectly damaged by the wind (35.7 versus 22.9 cm). Among the oaks, direct wind damage was highest for scarlet, black, and chestnut oak, representing 88 percent of all damage to those species. In contrast, only 66 percent of the damaged white oak basal area was due to direct wind damage.

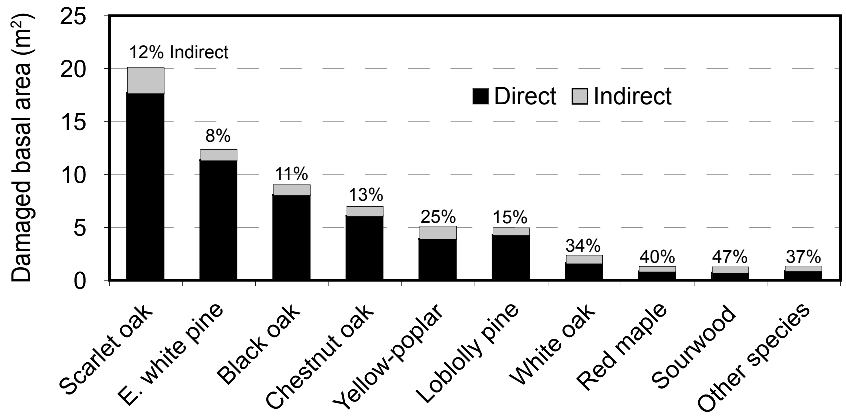

Figure 6—Relative contributions of direct and indirect wind effects on basal area damage, by species, across all sites.

A total of 594 separate mounds were created by uplifted root systems. The mean thickness of the soil layer uplifted with the roots was 71.3 cm, with a maximum of 198 cm. Rootball volume averaged 2.0 m^3; average surface area disturbed by each upturned root system was 2.4 m^2. Overall, 0.47 percent of the soil surface (47.2 m^2 ha^{-1}) was disturbed across all sites. Because pine stands had the greatest stem damage, they also incurred the greatest area of soil disturbance (203 m^2 ha^{-1}). However, even with the greater density of damaged stems, the disturbed soil represented only 2 percent of the ground surface in the pine areas.

The distinctly curved windfall pattern of the downed trees is consistent with tornadic rather than straight line winds (fig. 7). The pattern is even more consistent on the west of the highway than on the east. There is also a change in the average azimuth of tree fall from the west to the east side of the highway (fig. 8). The mean azimuth of tree fall west of the highway (N23°E) was 30° to the N/NW of the mean for the east side of the highway (N53°E). The mean azimuth of tree fall across the entire site was to the northeast (N45°E).

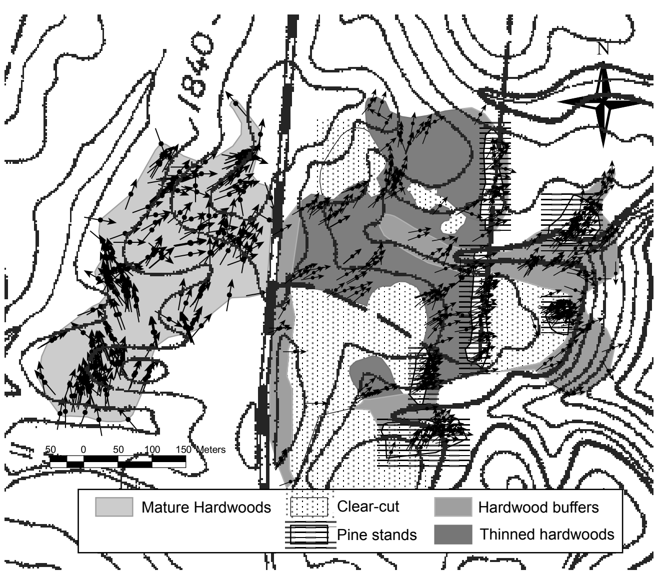

Figure 7—Tree fall azimuths and damage pattern across the March 2004 blowdown near Sewanee, TN.

On the west side of the highway, where the storm was moving toward the high point of the ridge, the highest tree fall densities occurred on the windward shoulders of the ridge (WSW). Less damage occurred within drainages on that side of the ridge. Once the storm passed the ridge, however, damage was highest within the pine stands and adjacent to the leeward forest edges of the clearcuts. All pine stands within the path of the storm were heavily damaged. While damage extended up to 100 m from the edges of the clearcuts, 50 percent of the damaged stems for both pines and hardwoods were within 30 m of a clear-cut edge (fig. 9), a distance less than 1.5 times the average canopy height (22 to 25 m). A greater number of trees fell within drainages on the leeward than the windward side of the ridge.

DISCUSSION

Damage from catastrophic winds can be influenced by two main types of variables: biotic and abiotic. Biotic variables include factors such as tree size, species, stand condition, and tree health, while abiotic variables include storm intensity and site factors such as topography, soil characteristics, and past disturbance. Everham and Brokaw (1996) discuss the relative importance of each variable and note that it is often difficult to separate the relative influence of each factor, especially when only post-storm data is available.

While tree size has been positively correlated to wind damage in a wide variety of studies, there have also been studies that indicated no relationship or even a negative relationship (Everham and Brokaw 1996). In our study, the average diameter of the damaged trees was 10 cm greater than the pre-storm mean diameter. The larger average diameter of the damaged trees indicates that this storm impacted canopy trees to a greater degree than intermediate or overtopped stems.

Wind damage variations among species have been correlated with factors such as shade tolerance, wood density, and leaf persistence (Everham and Brokaw 1996). Evergreens have generally been found to be more susceptible to wind throw than deciduous hardwoods, especially during the winter leafless period. Foster and Boose (1992) constructed a susceptibility ranking for wind damage in forests of central Massachusetts (eastern white pine > conifer plantations > eastern white pine – hardwood mixtures > hardwoods), and the high degree of pine damage relative to that of hardwoods in the current study

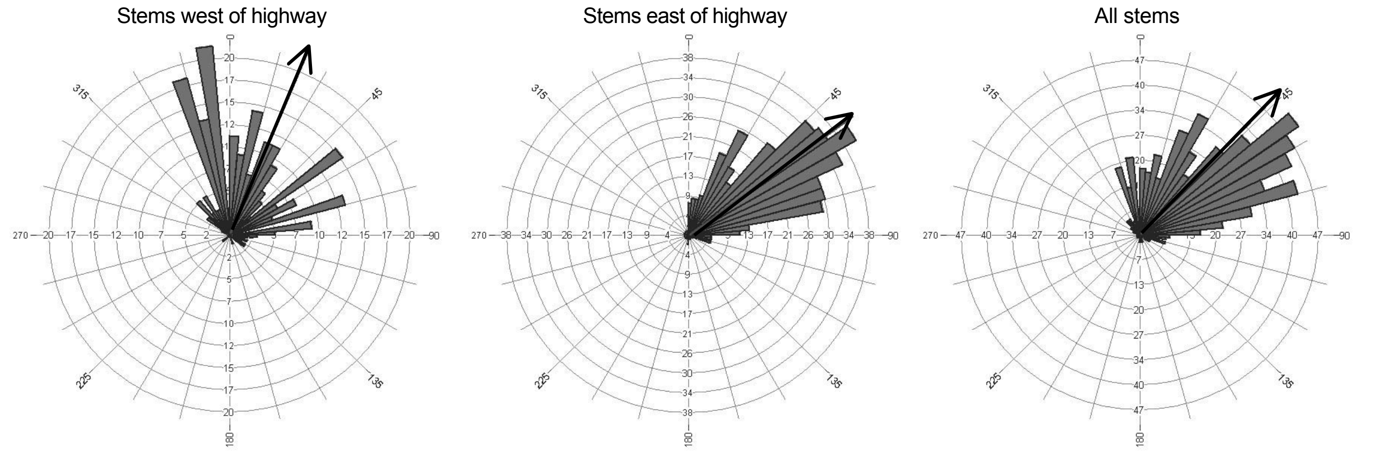

Figure 8—Tree fall azimuth for stems on different sides of TN Highway 56. The highway separated the blowdown into two distinct zones with respect to stand types and damage patterns.

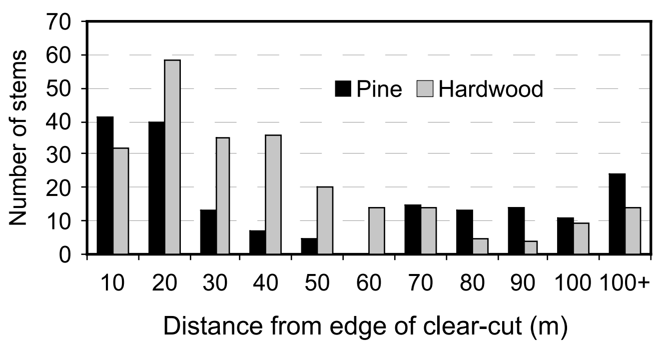

Figure 9—Stem damage by species type (pine or hardwood) at successive 10-m distances from the margins of the clearcuts.

(table 1) is similar to their results. Several characteristics of the pine stands in our study, including their small size, narrow shapes, location adjacent to clearcuts, and/or orientation perpendicular to the prevailing wind, may have contributed to their higher relative damage (pines made up 30 of the damaged stems yet only comprised 8 percent of the study area).

The difference in wind damage sustained among the oak species in this study may provide insight into the ecology of upland oaks on the Plateau and help explain the greater longevity of white oak compared to the other dominant oaks. Of the four major oak species, scarlet oak sustained the most damage and white oak the least, with chestnut oak and black oak intermediate. The storm damaged over 31 percent of the scarlet oak basal area, with a high percentage of that loss due to stem breakage. Previous studies have also found a high probability of stem breakage in scarlet oak (Cremeans and Kalisz 1988, Romme and Martin 1982). White oak, which had even more basal area than scarlet oak before the storm, only lost 1.2 percent of its basal area (fig. 3). While several factors might explain the low white oak damage in this study, including an inherent ability of white oak to withstand higher winds, it is possible that the smaller average size of the white oaks may explain the results. The average pre-storm diameter of white oak was 22 cm, below both the average pre-storm diameters of the other oaks (29 to 38 cm) and the 32-cm average diameter of stems damaged by the storm (fig. 2).

The hypothesis at the onset of this study was that thinned hardwood stands and hardwood buffer strips would show more damage than the unthinned, mature forest. It was thus surprising that the thinned hardwood areas actually sustained less damage/ha (2.0 m^2) than the unthinned, mature forest (3.1 m^2). Evidence from the literature is mixed, with some studies indicating increased damage in thinned areas and others showing increased damage in unthinned mature forests. Everham and Brokaw (1996) concluded that a key factor may be the timing of a thinning relative to a wind disturbance. They noted that more damage was generally associated with more recent thinnings. Following their reasoning, however, the damage in this study should have been higher in the thinned than unthinned stands because the thinning was completed less than 1 month before the storm. Several factors may have contributed to the reduced damage in the thinned areas of the current study: (1) because the trees were leafless, and the thinned areas were more open to wind movement, the trees provided less wind resistance; (2) the trees left after the thinning were mostly codominant stems that were already reasonably wind firm; and (3) the mature hardwood forest was located on the west side of the ridge where trees were more directly exposed to the force of the oncoming storm.

More direct wind damage than indirect damage in this storm and more uprooted than broken stems are consistent with the results in other studies (Clinton and Baker 2000, Coates 1997, DeWalle 1983). In their Southern Appalachian study, Clinton and Baker (2000) also found that indirectly damaged trees were much smaller in size than directly damaged trees (mean diameters: 16.6 versus 32.6 cm). While the difference between indirectly and directly damaged trees was slightly less in this study (22.6 versus 32 cm), it supports the conclusion that direct wind damage impacted mostly canopy trees while indirect wind damage occurred primarily to smaller stems that were either in the path of larger falling trees or attached to the rootballs of the uprooted stems.

Uplifted root systems disturbed, on average, 0.5 percent of the soil surface across the blowdown. In their study of pit and mound distribution on the Cumberland Plateau in Kentucky, Cremeans and Kalisz (1988) estimated that pits and mounds covered 0.4, 1.1, and 2.4 percent of the land surface on ridges, slopes, and coves, respectively. In our study of a single storm event, soil disturbance ranged from 0.5 to 2.0 percent of the soil surface. The cumulative effects of the uprooting of trees from many storms can have a significant impact on the spatial variability of forest soils and in the mixing of surface and subsurface soils. While the mean thickness of the soil layer uplifted with the roots in this study was 71.3 cm, a number of uprooted trees upturned soil to a depth of 2 m.

Wind damage was not spatially uniform across the blowdown in our study. Foster and Boose (1992) found that the spatial pattern of wind damage in forested landscapes in central Massachusetts was controlled by vegetation height and site exposure, with site exposure most strongly influenced by slope angle and orientation with respect to wind direction. In this study, damage west of the highway, where the storm was moving toward the high point of the ridge, was highest on the windward (WSW) shoulders of the ridge and least in the drainages (fig. 7). Everham and Brokaw (1996) noted, however, that the relationship between topography and wind damage can be quite complex, with wind sometimes causing greater damage in valleys than on ridges.

Interpreting damage patterns on the east side of the highway is complicated by the presence of small pine stands, gaps created from past harvests, and variations in stem density from past management activities. In addition, the storm's path east of the highway was one of progressively decreasing elevation. Damage east of the highway was highest within pine stands and adjacent to the windward facing edges of the clearcuts. Damage adjacent to the clearcut was not unexpected, as a number of studies have shown that clearcuts and even natural canopy gaps can deflect or concentrate the path of the wind (Everham and Brokaw 1996). DeWalle (1983) also noted a high degree of damage adjacent to clear-cuts and identified different factors that contributed to the damage. He determined that damage was increased where either (1) pines were a component of the stand, or (2) the soil was poorly drained. Both of these components were typical of the damaged areas east of the highway in our study, where increased damage was typical of both pine areas and poorly drained soils of stream drainages. DeWalle's study also indicated that the windward-facing edge of a clearcut seemed to sustain the greatest damage, a pattern apparent in our study from the large number of downed trees along the northern and eastern edges of the clearcuts.

CONCLUSIONS

Average diameter of damaged stems did not differ among stand types (32 cm across all sites). This diameter was almost 10 cm greater than the pre-storm average and indicated that damage was more prevalent in the larger trees that may have occupied dominant canopy positions.

By far the greatest basal area damage occurred in the pine stands, which covered only 8 percent of the total impacted area but sustained 29 to 30 percent of the damaged stems and basal area. Among the hardwood-dominated stands, basal area losses were higher west of the ridgeline, in the mature hardwood forest than east of the ridgeline in either the thinned hardwoods or the unthinned hardwood buffers. Very little damage occurred to the reserve trees in the clear-cut areas.

Over 75 percent of damaged basal area belonged to four species: scarlet oak, eastern white pine, chestnut oak, and black oak. Oaks composed 93 percent of the damaged basal area in the mature hardwood stand and 60 percent across the entire study area. Among the oaks, damage was greatest to scarlet oak, intermediate to chestnut oak and black oak, and least to white oak.

Direct wind effects accounted for 72 percent of stems damaged and 85 percent of the total basal area damage across all sites. The majority of the damaged stems were uprooted rather than broken (84 to 85 percent), with scarlet oak exhibiting the highest susceptibility to breakage (29 percent of its basal area loss). Disturbed soil averaged 0.5 percent of the surface area (range: 0.4 to 2.0 percent), and while the mean thickness of the uplifted soil was 71.3 cm, some roots upturned soil layers nearly 2-m thick.

Wind damage patterns differed on the west and east sides of the highway, which was positioned along a topographic ridge. Greatest damage on the west side of the highway was associated with the windward slopes of this ridge. Damage east of the highway (on the east side of the ridge) was concentrated in remnant pine stands and along the leeward (eastern) margins of the clear-cut areas.

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