

Ecological Impact of Glaze Storm Damage in an Appalachian Oak Forest

By

Michael P. Warrillow

Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
In
Forestry

Committee:

Dr. Mou Pu, Chair

Dr. Shepard M. Zedaker

Dr. Wallace M. Aust

February 2nd, 1999
Blacksburg, Virginia

Key words: Glaze damage, Tree susceptibility, Seedling regeneration, Appalachian forests

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(Abstract)

Glaze damage to canopy trees, gap size and seedling regeneration was surveyed relating to site topographic features after a major glaze storm at Fishburn Forest in the central Appalachian mountain region. The survey sites were stratified according to aspect and landform, and sample plots were randomly assigned to each topographic category. The canopy trees in the plots were tallied and their damage was visually classified.

The results demonstrated that different species had different susceptibilities to glaze damage and susceptibility of species varied as topography changed. Virginia pine was the most susceptible species. In general, trees had the greatest damage on steep slopes and eastern aspects, and least damage on toe-slopes. Some species varied greatly in their susceptibility to glaze damage across the topographic categories, such as red maple, while some species varied little, like blackgum. Basal area was reduced 6% and varied due to species and topography.

Where glaze damage was severe, gaps in the forest canopy were created. Gap sizes and the effects of gap size and topography on seedling regeneration within gaps caused by glaze damage were assessed. Seedlings were tallied by species and height in microplots within each sample plot and in the nearest gap, where gap size was measured. Gap size varied from 14,000 m² to less than 20 m². Average gap size was 255 m². Canopy tree damage, forest type and topography were the most important factors affecting gap size. Gaps tended to be larger on steep backslopes. Common seedling species in both gaps and understory were sassafras, serviceberry and red maple. Disturbance affected both seedling height and density, as did topography. However gap size had effect only on seedling height. The future forest in this area is unlikely to change significantly, as species composition of seedlings was largely unaffected by the glaze storm damage.

Acknowledgments

I would like to express my thanks to my major professor, Dr. P. Mou for his encouragement and energy. Other members of my graduate committee, Dr. W.M. Aust and Dr. S.M. Zedaker, gave helpful ideas and were valuable reviewers. Dr. W.M. Stuart provided help on the history of Fishburn forest.

Several research technicians helped in data collection and entry: John Peterson, Anita DeMatteo and Rhonda Harper. Special thanks go to Michelle Marini of the Statistical Consulting Center at Virginia Tech for her expertise, advice, and good humor. Family and friends provided invaluable support throughout my education. Thank you all.

The Forestry Department at Virginia Tech provided funding for this work.

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Preface

Glaze storms are a common meteorological phenomenon over much of North America causing significant damage to many forests. In the central and southern Appalachians, glaze storms have been a major frequent natural disturbance of the forest and played an important role in shaping local vegetation. Glaze damage varies from broken branches in a single tree to the toppling of a stand of canopy trees. Damage to tree crowns creates gaps in the forest canopy. Canopy gaps change forest environmental conditions (e.g., light, temperature, soil nutrients and water), which may profoundly alter understory communities, according to the size of gaps.

At the broad scale, the distribution of gaps and gap dynamics partially determines local vegetation dynamics. Glaze damage and gap formation is not spatially homogeneous in an area and is largely affected by topographical features and microclimate (Bennett 1959). Consequently, the spatial pattern of local vegetation should be related to heterogeneous glaze damage in those areas that have been frequently damaged by glaze storms.

A complete understanding of glaze storm damage and its role in forest dynamics is important to foresters, biologists, forest companies and the public. This knowledge may result in the development of silvicultural practices and natural resource management approaches that are adapted to frequent glaze storms.

The two objectives of this study were to identify topographic trends in canopy tree glaze damage and to examine the effects of gaps and topography on forest regeneration.

Chapter 1: Introduction

I. Tree susceptibility to glaze damage

Meteorology, occurrence and frequency of glaze storms

Glaze is defined by the U.S. Weather Bureau as homogenous, transparent ice layers that are deposited upon horizontal and vertical surfaces (Haynes 1947). Glaze is usually formed when supercooled rain falls on a surface below 0°C (Bennett 1959).

Glaze storms are most frequent in the northeast, central and Midwest of the U.S. (Bennett 1959, Sisinni *et al.* 1995), with occasional storms occurring in the southeast and northwest. Glaze storms have been reported at almost every location within the U.S., but are more common in an area known to meteorologists as the glaze belt. Bennett (1959) describes a glaze belt (an area in which glaze is frequent) many hundreds of miles wide, extending north from a line drawn across the U.S. from southern New England west-southwest to Ohio and then gradually curving into the southwest and south across Indiana, Illinois, Missouri, eastern Oklahoma and northwestern Texas. North of the glaze belt temperatures are generally too cold to form glaze, and snow falls, while south of the belt temperatures are too high, and precipitation falls as rain (Brooks 1930). In Rochester, NY, eleven glaze storms were recorded between 1913 and 1991 (Sisinni *et al.* 1995).

Recent severe glaze storms include the events of 1994 (National Climatic Data Center, NCDC, 1994b) which struck across several states in the southeast of the U.S., and the 1998 event which occurred in the northeast of the U.S. and across southeast Canada (Purvis 1998). The affected area of glaze-producing storms varies enormously from a few counties to many states (Bennett 1959). The average storm deposits glaze over 500 -1500 square kilometers.

Frequency and distribution data on glaze storms is rare with the best reviews being regional (Sisinni *et al.* 1995) or based on data from the 1920's (Bennett 1959). Glaze is recorded by the National Weather Service as a type of precipitation in its daily observational data sheets (NCDCa) and this data is forwarded to the National Climatic

Data Center (N.C.D.C). However, no specific report on glaze is produced by the NCDC. Instead, severe storms may be mentioned in annual generalized storm reports for each state (NCDCb). Therefore, glaze storms can only be accounted for by study of these annual reports for each state. This makes analysis of glaze storms difficult and probably accounts for the lack of literature on the frequency and distribution of glaze.

Damage caused by glaze storms

Trees may be uprooted, decapitated or suffer massive crown loss as a result of excessive glaze loads. Large branches may be broken off, causing loss of large portions of the crown, tree deformation and/or loss of growth (Lemon 1961). Trees may be bent over and deformed, although some eventually recover. The growth of damaged trees is usually greatly reduced and glaze damaged trees lose most of their timber value. Urban trees damaged by glaze lose their esthetic value and may need to be replaced. Conversely, light glaze may help to trim off small branches and faulty limbs on some species (Lemon 1961).

Severity of damage to a tree relates to the quantity of glaze accumulated, wind conditions and the physical characteristics of the tree. Branch breakage is common in glaze storms. The ratio of glaze mass to branch mass at which a branch breaks varies from 13 to 32 depending on the strength and flexibility of the branch (Lockwood 1922, Seeley 1922, Root 1924, Spencer 1929). Larger branches often bear proportionally less glaze load than smaller branches (Table 1.1). Little modern literature elaborates on the effects of wood and tree characteristics on glaze loading or damage.

Trees infected by fungi or insects are more likely to be damaged by glaze but wounds resulting from glaze damage also allow entry for insects and fungi. In many instances the greatest damage to commercial plantations is not from mechanical damage by glaze storms but aftermath infection by decay organisms (Cool *et al.* 1971). Often the invasion of decay organisms is not noticeable until several years after the initial infection. Glaze storms increased the spread of Dutch elm disease in the eastern United States (Deuber 1940).

Table 1.1 Ratio of glaze load to tree twig weight in glaze storms. Table taken from Bennett (1959)

Weight (grams) of		
Twig Alone	Glaze Formed	Ratio
0.7	24.3	34.7
1.25	21.75	17.4
27	146	5.4

Resistance of trees to glaze damage

Resistance of trees to glaze damage is determined by both physical characteristics such as wood strength, elasticity and growth form (Bruederle and Stearns 1985), and environmental factors. Physical characteristics determine the severity of injury. As these characteristics vary greatly by species and change with size and age, species-specific susceptibility to glaze storm damage is difficult to predict. Environmental factors such as topographic and climatic variations, stand and soil conditions add to this difficulty.

Tree characteristics affecting glaze damage

Trees with brittle and weaker wood are more susceptible to damage than those with pliant and stronger wood. Deuber (1940) reported that oak has greater resistance to glaze damage than maple or elm. He attributed this to the greater wood strength of oak. A more flexible tree is more likely to be bent over instead of broken under large loads of glaze (Lemon 1961). As trees age, wood strength and flexibility are reduced, and inevitably trees become more prone to glaze damage with time (Spaulding and Bratton 1946).

Tree size is another factor affecting susceptibility to glaze storm damage. Large trees dominate the forest canopy in both height and width, exposing them to more glaze. Consequently these trees frequently suffer greater damage than smaller trees (Downs 1938, Carvell *et al.* 1957, Bruederle and Stearns 1985, Boerner *et al.* 1988, Hauer *et al.* 1993, Rebertus *et al.* 1997). Smaller trees in the understory may not be directly damaged

by glaze as they are sheltered from glaze precipitation by surrounding larger trees. However, secondary damage to understory trees may occur due to falling branches or stems (caused by glaze damage) from surrounding trees (Lemon 1961).

Lemon (1961) and Deuber (1940) reported that heavy injury occurs in finely branching species as these trees have a greater canopy surface area and intercept more glaze. They speculated that the surface area of a tree canopy in winter directly relates to the glaze load of a tree.

Bennett (1959) and Sisinni *et al.* (1995) summarized and published tables (Table 1.2) listing canopy tree susceptibility of different species. The tables illustrate that susceptibility to glaze varies greatly from author to author for each species. For example, eastern hemlock (*Tsuga canadensis*) was rated as highly susceptible to glaze damage by one author, and highly resistant by two other authors. Such broad variation in estimation of glaze damage susceptibility makes prevention of damage difficult for foresters. Forest stand characteristics affecting glaze storm damage

Stand density is an important factor affecting glaze storm damage severity. Trees within a denser stand lend support to each other to withstand heavier canopy ice loads. Heavily glazed tree branches may gain support from the branches of adjacent trees. Stands that have recently been thinned are usually severely damaged by glaze storms (Downs 1938, Shepherd 1975, 1978). However, Ameteis and Burkhart (1996) reported that spacing had no effect on tree damage in their experimental loblolly pine (*Pinus taeda*) stands.

Little has been documented regarding the differences in glaze susceptibility between even-aged and uneven-aged stands. Uneven-aged stands may be more susceptible than even-aged stands since the trees of an even-aged stand are more similar in size and thus their crowns may be better able to support each other.

Table 1.2 A summary of the number of authors evaluating ice storm susceptibility for tree species of southeastern US. (from Bennett 1959, Lemon 1961, Siccama *et al.* 1975, Whitney & Johnson 1984, Bruederle & Stearns 1985, Boerner *et al.* 1988, Seischab *et al.* 1993). Species are ranked, ranks are calculated as weighted means by the number of authors and the given scores: strong (1), moderate (2) and weak (3). High rank value indicate high susceptibility.

Species	Strong	Moderate	Weak	Rank
Conifers				
<i>Tsuga canadensis</i>	4	1	1	1.5
<i>Pinus palustris</i>	1	1		1.5
<i>P. taeda</i>	1	1		1.5
<i>P. strobus</i>	3	2	2	1.86
<i>P. elliotii</i>		1		2
<i>P. virginiana</i>			1	3
Hardwoods				
<i>Juglans nigra</i>	1			1
<i>Platanus occidentalis</i>	3			1
<i>Franxinus spp.</i>	4	3	4	2
<i>Fagus grandifolia</i>	1	6	1	2
<i>Q. velutina</i>	1	7	1	2
<i>Nyssa sylvatica</i>		1		2
<i>Magnolia acuminata</i>		1		2
<i>Q. rubra</i>	1	4	1	2
<i>Liriodendren tulipifera</i>	2	1	2	2
<i>Quercus alba</i>	1	4	2	2.14
<i>Acer saccharum</i>	1	7	3	2.18
<i>Robinia pseudoacacia</i>	1	2	2	2.2
<i>A. rubrum</i>	1	5	4	2.3
<i>Betula lenta</i>		2	1	2.33
<i>B. alleghaniensis</i>		2	1	2.33
<i>Carya spp.</i>	1	1	4	2.5
<i>Populus spp.</i>		1	3	2.5
<i>Ulmus spp.</i>	1	1	6	2.63
<i>Q. coccinea</i>		1	2	2.67
<i>Prunus serotina</i>		2	5	2.71
<i>Tilia americana</i>		1	6	2.86
<i>A. negundo</i>			1	3

Effect of topography on glaze storm damage

Variances in micro-topography may cause a wide variation in glaze deposition. Elevation (Brooks 1930, Downs 1938, Nicholas and Zedaker 1989), slope (Boerner *et al.* 1988, Seischab *et al.* 1993, Rebertus *et al.* 1997, Rhoades 1999), aspect (Downs 1938, Bruederle and Stearns 1985, Rhoades 1999) and the composition of the land surface (Bennett 1959) all influence glaze deposition.

Aspect, slope and slope position affect exposure to both wind and glaze deposition. Trees on slopes that face the prevalent wind in a storm accumulate more glaze and are exposed to higher wind speeds, so are frequently and more heavily damaged (Boerner *et al.* 1988, Seischab *et al.* 1993, Rebertus *et al.* 1997, Rhoades 1999).

Aspect, slope and slope position also affect soil water condition and soil depth, which are critical influences on glaze damage (Pritchett and Fisher 1987). Gravity and erosion leave shallow soil on the upper slopes and ridge tops, and accumulate deeper soils on footslopes (Wild 1993). In addition, soils on slope bottoms are usually wetter than those on upper slopes as water accumulates there from the upper slopes and/or the water table is higher (Buol *et al.* 1989). Soils on different aspects have different water contents (Buol *et al.* 1989) as aspect affects exposure to precipitation and evaporation. In shallow and saturated soils, roots are unable to provide sufficient anchorage for heavily glazed trees and toppling is more likely (Carvell *et al.* 1957). Elevation influences glaze deposition because temperatures decrease as elevation increases, favoring glaze deposition at higher altitudes (Brooks 1930, Downs 1938, Nicholas and Zedaker 1989).

II. Ecological impact of glaze disturbances

Canopy trees destroyed by glaze create gaps in the forest canopy. The understory environment (light, temperature, soil, nutrients and water) is changed. Regeneration is affected by these changes in the environment and hence glaze may alter forest development and change forest communities. Topographic features and microclimate effect glaze damage and consequently gap formation. Therefore, local vegetation dynamics over the landscape are effected by the distribution of gaps. Forest gaps have been defined as the ground area under a canopy opening extending to the bases of canopy trees surrounding the canopy opening (Runkle 1981, McClure and Lee 1993) while others used the area of open canopy extending from the drip line of canopy trees surrounding the canopy opening (Canham *et al.* 1990).

Impact of gap size on forest environmental conditions

Canopy gaps significantly affect the nutrient and light status of understory herbs, shrubs and trees (Runkle 1985). The alteration in growing conditions may lead to a change in species composition in the forest (Clinton *et al.* 1994).

As gap size increases so does light availability (Canham and Marks 1985). The improvement in light conditions may increase seedling density and growth (Canham 1988). However, after gaps reach a certain size light availability reaches a maximum. Spies *et al.* (1990) found that gap size had no impact on seedling density, and Canham (1988) concluded that an increase in light levels alone was not a significant factor in the growth and density of seedlings. Instead as gap size increases, a number of other factors become increasingly more important in affecting seedling regeneration within gaps, including location within the gap, soil water conditions, and root competition for soil nutrients (McClure and Lee 1993).

Soil water conditions in gaps are altered by increases in water evaporation and a reduction in water interception and transpiration by the tree canopy (Pritchett and Fisher 1987). Soil water availability generally increases in gaps but also fluctuates more. Further, as large trees are killed they no longer take up soil nutrients and water, leaving more nutrients and water available for seedlings (Pritchett and Fisher 1987).

The destruction of a tree has a profound impact on soil conditions, adding a tremendous amount of organic matter to the forest floor. Changes in temperature and water conditions also cause changes in the microbial community and strengthen forest floor decomposition processes, further increasing soil nutrients available to seedlings (Bormann and Likens 1979, Pritchett and Fisher 1987). In addition, when a tree is toppled the soil surrounding the roots is aerated and exposed, causing some erosion and weathering of the soil and parent material (Pritchett and Fisher 1987). This may improve soil fertility and soil physical conditions. Consequently larger gaps have more light, higher temperatures, water and nutrients are more available. These environmental conditions are all beneficial to seedling growth.

The frequency and scale of glaze disturbance and its effect on succession

The size of gaps created by glaze, while a function of the dominant tree species and local topography, is ultimately an indication of the severity of the glaze disturbance. Large gaps that range from thousands of square meters to tens of thousands of square meters may be attributed to the toppling of several to many canopy trees (Runkle 1985). Smaller gaps that range from hundreds to a few thousand square meters in size can be caused by the canopy loss of a single tree. Very small gaps, less than one hundred square meters in size, are usually attributed to the partial loss of a tree canopy. Small disturbances usually do not have a profound effect on growing conditions at the forest floor (Canham and Marks 1985).

The spatial scale of disturbance is usually negatively related to disturbance frequency. Small scale disturbances are common while very large disturbances are rare (Lorimer 1989). Large fires or very severe storms (snow, glaze, or wind) create large scale forest disturbances. Lorimer (1989) estimated that large scale disturbances account for 20% of all disturbances by area. Large scale and small scale disturbances are somewhat related. Large scale disturbances may reduce the frequency of small scale disturbances through the removal of older, more susceptible individuals (Lorimer 1989).

While some disturbances do not occur at random, i.e. glaze storm disturbance is determined by topography and species composition, at a specified scale the turnover rate of a forest can be determined. Lorimer (1989) estimated that a typical eastern U.S. forest

stand turns over due to large scale catastrophic disturbances (greater than 1 hectare) every 1,000 years and due to all disturbances every 100 years. Runkle (1985) speculated 0.5 to 2% of eastern U.S. forests are affected per year by natural disturbances, and turn over in 50 to 200 years. Spies *et al.* (1990) estimated that the turnover rate on the west coast in mature and old growth stands was slower, 0.7 and 0.2 % per year respectively, with turnover in 140 to 500 years.

The frequency of disturbance is also a very important factor in affecting succession. A high frequency of large disturbances may result in succession remaining in the pioneer stage. Smaller disturbances occurring with lower frequency may speed up succession (Pickett and White 1985).

Disturbance has a profound impact on the course and speed of forest succession (Pickett and White 1985). Succession may be accelerated if pioneer species in the canopy sustain greater damage than later successional species in the understory (Abell 1934, Carvell *et al.* 1957, Lemon 1961, De Steven *et al.* 1991). However, succession may be set back if canopy gaps are large and the sapling community suffers severe damage. Large gaps usually start secondary succession from much earlier seral stages and shade - intolerant pioneer species are favored (Downs 1938, Siccama *et al.* 1976, De Steven *et al.* 1991).

The effect of glaze disturbance over the landscape

Glaze damage varies over the landscape due to variations in topography and microclimate. Variation in glaze damage creates gaps of varying sizes over the landscape. The frequency of glaze disturbance and the size of gaps created by glaze has a profound impact on the vegetative pattern over the landscape (Whitney and Johnson 1984).

Areas frequently damaged, where large gaps created by glaze are more common contain small individuals and early pioneer species (Whitney and Johnson 1984). Early pioneers dominate as gap sizes are large and environmental conditions favorable for very rapid growth and establishment (Siccama *et al.* 1976, De Steven *et al.* 1991, McClure and Lee 1993). Individuals may be small as glaze damage is so frequent that even rapidly growing species do not become large.

In areas that are rarely damaged by glaze, the forest is dominated by large late successional shade tolerant species (Whitney and Johnson 1984). These individuals survived as shade tolerant saplings beneath a close canopy until eventually they reached the canopy (Runkle and Yetter 1987). As canopy trees in a rarely damaged area they grow to be large individuals.

Since large disturbances are rare (Lorimer 1989) and small disturbances more common in the, the eastern U.S. forest landscape mostly consists of late successional species with smaller early sere species existing in scattered stands (Whitney and Johnson 1984, Rhoades 1995).

III. Justification

Glaze storms affect small non-industrial, federal, and industrial forest owners alike, through the destruction of trees. Landowners' objectives such as wildlife refuges, aesthetics, timber production, and recreation may be hindered. Damage caused by glaze storms may cost millions of dollars. The Appalachian glaze storm of 1994 caused over \$21 million of damage to forest lands alone in just six south-western Virginia counties (NCDC 1996b). Hauer *et al.* (1993) estimated replacement costs of \$1.1 million for ornamental trees in the city of Urbana, IL, damaged by a glaze storm in 1990. During January 1998 another very large glaze storm occurred across several New England states and in south-eastern Canada (Wilson-Smith 1998).

A better understanding of the phenomenon of glaze and its effects on forests is necessary. Despite numerous studies on the effects of glaze storms on forests (Lemon 1961, Whitney and Johnson 1984, Bruederle and Stearns 1985, Boerner *et al.* 1988, De Steven *et al.* 1991), the complexity of glaze storm damage to trees and to the forests has still not been fully studied. Particularly important issues include the effects of species and topography on canopy tree susceptibility to glaze storm damage.

There exists considerable variability in the literature for canopy tree susceptibility to glaze damage. This variation may be the result of differences in glaze deposition and tree characteristics between studies. Glaze deposition is affected by micro-climate and the degree of exposure of trees to glaze precipitation. Tree characteristics such as wood strength and wood flexibility affect the susceptibility of trees to breakage from glaze and vary from stand to stand.

Topography affects both tree characteristics and glaze deposition, by affecting micro-climate, exposure to glaze, site quality and species distribution. Therefore, topography is critical to glaze damage and may be the cause of the large variation reported in the literature. An investigation on the effects of species and topography is needed.

The U.S. forest products industry relies heavily on the timber resources of the South-east (Haymond 1988, Bergmann 1997, H.R. 2789 1997). Hardwood stands in the Appalachians cover 11 million hectares (Bechtold and Ruark 1988) mostly owned by private individuals (Scrivani and Liu 1998). Non landowners objections to clear cut

harvesting techniques have prompted changes to smaller harvests or group selection cuts which may be more acceptable. The openings created in group selection cuts, where single or clumps of trees are removed, mimic gaps created by glaze storms. Regeneration in such small gaps is insufficiently documented and gaps caused by glaze may provide supporting research. This study will provide information for improved management of hardwood forest in the central Appalachian region where glaze storm damage is a frequently a major disturbance.

In addition to examining regeneration, this study will look at the effects of glaze on forest regeneration. Across the southeast farmland has been abandoned during the past 40 years due to increased efficiency in land utilization and a decrease in the rural population. Much of this farmland has reverted to forests (Scrivani and Liu 1998). Many of these stands are dominated by early successional sere species (Stephenson *et al.* 1993). Disturbance caused by glaze may play a critical role in the development of these forests.

A forested landscape consisting of different seral stages is desirable from a biological conservation perspective. Forest stands at earlier successional stages may have greater species diversity and greater productivity (growth rates) than later seral stages and support grouse, turkey and deer (Kimmins 1987, Stephenson *et al.* 1993), while the later sere forests are more valuable in providing habitats for rare or endangered wildlife.

IV. Location and description of study site

This study was conducted at Fishburn Forest, located in Montgomery County, between Christiansburg, Blacksburg and Prices Fork, Virginia. The forest is approximately 500 hectares, located in the Ridge and Valley physiographical province in the Appalachian Mountains (37°11'N, 80°30'W). The major soil series in the forest are Berks (fine-loamy, mixed, mesic Typic Dystrochrepts) and Weikert (loamy-skeletal, mixed, mesic Lithic Dystrochrepts) series of relatively low productivity (Creggar *et al.* 1985). Jefferson (fine-loamy, siliceous, mesic Typic Hapludults), Craigsville (loamy-skeletal, mixed, mesic Fluventic Dystrochrepts) and Clymer soils (Fine-loamy, mixed, mesic Typic Hapludults) can also be found in small areas throughout the forest. The Berks and Weikert series are found on moderate to steep slopes all over the forest. Clymer soils are found on summits. Craigsville soils are found on footslopes and slopes bottoms. Jefferson soils are found on moderate slopes where soils have accumulated (Creggar *et al.* 1985). The main parent material for these soils are sedimentary rocks from the Mississippian age, mostly shale and sandstone (Creggar *et al.* 1985). Soil depth varies from about 30 cm for Berks and Weikert, to 180 cm for Craigsville. Site index for Northern red oak in the forest varies from 16 to 21 meters (base age of 50 years, Creggar *et al.* 1985). The forest covers the western half of Prices Mountain and is bounded north and south by two perennial streams (Stroubles Creek and Slate Branch). The forest has undulating topography with small hills, valleys, gullies and ephemeral streams throughout. Slope in the forest varies from less than 15% to 110%. Elevation varies from 580 to 850 meters above sea level. Montgomery County's climate is described by the National Oceanic and Atmospheric Administration (NOAA 1990) as cool temperate. The average annual temperature is 10.8°C, with a January mean of -0.6°C and a July mean of 21.7°C. Maximum rainfall occurs in months of April and September. The average annual precipitation is 102 cm (Cregger *et al.* 1985, NOAA 1990).

In this region the dominant vegetation type consists of mixed hardwood, primarily oak and hickory (Braun 1950, Whitney and Johnson 1984, Rhoades 1995). Species richness in the Fishburn Forest is high. Common trees species are Virginia pine (*Pinus virginiana* Mill.), pignut hickory (*Carya glabra* (Mill.) Sweet), mockernut hickory (*C.*

tomentosa (Poir.) Nutt.), chestnut oak (*Q. prinus* L.), white oak (*Q. alba* L.), scarlet oak (*Q. coccinea* Muenchh.), red maple (*Acer rubrum* L.) and white pine (*P. strobus* L.). Most of the forest consists of uneven-aged stands but some even-aged stands with a reduced number of species exist. Presumably, these areas have previously been disturbed by logging, glaze, or other weather phenomena (e.g., hurricanes, snow, and winds).

V. Land Use History

Coal was found in the late 1700's on Prices Mountain where Fishburn Forest is located and later large areas of forest were cleared for mining operations (La Lone 1997). By the end of the 19th century, the area around Fishburn was densely populated by farmers and miners. The forest was cut for agriculture and firewood in addition to clearing for mining and the provision of mining props (La Lone 1997). In the mid 1930's a portion of Prices Mountain was purchased by Mr. J.B. Fishburn, who leased out the land to mining companies. In 1953, upon Mr. Fishburn's death, the Fishburn Forest was bequeathed to the Commonwealth of Virginia (Aust, pers. comm.). The forest has largely been left to re-grow since then and has been used by the forestry department of Virginia Tech for teaching and research. In February and March of 1994, three severe glaze storms caused damage in 33 southwestern Virginia counties. Precipitation during the February event lasted for 18 hours and deposited six to ten centimeters (cm) of glaze over the whole region. In the town of Blacksburg, six cm of glaze was recorded (NCDC 1994a, b) and Rhoades (1999) recorded glaze depositions on trees in the Fishburn Forest as 2.5 cm on 2/13/94, 2.9 cm on 3/3/94 and 2.65 cm on 3/9/1994. Tree age within the Fishburn Forest varies from 70 -150 years (Rhoades 1999) and pre storm overstory basal area and density was 20 m²/ ha and 150 stems per hectare (Rhoades 1999).

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Chapter 2: Glaze Storm Damage To The Overstory Of An Appalachian Oak Forest

Introduction

Glaze storms, also commonly referred to as ice storms, are common throughout eastern North America, and frequently cause damage to trees in forests (Bennett 1959, NOAA 1990, Sisinni *et al.* 1995). Glaze is defined by the US Weather Bureau as homogeneous, transparent glaze layers that are deposited on horizontal and vertical surfaces during glaze storms (Haynes 1947). It is usually formed when supercooled rain falls on a surface with temperature less than 0°C (Bennett 1959). In the central and southern Appalachian Mountains, glaze storms have been a major natural disturbance in local forests, and have significant impacts on the distribution and dynamics of local forest vegetation (Whitney & Johnson 1984, Runkle 1985). Damage caused by glaze 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 (Cool *et al.* 1971, Hauer *et al.* 1993, Rhoades 1995, Sisinni *et al.* 1995, Rhoades 1999).

Damage to trees occurs when glaze adds excessive weight to leaves and branches of trees. Trees may be bent over, uprooted, decapitated, or suffer massive crown loss as large branches are broken off. Loss of large portions of the crown usually results in reduction of growth (Lemon 1961). Some trees eventually recover from glaze damage but many remain deformed and lose their value both aesthetically and financially. Light glaze damage may help trim off small branches and faulty limbs (Lemon 1961).

The glaze load and the physical resistance of the trees largely determines the severity of glaze damage. Glaze accumulation on tree crowns is affected by local environmental conditions and microclimate, while the resistance of trees to glaze damage depends on many physical characteristics of the trees, such as wood strength, elasticity and growth form (Seeley 1922, Root 1924, Spencer 1929, Croxton 1939, Hauer *et al.*

1993), and on stand characteristics such as density and vertical structure (Downs 1938, Shepherd 1975, 1978, Amateis & Burkhart 1996).

In general, trees with brittle and weak wood, fine branching, and large crowns are more likely to suffer glaze damage (Buttrick 1922, Seeley 1922, Root 1924, Spencer 1929, Abell 1934, Downs 1938, Reed 1939, Deuber 1940, Bennett 1959, Whitney & Johnson 1984, Boerner *et al.* 1988). However, studies often disagree on which species are most susceptible. Some researchers believe that conifers are usually less damaged than deciduous hardwood trees (Buttrick 1922, Abell 1934, Downs 1938, Reed 1939, Deuber 1940, Bennett 1959), while others have argued the opposite (Whitney and Johnson 1984, Boerner *et al.* 1988). Authors frequently disagree on the relative susceptibility of individual species (Table 2.1).

While many studies have focused on species characteristics related to glaze storm susceptibility, others have addressed the influence of elevation (Brooks 1930, Downs 1938, Nicholas & Zedaker 1989), slope (Boerner *et al.* 1988, Seischab *et al.* 1993, Rebertus *et al.* 1997, Rhoades 1999), aspect (Downs 1938, Bruderle & Stearns 1985, Rhoades 1999) and general topography (Bennett 1959), on glaze deposition. However, few of these studies controlled the independent effects of species and local topographic conditions on glaze damage.

Table 2.1. A summary of the number of authors evaluating ice storm susceptibility for tree species of southeastern US. (From Bennett 1959, Lemon 1961, Siccama *et al.* 1975, Whitney & Johnson 1984, Bruederle & Stearns 1985, Boerner *et al.* 1988, Seischab *et al.* 1993). Species are ranked, calculated as weighted means by the number of authors and the given scores: strong (1), moderate (2) and weak (3). High rank value indicate high susceptibility.

Species	Strong	Moderate	Weak	Rank
Conifers				
<i>Tsuga canadensis</i>	4	1	1	1.5
<i>Pinus palustris</i>	1	1		1.5
<i>P. taeda</i>	1	1		1.5
<i>P. strobus</i>	3	2	2	1.86
<i>P. elliotii</i>		1		2
<i>P. virginiana</i>			1	3
Hardwoods				
<i>Juglans nigra</i>	1			1
<i>Platanus occidentalis</i>	3			1
<i>Franxinus spp.</i>	4	3	4	2
<i>Fagus grandifolia</i>	1	6	1	2
<i>Q. velutina</i>	1	7	1	2
<i>Nyssa sylvatica</i>		1		2
<i>Magnolia acuminata</i>		1		2
<i>Q. rubra</i>	1	4	1	2
<i>Liriodendron tulipifera</i>	2	1	2	2
<i>Quercus alba</i>	1	4	2	2.14
<i>Acer saccharum</i>	1	7	3	2.18
<i>Robinia pseudoacacia</i>	1	2	2	2.2
<i>A. rubrum</i>	1	5	4	2.3
<i>Betula lenta</i>		2	1	2.33
<i>B. alleghaniensis</i>		2	1	2.33
<i>Carya spp.</i>	1	1	4	2.5
<i>Populus spp.</i>		1	3	2.5
<i>Ulmus spp.</i>	1	1	6	2.63
<i>Q. coccinea</i>		1	2	2.67
<i>Prunus serotina</i>		2	5	2.71
<i>Tilia americana</i>		1	6	2.86
<i>A. negundo</i>			1	3

In January and February of 1994 severe glaze storms caused forest damage in 33 southwestern Virginia counties. Precipitation during the February event lasted for 18 hours and deposited six to ten centimeters (cm) of glaze over the whole region. In the town of Blacksburg, six cm of glaze was recorded (NCDC 1994a, b). This glaze storm event provided an opportunity to investigate susceptibility (or resistance) of various tree species and the influence of topographic conditions. This study hypothesized that in addition to different physical characteristics of the tree species that lead to different susceptibilities to glaze damage, the susceptibilities of these tree species would further be affected by local topographic conditions. More specifically, different species would have different susceptibilities to glaze damage under the same topographic conditions, and that the susceptibility of one species may vary as the topography changes due to alterations of site conditions, community structure, and glaze load on crowns.

Methods

Survey Area

A field investigation was conducted on the Fishburn Forest owned by Virginia Polytechnic Institute and State University. Located within the Ridge and Valley physiographical province of the central Appalachian Mountains, the forest encompasses 500 hectares on the west side of Prices Mountain (37°11'N, 80°30'W), about 5 km from the university's main campus in Montgomery County, southwestern Virginia. Elevation ranges from 580 m to 840 m above sea level. Slopes vary from less than 15% to 110%. The major soil series are Inceptisols with Berks and Weikert series on backslopes, Clymer series on ridge tops, and Jefferson and Craigsville series at foot-slopes, valleys and flood plains along streams. The main parent materials for these soils are sedimentary rocks of Mississippian age, mostly shale and sandstone (Creggar *et al.* 1985). Site index for northern red oak (*Quercus rubra* L.) at 50 years varies from 16 to 21 m (Creggar *et al.* 1985). The average annual temperature is 10.8°C, with a January mean of -0.6°C and a July mean of 21.7°C (NOAA 1990). Average annual precipitation is 102 cm evenly distributed over the year (NOAA 1990). The original regional forests were part of the oak-chestnut association (Braun 1950), and were severely disturbed by logging, mining and fires. The forest has been largely left to grow since the forest came into public ownership in the early 1950s (La Lone 1997). Now, secondary forests of various seral stages occur, including stands dominated by Virginia pine (*Pinus virginiana* Mill.), pignut hickory (*Carya glabra* (Mill.) Sweet), mockernut hickory (*C. tomentosa* (Poir.) Nutt.), chestnut oak (*Q. prinus* L.), white oak (*Q. alba* L.), scarlet oak (*Q. coccinea* Muenchh.), red maple (*Acer rubrum* L.) and white pine (*P. strobus* L.). Elevational changes on the Fishburn Forest are not sufficient to result in well-defined elevational variation in vegetation.

Stratification of the site

In order to quantify the impact of topography on glaze damage, the forest was stratified according to topographic features, i.e., aspect, slope, and slope position. Sample plots were then randomly located in each topographic category on a U.S. Geological

survey 1: 24,000 scale topographic map of the Fishburn Forest (USGS 1983).

Topographic categories were obtained by modifying the Forest Site Quality Index by Smith and Burkhart (1976). The total possible combinations of different aspect, slope, and slope position classes was reduced to 15 categories (Table 2.1) by combining aspects into Aspect I from south to west, Aspect II from west to northeast, and Aspect III from northeast to south; eliminating some topographic categories that do not exist in the forest (i.e., steep slopes at summits, and steep slopes at toeslopes); and narrowing slope and slope position classes down to five classes of landform: summit, (i.e., ridge tops); 3 categories of backslope between ridge top and foothill (backslope I with slope less than 13%, backslope II with slope between 13% and 26%, and backslope III with slope greater than 26%); and toeslopes, including foothill and valley bottom (Table 2.2). There were 142 sample locations assigned on the map, with about nine sample points in each topographic category (Table 2.2).

In the field, the percentage slope, slope position and aspect of each location were measured with a compass and a clinometer to confirm that the location belonged in the topographic category on the map. Because of map errors, several points were actually in other topographic categories. These points were surveyed anyway and resulted in an uneven number of sample points for the topographic categories (Table 2.2).

Table 2.2. Number of plots in each topographic category of aspect and landform classes used to stratify topographic on the Fishburn Forest, Montgomery County, Virginia, for glaze damage survey. Aspect has three categories, I (south - west), II (west-northeast), III (northeast- south). Backslope has three categories I, II, III each with different slopes.

Landform	Slope	Aspect			N
		I	II	III	
Toeslope	< 13	6	6	6	18
Backslope I	< 13	12	8	5	25
Backslope II	13- 26	14	14	7	35
Backslope III	> 26	13	18	12	43
Summit	< 13	6	6	9	21
N		51	52	39	142

Survey of Glaze Damage

Trees were surveyed in the summer of 1996 for damage caused by the 1994 glaze storms. There were no damaging glaze storms in the interval. At each sample point, a circular area of 10 m radius (314 m²) was defined as the sample plot. After determination of landform and aspect, all trees (standing and toppled by the glaze) greater than 10 cm diameter at breast height (dbh) were tallied and their species, dbh, crown class, and glaze storm damage class were recorded. Three crown classes were used: intermediate (I, crown below the mean canopy), co-dominant (II, crown in the mean canopy), and dominant (III, crown above the mean canopy). Three damage classes were used: undamaged (class 1), where trees were not damaged or had less than 25% of the canopy lost; damaged (class 2), where 25-75% of the tree canopy was lost; and severely damaged (class 3), where more than 75% of the tree canopy was lost or the tree was toppled.

Data analysis

A total of 2811 canopy trees including 34 different tree species were surveyed. Twelve species occurred across most topographic categories and were analyzed. These species were Virginia pine, eastern white pine, table mountain pine (*P. pungens* Lamb.), chestnut oak, scarlet oak, white oak, black oak (*Quercus veluntina* Lam.), red maple, mockernut hickory, pignut hickory, sourwood (*Oxydendrum aboreum* (L.) DC.), blackgum (*Nyssa sylvatica* Marsh.)..

A Mean Damage Indicia (MDI) of each species in any categorical stratum, was used to indicate the susceptibility of a species to glaze damage, and was calculated as:

$$MDI = \sum_{i=1}^3 D_i P_i$$

where D is damage class from 1 to 3 and P_i is the proportion of the individuals of damage class i to the total number of surveyed trees of the species in any stratum. MDI is therefore a weighted mean of damage of a species in a plot, a topographic category, or species-wide. Theoretically, MDI varies from 1.0, indicating that none were damaged, to 3.0, indicating that all trees were severely damaged.

A mixed model ANOVA was used to assess the effects of topography, species and interactions on glaze storm damage. The mixed model procedure that was used accounts for the sub-sampling of individual trees within the randomly located plots in the forest (Littell *et al.* 1996) and treated plots as the experimental unit. Multiple comparisons of MDI across species and topographic categories were made by using the Tukey-Kramer HSD (Kramer 1956). Another Tukey-Kramer HSD compared MDI between species to determine which were significantly different. A two-tail Fisher's exact test (Sokal and Rohlf 1995) was used to examine the effects of slope and landform on glaze damage susceptibility for each species. A Tukey-Kramer HSD compared MDI between landforms and aspects for each significant species. Pre-storm basal area was compared to post-storm basal area for each species and for each topographic category. For basal area after the storm, damage class three trees were killed. Basal area before the glaze included all trees. A two way ANOVA tested the effect of crown on class and species on MDI.

Results

Among the 2811 surveyed canopy trees of 34 different species, hardwoods comprised 88% of the forest, while conifers comprised the remaining 12%. Chestnut oak, white oak, scarlet oak, and red maple were the four most dominant tree species (Table 2.3), comprising 63.6% of the total number of trees sampled. These four species occurred in almost all topographic categories but were less abundant on toeslopes. The most common conifer species was white pine (about 29% of all conifers surveyed) (Table 2.3).

Other widely distributed hardwood species included blackgum, black oak, and sourwood (Table 2.5). Like the four most common species, these species were also less abundant on toeslopes. Mockernut hickory and pignut hickory were scarce on toeslopes and summits (Table 2.5). White pine was widely distributed but less frequent on toeslopes and summits. The majority of Virginia pine was on toeslopes and backslopes of south to west facing aspects (aspect I), while table mountain pine was more frequent on backslopes.

Susceptibility of species to glaze storm damage

The three way ANOVA (table 2.4) demonstrated that there was a significant interaction between how species and aspect ($p < 0.001$) and species and landform ($p = 0.039$) affected MDI. Therefore, I tested the effect of species on MDI within each topographic category (Table 2.6) and the effect of topographic category on MDI within each species (Table 2.6).

As can be seen from the tables differences in MDI between species were evident in most topographic categories, but not in toeslopes of aspect I and aspect II, backslope I of aspect II, and backslope II and backslope III of aspect III (Table 2.5).

Table 2.3. Number of trees in glaze storm damage class, by species, in the Fishburn Forest, VA. Species are ranked by average weighted damage. Mean damages that are significantly different have different letters, tested using a Tukey- Kramer HSD (0.05 level). Damage class 1 trees had <25 % of their crowns lost or were undamaged, damage class 2 trees had 25 - 75 % of their crowns lost, and damage class 3 trees had >75% of their crowns lost or were toppled by the glaze storm. Percentage of trees damaged is calculated from the number of trees in damage class 2 and 3. Percentage of trees killed is calculated from the number of trees in damage class 3.

Damage class	1	2	3							
Species				N	Mean	Std dev	Sig.	Rank	% damaged	% killed
Black gum	85	5	1	91	1.08	0.3	d	1	7	1
Chestnut oak	692	40	19	751	1.10	0.38	cd	2	8	3
White oak	354	25	13	392	1.13	0.42	cd	4	10	3
Mockernut hickory	40	3	2	45	1.16	0.47	bcd	3	9	2
Scarlet oak	319	36	18	373	1.19	0.5	bcd	5	14	5
Red maple	226	20	26	272	1.26	0.62	bcd	6	17	10
Sourwood	186	15	24	225	1.28	0.65	bcd	7	17	11
Table mountain pine	63	3	9	75	1.28	0.67	bcd	7	16	12
Pignut hickory	20	8	0	28	1.29	0.46	bcd	9	29	0
Black oak	76	29	5	110	1.35	0.57	bc	10	31	5
White pine	73	11	12	96	1.36	0.7	ab	11	24	13
Virginia pine	41	7	30	78	1.86	0.95	a	12	47	38
Hardwoods	1999	181	107	2287	1.17	0.49	***		13	5
Conifers	177	21	51	249	1.49	0.81			29	20
Total	2176	202	158	2536	1.21				14	6

*** Hardwoods and conifers have significantly different damage, tested using one way ANOVA (p< 0.001)

The MDI of several species varied across topographic categories. Red maple, chestnut oak, mockernut hickory, table mountain pine and Virginia pine showed significantly different MDI ($\alpha < 0.05$) across the topographic categories, while MDI of other species were fairly consistent everywhere (Table 2.5).

When considering the effect of species alone on susceptibility the results of statistical analysis demonstrated significant MDI differences ($p < 0.001$) among 12 tree species (Table 2.4). In general, conifers (MDI = 1.454) were significantly more susceptible ($p = 0.029$) to glaze storm damage than hardwood species (MDI = 1.172). Virginia pine was the most susceptible tree species (MDI = 1.86, Table 2.3

Table 2.4 Three way mixed model ANOVA on the effect of species, aspect, and landform within sample plots on glaze damage to canopy trees in the Fishburn Forest, VA. Nominator and denominator degrees of freedom are denoted by NDF and DDF.

Source	NDF	DDF	F	P
Species (A)	11	597	4.90	0.0001
Aspect (B)	2	127	4.94	0.0086
Landform (C)	4	127	3.80	0.0060
A x B	22	597	2.72	0.0001
A x C	40	597	1.45	0.0390
B x C	8	127	0.65	0.7336
A x B x C	54	597	1.15	0.2209

Table 2.5. The effect of species, for 12 species, on glaze storm damage, on different topographies in the Fishburn forest, VA., tested using mixed model ANOVA, comparison tested using Tukey- Kramer HSD. Significantly different means have different letters (compare across columns). The number of trees is in () next to mean damage. Damage varies from 1, less than 25% of tree crown lost, to 3 more than 75% of tree crown lost. Back I is backslope <13 % slope, Back II is backslope 13-26 % slope, Back III is backslope >26 % slope. Aspect categories, I (south - west), II (west- northeast), III (northeast- south).

Species		black gum	black oak	chestnut oak	mockernut hickory	pignut hickory	red maple	Scarlet oak	sourwood	white oak	table mt. pine	Virginia pine	white pine
Aspect	Landform												
I	Toe-slope	1.00(3) a	/	1.00(3) a	1.00(2) a	1.00(1) a	1.82(11) a	1.20(5) a	/	/	/	2.23(35) a	/
	Back-slope I	1.00(4) ab	1.23(13) a	1.00(50) b	1.00(5) ab	1.00(1) ab	1.00(12) b	1.06(18) ab	1.00(4) ab	1.00(47) b	1.00(1) ab	/	1.00(11) b
	Back-slope II	1.08(13) b	1.25(12) b	1.04(79) b	1.00(4) b	1.33(3) ab	1.13(24) b	1.13(40) b	1.29(31) b	1.10(39) b	/	2.14(7) a	1.00(12) b
	Back-slope III	1.00(2) abc	1.75(4) abc	1.14(49) c	3.00(1) abc	1.00(1) abc	2.00(27) a	1.06(33) c	1.60(25) abc	1.03(29) c	/	1.78(18) ab	1.00(6) bc
	Summit	/	1.00(6) a	1.10(29) a	/	/	1.04(25) a	1.29(14) a	1.00(4) a	1.10(10) a	/	/	1.00(6) a
Aspect II	Toe-slope	1.00(3) a	/	/	1.00(1) a	/	1.33(9) a	1.00(2) a	1.00(1) a	1.00(9) a	/	1.00(10) a	1.20(5) a
	Back-slope I	1.00(2) a	1.20(10) a	1.04(24) a	1.00(2) a	/	1.00(17) a	1.26(34) a	1.00(8) a	1.18(28) a	1.33(6) a	/	1.15(13) a
	Back-slope II	1.04(27) b	1.00(5) b	1.00(129) b	1.00(4) ab	1.00(1) ab	1.04(53) b	1.12(68) b	1.19(52) b	1.05(44) b	1.8(5) a	1.00(2) ab	1.14(7) ab
	Back-slope III	1.11(9) ab	1.17(6) ab	1.07(90) b	1.67(3) ab	1.50(4) ab	1.14(37) b	1.16(55) ab	1.28(50) ab	1.26(70) b	1.2(59) b	/	1.75(16) a
	Summit	1.00(6) b	1.09(11) b	1.04(56) b	1.00(1) ab	/	1.13(8) b	1.26(31) b	1.13(15) b	1.06(32) b	/	/	2.00(5) a
Aspect III	Toe-slope	1.00(5) b	/	/	/	1.00(1) ab	1.00(4) b	/	/	1.00(4) b	/	1.40(5) ab	2.00(3) a
	Back-slope I	/	1.33(6) a	1.20(30) a	1.00(1) a	1.00(1) a	/	1.29(7) a	/	1.29(7) a	/	/	/
	Back-slope II	1.50(6) a	1.50(6) a	1.13(45) a	1.00(8) a	1.00(3) a	1.17(12) a	1.50(12) a	1.29(14) a	1.26(31) a	2.00(3) a	/	1.50(4) a
	Back-slope III	1.20(5) a	1.81(21) a	1.35(86) a	1.08(12) a	1.20(5) a	1.42(19) a	1.36(22) a	1.64(14) a	1.28(25) a	3.00(1) a	/	2.14(7) a
	Summit	1.00(6) a	1.40(10) a	1.18(79) a	1.00(1) a	1.57(7) a	1.79(14) a	1.28(32) a	1.00(7) a	1.06(17) a	/	1.00(1) a	2.00(1) a

Table 2.6. The effect of topography on glaze storm damage for 12 species in the Fishburn forest, VA, tested using mixed model ANOVA, means comparisons tested using Tukey- Kramer HSD. Significantly different means have different letters (compare down columns). The number of trees is in () next to mean damage. Damage varies from 1, less than 25% of tree crown lost, to 3 more than 75% of tree crown lost. Back I is backslope <13 % slope, Back II is backslope 13-26 % slope, Back III is backslope >26 % slope. Aspect categories, I (south - west), II (west- northeast), III (northeast- south).

Species		black gum	black oak	chestnut oak	mockernut hickory	pignut hickory	red maple	scarlet oak	sourwood	white oak	table mt. pine	Virginia pine	white pine
Aspect	Landform												
I	Toe-slope	1.00(3) A	/	1.00(3) AB	1.00(2) B	1.00(1) A	1.82(11) AB	1.20(5) A	/	/	/	2.23(35) A	/
	Back-slope I	1.00(4) A	1.23(13) A	1.00(50) B	1.00(5) B	1.00(1) A	1.00(12) D	1.06(18) A	1.00(4) A	1.00(47) A	1.00(1) B	/	1.00(11) A
	Back-slope II	1.08(13) A	1.25(12) A	1.04(79) B	1.00(4) B	1.33(3) A	1.13(24) D	1.13(40) A	1.29(31) A	1.10(39) A	/	2.14(7) AB	1.00(12) A
	Back-slope III	1.00(2) A	1.75(4) A	1.14(49) AB	3.00(1) A	1.00(1) A	2.00(27) A	1.06(33) A	1.60(25) A	1.03(29) A	/	1.78(18) BC	1.00(6) A
	Summit	/	1.00(6) A	1.10(29) AB	/	/	1.04(25) D	1.29(14) A	1.00(4) A	1.10(10) A	/	/	1.00(6) A
Aspect II	Toe-slope	1.00(3) A	/	/	1.00(1) B	/	1.33(9) ABCD	1.00(2) A	1.00(1) A	1.00(9) A	/	1.00(10) D	1.20(5) A
	Back-slope I	1.00(2) A	1.20(10) A	1.04(24) B	1.00(2) B	/	1.00(17) D	1.26(34) A	1.00(8) A	1.18(28) A	1.33(6) AB	/	1.15(13) A
	Back-slope II	1.04(27) A	1.00(5) A	1.00(129) AB	1.00(4) B	1.00(1) A	1.04(53) D	1.12(68) A	1.19(52) A	1.05(44) A	1.8(5) AB	1.00(2) D	1.14(7) A
	Back-slope III	1.11(9) A	1.17(6) A	1.07(90) B	1.67(3) A	1.50(4) A	1.14(37) D	1.16(55) A	1.28(50) A	1.26(70) A	1.2(59) B	/	1.75(16) A
	Summit	1.00(6) A	1.09(11) A	1.04(56) B	1.00(1) B	/	1.13(8) BCD	1.26(31) A	1.13(15) A	1.06(32) A	/	/	2.00(5) A
Aspect III	Toe-slope	1.00(5) A	/	/	/	1.00(1) A	1.00(4) BCD	/	/	1.00(4) A	/	1.40(5) C	2.00(3) A
	Back-slope I	/	1.33(6) A	1.20(30) AB	1.00(1) B	1.00(1) A	/	1.29(7) A	/	1.29(7) A	/	/	/
	Back-slope II	1.50(6) A	1.50(6) A	1.13(45) AB	1.00(8) B	1.00(3) A	1.17(12) BCD	1.50(12) A	1.29(14) A	1.26(31) A	2.00(3) A	/	1.50(4) A
	Back-slope III	1.20(5) A	1.81(21) A	1.35(86) A	1.08(12) AB	1.20(5) A	1.42(19) BCD	1.36(22) A	1.64(14) A	1.28(25) A	3.00(1) A	/	2.14(7) A
	Summit	1.00(6) A	1.40(10) A	1.18(79) AB	1.00(1) B	1.57(7) A	1.79(14) ABC	1.28(32) A	1.00(7) A	1.06(17) A	/	1.00(1) D	2.00(1) A

Effect of species and basal area on damage

Over the entire sample area there was a 6% reduction in basal area due to the glaze storm (Table 2.7). Pre-storm basal areas ranged from 9.6 m²/HA to 0.2 m²/HA. The glaze storm reduced basal area for almost all species ranging from 28% (Virginia pine) to 0 % (pignut hickory).

Table 2.7. Pre-storm and Post-storm basal area in the Fishburn Forest, VA. Post-storm trees lost less than 75% of their crowns (damage class 1 and 2). Basal area (m²) is calculated for each tree, totaled, and divided by the total area surveyed. Species are sorted by percentage change in basal area. MDI (mean damage) varies from 1, less than 25% of the tree crown lost, to 3, more than 75% of the tree crown lost.

Species	BA m ² /HA			
	MDI	Prestorm	Poststorm	% change
Virginia pine	1.86	0.79	0.57	-28
Table mountain pine	1.28	0.95	0.81	-15
Red maple	1.26	1.53	1.42	-7
Sourwood	1.28	1.5	1.39	-7
Scarlet oak	1.19	5.61	5.25	-6
Black oak	1.35	1.96	1.87	-5
White pine	1.36	1.54	1.46	-5
Chestnut oak	1.1	9.62	9.22	-4
White oak	1.13	5.67	5.49	-3
M. Hickory	1.16	0.32	0.31	-3
Blackgum	1.08	0.36	0.35	-3
P. Hickory	1.29	0.22	0.22	0
Conifers	1.49	3.28	2.84	-13
Hardwoods	1.17	26.79	25.52	-5
Total	1.21	30.07	28.36	-6

Effects of landform and aspect on glaze damage

Both landform and aspect significantly affected the severity of glaze damage by interacting with species (Table 2.4). Although only five species showed significantly different MDI across different topographic categories in a Tukey- Kramer HSD multiple comparisons (Table 2.5), more species demonstrated susceptibility variation when the MDI data were analyzed separately for different landforms and different aspects (Table 2.8 and 2.9). MDI of four species varied significantly ($\alpha < 0.05$) according to landform: black

oak ($p= 0.023$), chestnut oak ($p<0.001$), red maple ($p<0.001$), and white pine ($p<0.001$) (Table 2.8). MDI of eight species varied significantly ($\alpha < 0.05$) according to aspects: black oak ($p<0.001$), chestnut oak ($p<0.001$), red maple ($p<0.001$), scarlet oak ($p=0.022$), table mountain pine ($p= 0.005$), Virginia pine ($p<0.001$), white oak ($p<0.001$) and white pine ($p<0.001$) (Table 2.9). The decrease in number of categories for comparison, and therefore an increase in sample number in each category, might be part of the reason that MDI of more species tested significantly different in the aspect comparisons than in the landform comparisons.

Table 2.8. The number of trees in each glaze damage class across different landforms in the Fishburn forest, VA. A multiple comparison (Tukey Kramer HSD) of MDI across landforms within species was performed. Different letters in () indicate significant MDI differences (alpha <0.05). Damage class varies from 1, less than 25% of tree crown lost, to 3, more than 75% of tree crown lost. Only species for which landform had an effect on glaze damage, tested with Fisher's exact test (2 tailed), are listed. Back I is backslope <13 % slope, Back II is backslope 13-26 % slope, Back III is backslope >26 % slope

Species	Landforms	Damage class			n	MDI
		1	2	3		
Black oak	Toeslope	0	0	0	0	
	BackslopeI	23	5	1	29	1.241(a)
	BackslopeII	17	6	0	23	1.261(a)
	BackslopeIII	14	13	4	31	1.677(b)
	Summit	22	5	0	27	1.185(a)
Chestnut oak	Toeslope	5	0	0	5	1.000*
	BackslopeI	98	5	1	104	1.067(b)
	BackslopeII	244	9	0	253	1.036(b)
	BackslopeIII	197	13	15	225	1.191(a)
	Summit	148	13	3	164	1.116(ab)
Red maple	Toeslope	17	2	5	24	1.500(a)
	BackslopeI	29	0	0	29	1.000(b)
	BackslopeII	83	5	1	89	1.079(b)
	BackslopeIII	59	8	16	83	1.482(a)
	Summit	38	5	4	47	1.277(ab)
White pine	Toeslope	4	4	0	8	1.500*
	BackslopeI	23	0	1	24	1.083(b)
	BackslopeII	21	1	1	23	1.130(b)
	BackslopeIII	17	4	8	29	1.690(a)
	Summit	8	2	2	12	1.500(ab)

* not included in comparison due to uneven and low number of individuals

Table 2.9 . The number of trees in each glaze damage class across different aspects in the Fishburn forest, VA. A multiple comparison (Tukey Kramer HSD) of MDI across aspects within species was performed. Different letters in () indicate significant MDI differences (alpha <0.05). Damage class varies from 1, less than 25% of tree crown lost, to 3 more than 75% of tree crown lost. Only species for which landform had an effect on glaze damage, tested with Fisher's exact test (2 tailed), are listed. Aspect categories, I (south - west), II (west- northeast), III (northeast- south).

Species	Aspect	Damage Class			n	MDI
		1	2	3		
Black oak	I	27	7	1	35	1.257(b)
	II	28	4	0	32	1.125(b)
	III	21	18	4	43	1.605(a)
Chestnut oak	I	203	5	4	212	1.061(b)
	II	292	5	2	299	1.030(b)
	III	197	30	13	240	1.233(a)
Red maple	I	77	4	18	99	1.404(a)
	II	115	7	2	124	1.089(b)
	III	34	9	6	49	1.429(a)
Scarlet oak	I	99	9	2	110	1.118(b)
	II	166	14	10	190	1.195(b)
	III	54	13	6	73	1.206(a)
Table mountain pine	I	1	0	0	1	1.000*
	II	61	2	7	70	1.229*
	III	1	1	2	4	2.250*
Virginia pine	I	24	7	29	60	2.083(a)
	II	12	0	0	12	1.000(b)
	III	5	0	1	6	1.333*
White oak	I	119	6	0	125	1.048(b)
	II	166	7	10	183	1.148(ab)
	III	69	12	3	84	1.214(a)
White pine	I	35	0	0	35	1.000(c)
	II	32	7	7	46	1.457(b)
	III	6	4	5	15	1.933(a)

* not included in comparison due to uneven and low number of individuals

Effect of basal area and topography on glaze storm damage

Basal area was very different for each topographic position (Table 2.10). Basal area loss due to glaze damage was greatest on aspect one toeslopes (-20 %) and was generally higher on steep backslopes. For two topographic categories there was no overall basal area loss, aspect I backslopes less than 13% slope and aspect II toeslopes.

Table 2.10. Pre-and post-storm basal area per hectare (HA) in the Fishburn Forest, VA. Post-storm trees lost less than 75% of their crowns (damage class 1 and 2). Basal area (m²) is calculated for each tree, totaled, and divided by the total area surveyed in that topographic category. MDI (mean glaze damage) varies from 1, no damage, to 3, killed. Aspect has three categories, I (south - west), II (west- northeast), III (northeast- south), Backslope has three categories: I, <13%; II, 13- 26%; III >26%.

Aspect	Landform	MDI	BA m ² /HA		% change
			Prestorm	Poststorm	
I	Toeslope	1.85	11.91	9.55	-20
I	BackslopeI	1.02	24.97	24.97	0
I	BackslopeII	1.14	31.50	30.66	-3
I	BackslopeIII	1.37	26.07	23.35	-10
I	Summit	1.10	28.56	26.69	-7
II	Toeslope	1.10	10.50	10.45	0
II	BackslopeI	1.15	32.43	30.85	-5
II	BackslopeII	1.07	43.69	42.70	-2
II	BackslopeIII	1.20	38.87	36.10	-7
II	Summit	1.13	50.54	48.75	-4
III	Toeslope	1.23	4.96	4.72	-5
III	BackslopeI	1.23	7.09	6.68	-6
III	BackslopeII	1.26	40.79	39.93	-2
III	BackslopeIII	1.42	33.19	27.85	-16
III	Summit	1.25	28.98	28.06	-3
Total		1.21	30.07	28.36	-6

Effect of crown class on glaze damage

Although there were no statistically significant differences in MDI among the three crown classes (dominant, co-dominant and intermediate of all species), dominant trees in general tended to have less damage.

A majority (79%) of the damaged dominant trees were in damage class II, while half of the damaged intermediate trees were in damage class III (Table 2.11). Much of the damage to intermediate trees was caused by falling branches and stems of dominant and co-dominant trees (field observation). Most dominant hardwoods had higher MDI than other crown classes when compared within a species, an apparent trend that was reversed for conifers and a few hardwoods (Table 2.12).

Table 2.11. A comparison of numbers of trees across glaze damage classes and crown classes. Damage class varies from 1, less than 25% of tree crown lost, to 3 more than 75% of tree crown lost. Numbers in square parentheses [] are percentages of trees in each glaze damage category. Numbers in round parentheses () are percentages of trees in a crown class category.

Canopy class	Damage class			Total (%)
	1 [%]	2 [%]	3 [%]	
Dominant (%)	312 (84.3) [12.9]	46 (12.4) [20.6]	12 (3.3) [7.8]	370 (100) (13.2)
Co-dominant (%)	1034 (88.4) [42.9]	74 (6.3) [33.2]	62 (5.3) [35]	1170 (100) (41.6)
Intermediate (%)	1066 (83.8) [44.2]	103 (8.1) [46.2]	103 (8.1) [58.2]	1271 (100) (45.2)
Total (%)	2411 (85.8) [100]	223 (7.9) [100]	177 (6.3) [100]	2811 (100) 100)

Table 2.12. Number of trees in damage class by species and crown class, in the Fishburn Forest, VA. Damage class varies from 1, <25% of crown lost, to 3, where the tree was killed by glaze due to loss of >75% of its crown, decapitation or toppling. Crown classes were intermediate (I), co-dominant (II), and dominant (III).

Species	Crown Class	Damage class			N	MDI
		1	2	3		
Blackgum	I	81	5	1	87	1.08
	II	3	0	0	3	1
	III	1	0	0	1	1
Black oak	I	16	2	2	20	1.3
	II	53	18	2	73	1.3
	III	7	9	1	17	1.65
Chestnut oak	I	244	17	5	266	1.1
	II	367	16	11	394	1.1
	III	81	7	3	91	1.14
Mockernut Hickory	I	30	1	0	31	1.03
	II	7	2	1	10	1.4
	III	3	0	0	3	1
Pignut Hickory	I	13	5	0	18	1.28
	II	7	1	0	8	1.13
	III	0	2	0	2	2
Red maple	I	179	19	23	221	1.29
	II	44	0	2	46	1.09
	III	3	1	1	5	1.6
Scarlet oak	I	66	3	4	73	1.15
	II	198	21	11	230	1.19
	III	55	12	3	70	1.26
Sourwood	I	129	13	22	164	1.35
	II	56	2	2	60	1.1
	III	1	0	0	1	1
Table mountain pine	I	9	0	2	11	1.36
	II	33	3	6	42	1.36
	III	21	0	1	22	1.09
Virginia pine	I	9	4	14	27	2.19
	II	14	2	16	32	2.06
	III	18	1	0	19	1.05
White oak	I	142	13	5	160	1.14
	II	156	3	7	166	1.1
	III	56	9	1	66	1.17
White pine	I	39	8	10	57	1.49
	II	17	0	2	19	1.21
	III	17	3	0	20	1.15

Effect of wood strength on glaze damage

Wood strength of different tree species was evaluated based on bending strength (psi, [pounds per square inch]), stiffness (psi x 1,000) and splitting resistance (pounds per inch). The ranks of wood strength of the 12 species in this study are listed in Table 2.13 (Toennisson 1992). There is an apparent relationship between wood strength and MDI. As wood strength increases, MDI also increases, there are several exceptions to this relationship but the general principle still holds.

Table 2.13. A list of wood bending strength (psi, [pounds per square inch]), stiffness (psi x 1,000) and splitting resistance (pounds per inch) ranks for 12 species. The ranks in the table represent evaluations: 1 = good, to 5 = poor (for bending); or 1 = hard, to 5 = soft (for stiffness), or 1 = strong, to 5 = weak (for splitting) (compiled from Toennisson 1992).

Species	Bending	Stiffness	Splitting	MDI
White pine	5	4	5	1.36
Blackgum	3	4	3	1.08
Virginia pine	3	3	4	1.86
Red maple	3	2	3	1.26
Sourwood	3	2	2	1.28
White oak	2	3	2	1.13
Black oak	2	3	2	1.35
Chestnut oak	2	2	2	1.10
Scarlet oak	2	2	2	1.19
Mockernut hickory	1	1	n/a	1.11
Pignut hickory	1	1	n/a	1.29
Table mountain pine	n/a	n/a	n/a	1.28

Discussion

As in many previous studies, my results demonstrated that different species had different susceptibilities to glaze damage. This study agrees with those authors (Boerner *et al* 1980, Whitney and Johnson 1984) who suggested that conifers, as a group, are more easily damaged by glaze than hardwood species (Table 2.3). Overall, Virginia pine was the most susceptible species, white pine, table mountain pine, black oak, red maple, sourwood, pignut hickory, and scarlet oak showed medium susceptibility; and white oak, mockernut hickory, chestnut oak, and black gum were the most resistant species (Table 2.3). These results also agree in general with the conclusions from previous studies (Table 2.1).

Other characteristics also affect the susceptibilities of different species. The shallow root system of Virginia pine (Carter & Snow 1990) may have made it particularly vulnerable to glaze damage. In field observations many damaged Virginia pines were uprooted and toppled. Most literature (Hack & Goodlett 1960, Zobel 1969, Della-Bianca 1990) regards Table mountain pine as one of the most susceptible species to glaze and heavy wet snow, but our data indicated a moderate MDI. This probably occurred because a majority of the surveyed Table mountain pine individuals were small (56% co-dominant and 16% intermediate). Like other conifer species, co-dominant and intermediate Table mountain pines were less damaged than the dominants.

Most oaks were moderately susceptible to glaze damage (Table 2.3). Among the four oak species surveyed, black oak and scarlet oak suffered more damage than white oak and chestnut oak. At the Fishburn Forest, more than 60% of dominant black oaks were damaged while the damage percentages (the number of damage class two and three trees divided by the number of trees surveyed) of intermediate and co-dominant individuals was less (20% and 27% respectively, Table 2.12). The greater susceptibility of scarlet oak than white oak or chestnut oak may be due to a high rate of heart rot (Johnson 1990) which may weaken the stems. Canopy class of the species did not seem to affect glaze damage. Wood strength of scarlet oak is comparable to the other oaks, Table 2.12.

Chestnut oak was the most abundant species surveyed. Damage was more severe in dominant trees (11% of trees in damage class II and III) than in co-dominants (6.9% of

trees in damage class II and III) and intermediates (8.3% of trees in damage class II and III, Table 2.12). Therefore, the high abundance of smaller trees (88% of all chestnut oaks were intermediates and co-dominants) might be the cause of its low MDI and damage percentage (7.86%). In addition, chestnut oak is resistant to heart rot (McQuilkin 1990) which may increase its resistance to glaze damage. White oak had high damage percentages of dominant (12%) and intermediate (9.4%) individuals, but extremely low damage percentage of co-dominants (1.2%, Table 2.12). This damage percentage distribution was peculiar to white oaks.

Most red maples (81%) at the Fishburn forest were of intermediate size, and had a particularly low damage percentage relative to the co-dominants and dominants (Table 2.12). This resulted in an overall low MDI (1.26) for this species. The class III damage percentage of red maple (9.6%) from this study was relatively low compared to a reported 16% of severe damage percentage after a severe glaze storm in Pennsylvania (Hepting 1971). However, in the nearby town of Blacksburg, many planted red maples growing in the open were severely damaged (personal obs.); therefore, a greater MDI might be expected if the percentage of large red maple trees in the forest had been higher.

Sourwood rarely reaches a dominant canopy position; most surveyed trees were small. Almost all (38 out of 39) damaged sourwood individuals in the survey were intermediate (Table 2.12), and most of them were damaged by falling branches from nearby trees (field observation).

Hickories are believed to be very resistant to glaze damage (Smalley 1990, Seischab *et al.* 1993, Bruedeler & Sterns 1985), probably because of their strong wood, and our results generally agreed. Mockernut hickory had a very low MDI of 1.11, while pignut hickory had a higher MDI of 1.29, but none of the damaged trees were severely damaged (Table 2.3, 2.12).

Blackgum was among the least damaged species in the Fishburn Forest although it was widely distributed across different topographic areas. The species is shade tolerant and rarely reaches the dominant crown position (McGee 1990). More than 95% of surveyed blackgums were intermediate individuals (Table 2.12). The lower canopy status of this species may help to reduce glaze load on branches. Reports on the wood strength

of blackgum conflicted as either strong (Sargent 1965) or weak (Toennisson 1992). However, its flexible branches (Sargent 1965, McGee 1990) and lower canopy status may increase its resistance to glaze damage.

The MDI of the tree species varied differently across different topographic categories, as indicated by the significant interactions in ANOVA (Table 2.4). Red maple was the most variable species in its susceptibility to glaze damage. Its MDI varied from 2.00 at backslope III of aspect I, where it was the most damaged species, to 1.00 at backslope I of aspect II where it was among least damaged species (Table 2.5). Blackgum damage, on the other hand, did not vary greatly across topographic categories (Table 2.5). This indicated that the most susceptible species in one topographic category may not be the most susceptible species in another category. More species had significantly different MDI when aspects and landforms were considered separately (Table 2.6 and 2.7). The interaction between topography and species may be one of the reasons that evaluations of glaze damage susceptibility by different authors conflict (Bennett 1959, Siccama *et al.* 1975, Whitney & Johnson 1984, Bruederle & Stearns 1985, Boerner *et al.* 1988, Seischab *et al.* 1993).

The Virginia Department of Forest recommends to landowners that on some poor sites in the mountains of Virginia they convert their hardwoods stands into white pine plantations (Aust Pers. Comm., Grimm Pers. Comm.). White pine grows more rapidly on poorer sites than oaks (Beck 1971, Balmer and Williston 1983) and there is an active market for pine making this conversion very attractive to landowners interested in income from timber production (Wendel 1971, Sims 1985). However this study has demonstrated that this replacement must be considered carefully given the susceptibility of white pine to glaze storm damage when compared to the susceptibility of the replaced oak species. Regardless of topography white pines are approximately twice as likely to be damaged by glaze than chestnut oak, white oak and scarlet oak and three times more likely to be killed by glaze (Table 2.3).

Over the lifetime of a white pine plantation assuming a rotation age of 40 years (small logs for the furniture market, Sims 1985) and a frequency of severe glaze storms once every 20 years (Abell 1920) there will be at least two severe storms that impact the

plantation. If these glaze storms both kill 13% of white pines then over a quarter of the trees are lost over the life of the stand. A white oak stand with a rotation age of 60 years (small logs for the furniture market) and three glaze storms each killing 3% of the stand results in less than 10 % tree loss. Over a shorter rotation age, the advantages of keeping stands as hardwoods increases. The risk of damage increases even further if hardwood stands are converted to Virginia Pine. This study indicated almost 40% of Virginia Pines were killed (Table 2.3).

The reduction in basal area for oaks and white pines, due to glaze, is similar (3- 6 %, Table 2.7). The large percentage of white pines killed by glaze but low percentage reduction in basal area is because larger oaks are more susceptible to glaze damage than large white pines but smaller white pines are more susceptible than small oaks (Table 2.12). Therefore I would recommend against planting white pines and shorter rotation ages for oaks.

Aspect and landform significantly affect glaze damage on trees by modifying microclimate, soil conditions and the relative position of the forest canopy (Downs 1938, Bennett 1959, Bruderle & Stearns 1985, Rhoades 1999). On the Fishburn Forest, however, it was very difficult to designate a general aspect where glaze damage was more severe, although trees on aspect III were damaged the most. The complex topography of the Ridge and Valley region may expose all aspects to winds during glaze storms. Furthermore, other factors, such as species distribution, may influence the analysis. Among the species whose MDI were significantly different on different aspects, all but Virginia pine had the most damage on aspect III (NE-S facing aspect). Virginia pine was most damaged on aspect I (S-W facing aspects) (Table 2.9). In addition, more than 90% of table mountain pines were on aspect II, and about 84% of white pine were on aspects I and II (Table 2.9). The MDI of both species on aspect III were calculated from small samples.

MDI of four species were significantly different among the 5 landforms. All four species had much higher MDI on backslope III than on other landforms, and their MDI tended to increase as the slope became steeper (Table 2.8). Soils on steep slopes are usually shallow (Cregger *et al.* 1985, Brady 1990) and therefore trees tend to be shallow-

rooted (Fitter & Hay 1987) with reduced anchor strength. The canopy exposure of trees to glaze storm also increases as the slope becomes steeper. In addition, in field observations tree crowns were usually asymmetric on steeper slopes but extend more toward the outside (away from slope) for more light, resulting in their receiving more glaze during an glaze storm. Combining all these factors, damaged trees on steep slopes tend to topple in the downhill direction because of a greater glaze load on the outside half of the crowns. Large gaps tend to be created due to a domino effect of tree falling. In field observations, more trees were found fallen in the downhill direction.

Trees on toeslopes, footslopes, and valley bottoms were less damaged, probably because they received less glaze, and grow in deeper soils that may provide a better anchor. In addition, a higher tree density there may allow tree canopies to provide mutual support for each other. Species on toeslopes were much less damaged except Virginia pine (Table 2.5).. Many fallen Virginia pines were found at the toeslopes, probably because of the shallow root system of the species, and soils that might have been saturated by rain before the glaze storm.

Basal area losses were greatest on steep backslopes and generally followed the trends in MDI noted above. Rhoades who also survey glaze damage in the Fishburn Forest (1999) reported far greater basal area losses than those in this study. In his survey there was a reduction in scarlet oak basal area of 66%, compared to 6% in this study and a 37% reduction of chestnut oak basal area compared to 4% from this study (Table 2.7). These large differences are difficult to account for but may be due to the small sample size used by Rhoades and the lack of topographic variation in sampling. This study also demonstrated that basal area losses vary substantially due to topography (Table 2.10).

Site qualities at summits in the Fishburn Forest are normally low due to shallow, infertile soils with low water holding capacity (Cregar *et al.* 1985), and the trees were smaller (field observation). Forests there are dominated by chestnut oak, scarlet oak, and white oak, with a few black oak, red maple, hickories, and white pine (Table 2.5). Glaze damage on summits was not severe because none of the highly susceptible species were abundant. The four species with significant MDI variation across landforms had moderate damage at summits. Trees on summits might receive less glaze due to relatively smaller

crown exposure, and gain more mutual support from each other than those on backslopes due to greater densities.

Damage differences among species were apparently smaller on topographic sites where the overall damage was either the most or least severe (such as backslope III of aspect III, and toeslopes). For topographies where the overall MDI were moderate (such as backslope III of aspect I), the species differences in MDI increased (Table 2.5). It is reasonable that tree susceptibility to glaze damage would be best tested on moderately damaged forest sites.

Summary

In general, different tree species have different susceptibilities to glaze damage. On the Fishburn Forest, Virginia pine was the most susceptible species, while black gum was the most resistant. Dominant hardwood canopy trees suffered more damaged than co-dominant and intermediate trees. This trend was reversed for conifers.

Aspect, slope, and slope position profoundly affected the severity of damage, and therefore, the damage to most species varied across the landscape. Trees suffered more severe damage on steeper slopes, and on east facing slopes. Most species on toeslopes had little damage. On steep slopes, many damaged trees fell downhill because of shallow soil, asymmetric canopies, and unbalanced canopy glaze loads.

Damage to some species (e.g., red maple and Virginia pine) varied greatly across different topographies, while others varied little (e.g., black gum). In addition, variations in damage were not parallel across topography. Therefore, the most susceptible species at one topographic position may be a less susceptible species at another topographic position. Furthermore, damage differences among species were less on sites where the trees were damaged the most or least. Differences were more significant on sites where the overall damage was moderate. Thus, susceptibility of canopy trees to glaze damage is determined not only by the species characteristics per se, but also by site conditions, including aspect and landform.

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Chapter 3: Seedling Regeneration in an Appalachian

Oak Forest

Introduction

Glaze storms, also referred to as ice storms, are a frequent natural meteorological event in eastern north America and frequently cause damage to forests (Downs 1938, Spaulding and Bratton 1946, Carvell *et al.* 1957, Lemon, 1961, Siccama *et al.* 1976, Whitney and Johnson 1984, Boerner *et al.* 1988, Seischab *et al.* 1993). During glaze storms supercooled rain freezes, accumulating on tree limbs causing damage to trees by breaking branches, stems and toppling whole trees (Bennett 1959, Lemon 1961). The severity of damage to forests varies according to the quantity and duration of freezing rain and winds, topographic features, and the forest structure including species composition and distribution. Severe damage to large trees creates gaps in the forest canopy and has a large impact on the distribution and dynamics of local forest vegetation (Bennett 1959, Whitney and Johnson 1984, Runkle 1985).

Gap dynamics and mechanisms have been intensively studied during the past two decades including the influences of gaps on light (Canham and Marks 1985, Canham 1988a, b), water (McClure and Lee 1993), nutrient cycling (Bormann and Likens 1979), and regenerating vegetation (Lorimer 1989, Runkle 1990). As gap size increases so does light, temperature and soil water availability (Canham and Marks 1985, Pritchett and Fisher 1987) as the removal of canopy trees reduces light interception and water transpiration. However temperature and soil water availability also fluctuate more as the buffering provided by the forest canopy is removed (McClure and Lee 1993). Soil nutrient levels rise due to greater quantities of organic matter, increased decomposition rates and a reduction in uptake by canopy trees (Bormann and Likens 1979, Pritchett and Fisher 1987).

Many studies have demonstrated that different tree species have greatly different susceptibilities to glaze damage (Downs 1938, Reed 1939, Deuber 1940, Bennett 1959,

Whitney and Johnson 1984, Boerner *et al.* 1988, Seischab *et al.* 1993, Rebertus *et al.* 1997, Rhoades 1999) but the literature contains few studies of the effects of topography on glaze created gaps. The topographic effects on the susceptibility of tree species to glaze damage was discussed in Chapter Two, where I determined that glaze damage was different for different species on different topographies. Therefore, over the landscape glaze-created gaps may vary in size due to topographic and species changes.

While most studies of glaze damage on forests have focused on species susceptibility to glaze damage, a few have looked at the impact of glaze damage on forest regeneration (Whitney and Johnson 1984, Nicholas and Zedaker 1989, De Steven *et al.* 1991). Regeneration after forest disturbance is of great interest to foresters, biologists, and ecologists. For regions where glaze storms are a major disturbance, regeneration in glaze created gaps are particularly important to forest dynamics. In addition, further knowledge of regeneration in small gaps is necessary as the forest industry moves to smaller sized harvest areas and group selection techniques (Bergman 1997, U.S. House of Representatives 1997).

In January and February of 1994 severe glaze storms caused damage in 33 counties in southwestern Virginia. The second glaze storm lasted for 18 hours depositing six to ten centimeters (cm) of glaze over the whole region (NCDC 1994a, b). These glaze storms provided an opportunity to survey damage to forest stands at different topographic sites and to investigate regeneration within gaps created by glaze to determine the influence of glaze storm damage on vegetation dynamics and local forested landscapes. The objectives of this study were: 1) to relate topographic features to glaze damage at the forest community level, i.e. gap size and distribution; 2) to examine the impacts of the canopy gaps created by glaze on seedling regeneration. I hypothesized that since different species have different susceptibilities to glaze damage at different topographic locations (see Chapter Two), forests on different topographic locations have different species compositions. Therefore, glaze damage to forests, indicated by the size and number of canopy gaps will be correlated to topographic location. I also hypothesized that since environmental conditions are altered by the creation of gaps and gap size, gap

regenerating communities will be different from understory communities, and will vary as gap sizes change, in terms of species composition, density and height growth.

Methods

Survey Area

A field investigation was conducted on the Fishburn Forest of Virginia Polytechnic Institute and State University. Located within the Ridge and Valley physiographical province of the central Appalachian Mountains, the forest encompasses 500 hectares on the west side of Prices Mountain (37°11'N, 80°30'W), about 5 km from the university's main campus in Montgomery County, southwestern Virginia. Elevation ranges from 580 m to 840 m above sea level. Slopes varies from less than 15% to 110%. The major soil series are Inceptisols with Berks and Weikert series on backslopes, Clymer series on ridge tops, and Jefferson and Craigsville at foot-slopes, valleys and flood plains along streams. The main parent materials for these soils are sedimentary rocks of Mississippian age, mostly shale and sandstone (Creggar *et al.* 1985). Site index for northern red oak (*Quercus rubra* L.) at 50 years varies from 16 to 21 m (Creggar *et al.* 1985). The average annual temperature is 10.8°C, with a January mean of -0.6°C and a July mean of 21.7°C (NOAA 1990). Average annual precipitation is 102 cm evenly distributed over the year (NOAA 1990). The original regional forests were part of the oak-chestnut association (Braun 1950), and were severely disturbed by logging, mining and fires. The forest has been largely left to grow since the forest came into public ownership in the early 1950s (La Lone 1997). Now, secondary forests of various seral stages occur, including stands dominated by Virginia pine (*Pinus virginiana* Mill.), pignut hickory (*Carya glabra* (Mill.) Sweet), mockernut hickory (*C. tomentosa* (Poir.) Nutt.), chestnut oak (*Q. prinus* L.), white oak (*Q. alba* L.), scarlet oak (*Q. coccinea* Muenchh.), red maple (*Acer rubrum* L.) and white pine (*P. strobus* L.). Elevational changes on the Fishburn Forest are not sufficient to result in well-defined elevational variation in vegetation.

Stratification of the site

In order to quantify the impact of topography on glaze damage, the forest was stratified according to topographic features, i.e., aspect, slope, and slope position. Sample plots were then randomly located in each topographic category on a U.S. Geological survey 1: 24,000 scale topographic map of the Fishburn Forest (USGS 1983). Categories

were obtained by modifying the Forest Site Quality Index by Smith and Burkhart (1976). The total possible combinations of different aspect, slope, and slope position classes was reduced to 15 categories (Table 3.1) by combining aspects into Aspect I from south to west, Aspect II from west to northeast, and Aspect III from northeast to south; eliminating some topographic categories that do not exist in the forest (i.e., steep slopes at summits, and steep slopes at toeslopes); and narrowing slope and slope position classes down to five classes of landform: summit, (i.e., ridge tops); 3 categories of backslope between ridge top and foothill (backslope I with slope less than 13%, backslope II with slope between 13% and 26%, and backslope III with slope greater than 26%); and toeslopes, including foothill and valley bottom (Table 3.1). There were 142 sample locations assigned on the map, with about nine sample points in each topographic category (Table 3.1).

In the field, the percentage slope, slope position and aspect of each location were measured with a compass and a clinometer to confirm whether the location belonged in the topographic category on the map. Because of map errors, several points were actually in other topographic categories. These points were surveyed anyway and resulted in an uneven number of sample points for the topographic categories (Table 3.1).

Table 3.1. Aspect and landform classes used to stratify topographic categories on the Fishburn Forest, Montgomery County, Virginia, for glaze damage survey, and number of sample points in each category.

Landform	Slope	Aspect			N
		I	II	III	
Toeslope	< 13	6	6	6	18
Backslope I	< 13	12	8	5	25
Backslope II	13- 26	14	14	7	35
Backslope III	> 26	13	18	12	43
Summit	< 13	6	6	9	21
N		51	52	39	142

Gap size seedling and measurement

At each sample point a circular area 314 m² (10 m radius) was defined as the sample plot. All trees greater than 10 cm diameter at breast height (dbh) within the plot were tallied, species, dbh and damage class of each tree were recorded. Three damage classes were used: undamaged (class 1), where trees were not damaged or had less than 25% of the canopy lost; damaged (class 2), where 25-75% of the tree canopy was lost; and killed (class 3), where more than 75% of the tree canopy was lost or the tree was toppled. Within the sample plot four one m² micro-plots were randomly chosen. All tree seedlings in each micro-plot less than 2 m in height were tallied by height to the nearest 0.1 m (using a meter stick) and species.

The nearest canopy gap to the sample location was identified and the distance to the plot center to the gap center was measured. A gap was any canopy opening caused by a canopy tree that had lost more than 75 % of its canopy or was toppled due to glaze. The long axis of the gap and the axis perpendicular to it were measured using an optical rangefinder (KVH datascope). The gap shape was assumed elliptical and gap size was estimated from the length (L) and width (W) of the gap using the equation:

$$\text{Area} = \pi L W/4$$

Four 1 m² random micro-plots were placed within the gap. Like the understory seedling survey all seedlings less than 2 m in height were tallied by height to the nearest 0.1 m (using a meter stick) and species. The seedling survey therefore created two sets of seedling data; understory (undisturbed) and gap (disturbed).

Data analysis

Species composition in the Fishburn Forest varied greatly across different topographic categories, and susceptibility of different tree species to glaze damage was affected by species physical characteristics and topography (Chapter Two). Therefore, the susceptibility of forest communities to glaze damage was inevitably an important factor affecting the size of gaps created by glaze storms.

To characterize susceptibility of forest communities to glaze damage, a community susceptibility index (CSI) for each sample plot was calculated using the following equation:

$$CSI = \sum_{i=1}^n A_i MDI_i$$

where A_i is the relative abundance of species i based upon basal area, and MDI_i is the average damage index of species i in the same topographic category (Chapter 2) and was calculated as:

$$MDI_i = \sum_{z=1}^3 D_z P_z$$

where D_z is damage class from 1 to 3 and P_z is the percentage of the individuals of class z to the total surveyed trees of the species. MDI_i is a weighted average of damage classes of the species i at a given topographic category, and varies from 1.0 indicating none were damaged, to 3.0 indicating all trees were severely damaged and killed. CSI, then, is the weighted average susceptibility of the forest community at each sample plot factored by relative species abundance at each sample plot. An Analysis of Variance (ANOVA, Sokal and Rohlf 1995) was performed to examine the effect of topography, aspect, landform, CSI, and their interactive influences on gap size. A Tukey-Kramer HSD test (Kramer 1956) was performed to determine if there was a difference in gap size among the 15 topographic categories.

Seedling data were summed for analysis for the four micro-plots within each plot. The effects of topography (all 15 categories), disturbance, species and their interactions on seedling density were tested using an ANOVA (Sokal and Rohlf 1995). A two sample T test (Sokal and Rohlf 1995) was performed separately for each species to compare seedling density and height between undisturbed stands and gaps. A paired T test was also used to test the effect of topographic category on seedling density (Sokal and Rohlf 1995). The effect of gap size and species on seedling height and density was tested using ANOVA (Sokal and Rohlf 1995). The effect of gap size and species on seedling height

was tested using a mixed model ANOVA. The mixed model procedure used accounts for the subsampling of individual seedlings within the randomly located forest plots (Littell *et al.*) and treated plots as the experimental unit.

Results

Influence of topography and canopy tree community on gap size

Aspect, landform and CSI all had a significant effect on the sizes of gaps caused by the glaze storms ($p < 0.0001$ for all factors, Table 3.2). The interactive effects between aspect and landform, between CSI and aspect, and between CSI and landform, were all also highly significant ($p < 0.0001$ for all factors, Table 3.2). However, the significance of the three way interaction between CSI, aspect and landform was marginal ($p = 0.048$, Table 3.2)

Table 3.2 ANOVA table for effect of topography (aspect, landform) and community susceptibility index (CSI) on gap size after glaze storm at the Fishburn Forest, VA.

Source	SS	DF	MS	F	p-value
Aspect (A)	4430661	2	2215331	31.40	<0.0001
Landform (B)	9185375	4	2296344	32.55	<0.0001
CSI (C)	9366032	7	1338005	18.96	<0.0001
A x B	43168510	8	5596063	76.48	<0.0001
A x C	31156316	7	4450902	63.08	<0.0001
B x C	101007765	10	10100776	143.16	<0.0001
A x B x C	281574	1	281574	3.99	0.048
Residual	7182532	102	70417		
Model	198610561	39	5092211	72.17	<0.0001
Total	205793093	141	1459526		

Adj. $R^2 = 0.95$

The Tukey- Kramer HSD test (Kramer 1956) determined that there was no significant difference between mean gap size for any topographic categories. However, there was a pattern of gap size distribution among landform and aspect categories, certain categories had larger gaps (Table 3.3). For example there were many more medium and large gaps on backslope III, than in other landform. There were also more large gaps on Aspect III than on any other aspect.

Table 3.3 Gap size distribution across five landforms and three aspects after 1994 glaze storm in the Fishburn Forest, Montgomery Co.
 VA. Backslope I is < 13%, backslope II is 13-26%, and backslope III is >26%. Aspect I is south to west, aspect II is west to northeast, and aspect III is northeast to south.

Gap size categories	no gap	<100m ²	1-200m ²	2-400m ²	4-1000m ²	1-5000m ²	>5000m ²	Total (N)	Total area (m ²)	Mean gap size (m ²)
Landform										
Toeslope	6	6	2	2	2	0	0	18	3119	173
Backslope I	0	20	5	0	0	0	0	25	1782	71
Backslope II	0	23	9	4	0	0	0	36	2833	81
Backslope III	0	15	9	10	5	3	1	43	26550	617
Summit	3	13	3	0	1	0	0	20	1754	84
Aspect										
Aspect I	2	36	6	5	2	1	0	52	8050	158
Aspect II	4	23	14	8	1	1	0	51	7883	151
Aspect III	3	18	8	3	5	1	1	39	20106	515
Total (N)	9	77	28	16	8	3	1	142		
Total area (m ²)	0	3715	3976	4199	5881	4131	14137		36039	
Mean size (m ²)	0	48	140	263	617	1762	n/a	255		255

Gap size was extremely variable over the survey site, ranging from about 20 m² to over 14,000 m² (Table 3.3). Mean gap size was 255 m². Median gap size was 73 m². Total gap area was 36,220 m². There were nine sample points where no gaps occurred.

Influence of gap size and topography on seedling density

At the 142 understory sample points 4440 individual woody seedlings of 33 species were surveyed. Within the 133 gaps 3595 individual woody seedlings of 39 species were surveyed. Seedling density was approximately 69,000 per hectare (ha) in the gaps, and was 78,000 per ha in the understory. In both understory and gaps red maple, serviceberry (*Amelanchier arborea* (Michx. F.) Fern), and sassafras (*Sassafras albidum* (Nutt.) Nees) were the most common seedling species both in understory and gaps, comprising 56% and 52% of seedlings surveyed respectively (Table 3.4).

Overall seedling densities in the gaps were significantly lower than in the understory ($p < 0.0001$) by about 10,000 seedlings per ha on average. However densities were very different for different species, for many species density was significantly greater within gaps (Table 3.4). Topography (15 combinations of aspects and landforms), canopy condition (gap or undisturbed) species and their interactions all had significant effects on seedling density (Table 3.5).

Table 3.4. Average density of seedlings per m² observed in understory and gaps created by glaze storms in the Fishburn Forest, VA. Total number of seedlings sampled is also shown (N). Density (per m²) was calculated by dividing the total number of seedlings by the total number of 1m² micro plots. Density (per ha) was calculated by multiplying density per m²) by 10,000. The effect of disturbance on density was tested using 2 sample T -test with a Satterthwaite correction, significant species (at the 0.05 level) have three stars.

Species	Understory			Gaps			sig.
	N	Den. (m ²)	Den. (ha)	N	Den. (m ²)	Den. (ha)	
American chestnut	15	0.026	260	34	0.064	640	***
black cherry	23	0.04	400	37	0.07	700	***
black oak	101	0.178	1780	90	0.169	1690	
blackgum	144	0.254	2540	129	0.242	2420	
blackhaw	15	0.026	260	46	0.086	860	***
chestnut oak	416	0.732	7320	214	0.402	4020	***
dogwood	48	0.085	850	23	0.043	430	***
eastern hemlock	11	0.019	190	14	0.026	260	
hazelnut	88	0.155	1550	82	0.154	1540	
ironwood	0	0	0	14	0.026	260	***
maple leaf vibernum	344	0.606	6060	277	0.521	5210	***
mockernut hickory	34	0.06	600	41	0.077	770	
mountain maple	5	0.009	90	8	0.015	150	
musclewood	42	0.074	740	19	0.036	360	
northern red oak	7	0.012	120	9	0.017	170	
pignut hickory	8	0.014	140	18	0.034	340	***
red maple	1397	2.46	24600	917	1.724	17240	***
Rhododendron	15	0.026	260	38	0.071	710	***
sassafrass	478	0.842	8420	416	0.782	7820	
Scarlet oak	366	0.644	6440	340	0.639	6390	***
serviceberry	633	1.114	11140	529	0.994	9940	
sourwood	7	0.012	120	25	0.047	470	***
Virginia pine	0	0	0	2	0.004	40	
white oak	135	0.238	2380	114	0.214	2140	
white pine	39	0.069	690	26	0.049	490	
witch hazel	35	0.062	620	53	0.1	1000	
yellow buckeye	7	0.012	120	4	0.008	80	
yellow poplar	15	0.026	260	14	0.026	260	
Total	4428	7.796	77960	3533	6.641	66410	***

Table 3.5. ANOVA table for effects of canopy condition (gap or understory), topography, and species on seedling density after glaze storm at Fishburn Forest, VA. Density (per m²) was calculated by dividing the number of seedlings by the number of 1m² micro plots.

Source	SS	DF	MS	F	p-value
Canopy Condition (A)	293.62	1	293.62	65.78	<0.0001
Species (B)	12006.33	32	375.20	84.06	<0.0001
Topography (C)	1972.69	14	140.91	31.57	<0.0001
A x B	541.57	27	20.60	4.49	<0.0001
A x C	428.87	14	30.63	6.86	<0.0001
B x C	5533.39	239	23.15	5.19	<0.0001
A x B x C	1116.80	128	8.72	1.95	<0.0001
Residual	8614.13	1930	4.46		
Model	21893.28	455	48.12	10.78	<0.0001
Total	30507.41	2385	12.79		

Adj. R² = 0.65

Across different topographic categories, seedling densities were mostly lower in the gaps but significantly higher at backslope II of aspect III (Table 3.6). Seedling densities between gaps and the understory were not significantly different in the following topographic categories: toeslopes, summits and backslopes I of aspect I, toeslopes, backslopes I and III of aspect III.

At the species level, the results of a paired T-test on seedling density differences between gap and undisturbed understory plots indicated that American chestnut (*Castanea dentata* (Marsh) Borkh), blackhaw (*Viburnum prunifolium*), rhododendren (*Rhododendren maximum* L.), pignut hickory, iron wood (*Ostrya virginiana* L.), black cherry (*Prunus serotina* ehrh) and sourwood (*Oxydendrum arboreum* (L.) DC) seedlings were significantly ($p < 0.05$) denser in gaps than in the undisturbed understory (Table 3.6). Dogwood (*Cornus florida* L.), maple-leaf-viburnum (*Viburnum acerifolium* L.), red maple, scarlet oak, and chestnut oak seedlings were significantly denser in the undisturbed understory (Table 3.6). Seedling densities of all other species were not significantly different between gap and understory communities. The effect of canopy gaps on seedling density for most surveyed seedling species varied across different topographies.

Therefore, gap seedling densities were higher than understory seedling densities on some

topographic categories and lower on others (Table 3.6). There was no significant effect of gap size on seedling density (Table 3.7).

Table 3.6. The differences in seedling density (number of stems per m²) between stands that were disturbed and undisturbed by glaze in each different topographic category. Positive values indicate an increase in stem density within gaps. Paired T-test (Sokal and Rohlf 1995) indicated significant differences (*** <0.001, ** <0.01, * <0.05) in the means.

Topographic category	Aspect I					Aspect II					Aspect III					Total
	toe	backI	backII	backIII	summit	toe	backI	backII	BackIII	summit	toe	backI	backII	backIII	summit	
Species																
Am. Chestnut	0	0.42*	0.36	0.15	0.14	-0.67*	1.13	-0.21	-0.06	0	0	0	0	0	0.44*	0.13*
Black cherry	0	0	0.14	0.23*	0.71	-0.17	0	0.14	0.61***	0	-0.17	-0.2	0.29	0.25	-0.78*	0.09*
Black oak	0.17	0.67	-0.86	0.08	0.43	-0.5*	0.5	-0.5*	0.28	-1.6*	0	-0.2	0.86*	-0.25	-0.33	-0.13
Blackgum	-0.17	1.42***	-0.14	-0.85	0.14	-0.33	-1.38**	0.07	-0.67	-1*	0.33	-0.4	1*	0.25	0.33	-0.17
Blackhaw	0.17	0	0	0	-0.29	-0.17	0	0.36*	0.22*	0	-0.33	0	0.86*	0.58*	1.56*	0.21*
Chestnut oak	0	0.17	-0.57	-3.6***	-0.29	0	-1**	-2.6***	-0.5	-2.2**	0	-1.4	1*	-5.1***	-3.4***	-1.62*
Dogwood	0	0.083	-0.5*	-0.31*	-0.29	-0.83	0	-0.07	0.06	-0.6	0.17	0	0.57*	0.08	-1.22	-0.20*
E. hemlock	0	0	0	0.38	0	-0.2	0	0	0	0	0	0	0	0	-0.1	0.02
Hazelnut	1.67	0.08	0	0	-0.57	-3.17	0	1.36***	-0.11	0	1.17	0	1.57*	-1.83**	0	-0.08
Maple lf vib.	2.17*	-0.8*	-0.8	0.38	-3.6*	-5**	-0.4	-0.6	1.44*	-4.8	-0.2	0.6*	2.86***	-1.9**	1.22	-0.64*
Mock. Hickory	0	0.17	0.21	0.39*	0.29	0	0	-0.14	0	-0.4	0.17	0	0.29	0	-0.22	0.03
Mtn maple	0.33	0	0.71	0	0	0	0	0	0	0	0	0	0	0	0	0.02
Ironwood	3.5*	0	0	0	0	0.67	0	0.14	0	0	0.67	0	0.29	0	0	0.10*
N. red oak	0.5*	0	-0.14	0	0.143	0	0	-0.07	0	0	0.667	0	0	-0.25*	0	0.01
Pignut	0	0	-0.07	0	0.14	0	0	0.36*	0	0	-0.17	0	0.86	0	0	0.07*
Hickory																
red maple	0.5	-4.8***	-2.86	-5.7***	-0.29	-3.83*	-4.38*	-10***	-4.6***	-4.8	-0.33	-2	8	5.14**	1.08	-4.89*
Rhododendren	0.67	0	-0.14	0.15	0	0	0	1.21***	0.11	0	0	0	0	0	0	0.15*
Sassafras	0.17	1.58*	1.71	-2.5***	-4.57*	-0.17	-1.25	-0.79	-0.89*	-10	0.333	0	0.857	2.75**	-0.44	-0.66
Scarlet oak	0.83*	0.67	-2.36*	-0.62	1.29	-0.33	2.25*	-0.36	-0.5	-0.4	0.167	-0.8*	1.43***	-1	0.78	-0.13*
Serviceberry	-6.83**	0.83	-3.57	-1.38**	0.86	-2.17*	-0.25	0.07	-2.2***	-5*	-0.67	-1.2*	6.14***	3.42*	0.67	-1.03
Sourwood	0	0.58**	0	-0.38	0	0	0	0.86***	-0.06	0.2	0	0	0	0.25*	0	0.12*
Table mtn	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0	0	0.01
pine																
Virginia pine	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0.11	0.01
White oak	2*	0.17	-0.79	-0.08	-0.43	-0.33	-0.88	-1*	0.06	-3.2***	0.33	0.4	1.14	0.25	-0.33	-0.21
White pine	-0.17	0.08	-0.14	-0.08	0.43	-0.17	0.13	-0.14	-0.28	-0.4	0.17	0	-0.14	0	-0.33	-0.11
Witch hazel	-1.83*	0	-0.21	-0.08	0	0	0	0.57***	0.5	0	-0.67	0	0	1.83***	-0.11	0.11
Y. buckeye	0	0	0	-0.08	0	0.17	0	0	0	0	-0.5	0	0	0	0	-0.02
Yellow poplar	-0.17	0	-0.14	0	0	0	0	-0.29	0	0.4	0.33	0	0.29	0	0	-0.01
Total	2	1.25	-10.8***	-13.9***	-5.71	-18.2*	-5.5*	-11.7***	-6.6***	-33.8*	-2.67	-1.4	25.6***	0.42	-7*	

Table 3.7. Two way ANOVA testing the effect of gap size and species on seedling density after glaze storm at the Fishburn Forest, VA.

Source	SS	DF	MS	F	p-value
Gap size (A)	4.35	5	0.87	0.12	0.987
Species (B)	962.97	32	30.09	4.28	<0.0001
A x B	287.27	99	2.90	0.41	1
Residual	7425.75	1056	7.03		
Model	4480.04	136	32.94	4.68	<0.0001
Total	11905.79	1192	9.99		

Adj $R^2 = 0.30$

Influence of topography and gap on seedling height

Topography (the 15 combinations of aspect and landform), species, and canopy condition (understory or gap) all interacted in a marginally significant way ($p=0.057$, Table 3.8) to affect seedling height. Topography also had significant interactions with species ($p<0.001$) and with canopy condition ($p=0.017$, Table 3.8).

At the species level, American chestnut, chestnut oak, and scarlet oak seedlings were significantly taller in gaps than in the undisturbed understory (Table 3.9). Pignut hickory seedlings were significantly shorter in the gaps (Table 3.9). For the remaining species, there was no significant difference in heights between gaps and the undisturbed understory (Table 3.9). Gap size, species, and the interaction between the two factors had a significant effect on seedling height ($p< 0.0001$ Table 3.10)

Table 3.8. ANOVA table for effects of canopy condition (gap or understory), topography, and species on seedling height after glaze storm at Fishburn Forest, VA. Nominator and Denominator degrees of freedom are denoted by NDF and DDF.

Source	NDF	DDF	F	p-value
Canopy Condition (A)	1	6192	0.00	0.9997
Species (B)	38	1231	7.82	0.0001
Topography (C)	14	127	2.06	0.0184
A x B	26	6192	1.14	0.2827
A x C	14	6192	1.97	0.0165
B x C	137	1231	2.18	0.0001
A x B x C	78	6192	1.27	0.0574

Table 3.9. Average height of seedlings observed in gaps and understory by glaze storms in the Fishburn Forest, VA. Number of seedlings is shown in parenthesis. The effect of disturbance on height was tested using two sample T -test with a Satterthwaite correction, significant species (at the 0.05 level) have three stars.

Species	Av. ht. (m) u/s	Av. ht. (m) gaps	sig.
American chestnut	0.28 (15)	0.60 (34)	***
black cherry	0.16 (23)	0.45 (37)	
black oak	0.24 (101)	0.28 (90)	
blackgum	0.48 (144)	0.40 (129)	
blackhaw	0.43 (15)	0.30 (46)	
chestnut oak	0.18 (416)	0.29 (214)	***
dogwood	0.26 (48)	0.33 (23)	
eastern hemlock	0.35 (11)	0.41 (14)	
hazelnut	0.37 (88)	0.39 (82)	
ironwood	(0)	0.64 (14)	n/a
maple leaf vibernum	0.26 (344)	0.23 (277)	
mockernut hickory	0.29 (34)	0.38 (41)	
mountain maple	0.12 (5)	0.25 (8)	
musclewood	0.29 (42)	0.16 (19)	
northern red oak	0.31 (7)	0.19 (9)	
pignut hickory	0.40 (8)	0.32 (18)	***
red maple	0.16 (1397)	0.22 (917)	
Rhododendron	0.53 (15)	0.43 (38)	
sassafrass	0.31 (478)	0.37 (416)	
Scarlet oak	0.20 (366)	0.24 (340)	***
serviceberry	0.23 (633)	0.24 (529)	
sourwood	0.24 (7)	0.52 (25)	
Virginia pine	(0)	0.80 (2)	n/a
white oak	0.19 (135)	0.23 (114)	
white pine	0.57 (39)	0.46 (26)	
witch hazel	0.34 (35)	0.63 (53)	
yellow buckeye	0.59 (7)	0.78 (4)	
yellow poplar	0.11 (15)	0.12 (14)	
Total	0.23	0.28	***

Table 3.10. Two way ANOVA testing the effect of gap size and species on seedling height after glaze storm at the Fishburn Forest. Nominator and Denominator degrees of freedom are denoted by NDF and DDF.

Source	NDF	DDF	F	p-value
Gap size (A)	1	3391	4.75	0.0294
Species (B)	34	3391	8.74	0.0001
A x B	34	3391	2.97	0.0001

Discussion

Influence of topography and canopy tree community on canopy disturbance

The 1994 glaze storms created a large number of very different sized gaps in the Fishburn forest indicating that damage was widespread and varied in severity (Table 3.3). The majority of the gaps were small and the distribution of gap sizes follows a reverse J shape curve (Table 3.3) which agrees with other earlier studies (Runkle 1982, Brokaw 1985). This study revealed that almost all of the variation in gap size was affected by topography (landform and aspect), and community susceptibility to glaze damage (CSI) which combines species glaze damage susceptibility and overstory species composition and their interactions (Table 3.2). Interactions, particularly the interaction between CSI and landform (explaining approximately 50% of the variation in gap size, calculated using sum of squares from Table 3.2), indicate the close relationships between topography and forest type, and the large impact topography has on the susceptibility of different forest types.

In the Appalachian Ridge and Valley region, topography has been recognized as a leading factor affecting forest type due to its direct effects on soil, water, light and temperature conditions (Adams and Stephenson 1983, Stephenson *et al.* 1993). In addition, the impact of topography on microclimate causes a great variation in glaze storm severity. Furthermore, different tree species have different susceptibilities to glaze damage (Chapter Two). Therefore different forest types with different overstory species composition at different topographic locations largely determines the severity of glaze damage to the forest stand. Forest types dominated by conifers contained larger gaps as conifers are generally more susceptible to glaze damage than hardwoods (Boerner *et al.* 1988, Seischab *et al.* 1993, Rebertus *et al.* 1997). In this study large gaps were found in the stands dominated by Virginia pine (field observation). While hardwoods were generally less susceptible, glaze created gaps in the forest stands dominated by scarlet oaks and black oaks (*Quercus velutina* Lam.), however these gaps were mostly small to

medium sizes although the two species were among the more susceptible hardwoods (Chapter Two).

Oaks (chestnut, scarlet and white) generally dominate backslopes and the summits of the Fishburn Forest (Chapter Two). The forest canopy suffered different glaze damage over these different landforms. Almost all large gaps were formed on steep backslopes because of greater exposure that led to higher glaze loads on forest canopies, and shallow soils, which reduced root anchor strength. In addition trees on steep slopes tend to develop asymmetric crowns so that glaze loads are unbalanced. All these factors cause trees to fall in the downslope direction. The toppling of large trees may cause a domino effect, initiating secondary damage and creating larger gaps. Field observations in the large gaps confirmed the importance of domino effect. A relatively high percentage of Virginia Pines among the fallen trees (field observation) indicated that a higher percentage of more susceptible species in the forest might also promote gap creation and increase the likelihood of a large gap.

The different disturbance severities for forest stands on sites with different topography suggests different turnover rates for these stands. Forest turnover rate is an important measure of forest dynamics and illustrates how the forest may change in response to natural disturbance. Runkle (1985) reported that 0.5 to 2% of eastern hardwood forest is disturbed each year on average. This suggests that the turnover rates of these forests are between 50 to 200 years. However, if the disturbance regime is characterized by periodical severe disturbances forest turnover will be highly correlated to the frequency and the severity of the disturbance. In the Fishburn Forest with the current glaze storm frequency, areas where damage is more severe will have the highest turnover rates. Therefore, forest stands on steep slopes in the Fishburn Forest are expected to be younger, with smaller trees and more seral forest types than those on toeslopes and valley bottoms where glaze damage is usually minor given that glaze storms are the major natural disturbance of the area. Therefore, less frequent and less severe glaze damage may contribute to the development of mesic cove forest stands on toeslopes and valley bottoms.

Influence of topography and gap size on seedling height and density

Seedlings of gap phase species such as black cherry and sourwood increased in density within gaps as expected. These species are able to quickly sprout in response to the increased light, nutrient and water availability within gaps (Marquis 1990, Overton 1990, Stephenson *et al.* 1993). Conversely more shade tolerant species such as scarlet oak and chestnut oak (Johnson 1990, McQuilkin 1990, Walter and Yawney 1990) had higher densities in the undisturbed understory.

Topography had a profound impact on seedling density for most species. Seedling density was very different for different topographic categories. Topography affects soil, water, light and temperature conditions, all of which have a profound influence on seedling density. Light and consequently temperature are affected by aspect; northern aspects are cooler than south facing slopes (Kimmins 1987). Landform affects water availability (Pritchett and Fisher 1987); toeslopes are frequently more moist than steep backslopes.

There was a significant change in seedling height due to gap size. This agrees with work by Canham and Marks (1985), Runkle (1985), and Clinton *et al.* (1994). When gap size increases so does light availability, particularly when gaps are smaller (Canham *et al.* 1990). The majority of the gaps in this study were small and medium in size and light conditions vary greatly in this size range. Other important factors that accelerate seedling growth in gaps may include improved soil water conditions, reduced root competition for soil nutrients (McClure and Lee 1993) and accelerated forest floor decomposition (Bormann and Likens 1979).

Gap size was not stratified during field sampling and consequently a large percentage of plots came from small gaps, reducing the strength of analyses for seedling density and height. Environmental conditions (light, water and nutrients) in the majority of small gaps surveyed were not greatly different from the understory.

Few species found in the Fishburn forest showed a significant difference in seedling height between the undisturbed understory and gaps caused by glaze. American chestnut was taller in gaps but this species very rarely grows large enough to reach the forest canopy, due to chestnut blight (Stephenson *et al.* 1993). Pignut hickory was smaller

within gaps. It has been classified as a tolerate climax species in the southeastern U.S. and gap conditions may reduce its competitive ability (Smalley 1990). The higher light availability in gaps was beneficial to the height growth of chestnut oak, an intermediate shade tolerant species (McQuilkin 1990) and scarlet oak, a very shade intolerant species (Johnson 1990) (Table 3.9).

While the height of chestnut oak and scarlet oak did increase in gaps, density of these species decreased. Was this decrease in density biologically significant? Mortality rates for seedlings are normally very high (Canham and Marks 1985, Kimmins 1987) and may be even higher in gaps because environmental conditions fluctuate more. However, the number of seedlings present in gaps was sufficiently high for these species to maintain dominance within the forest stand. With the increased height growth of chestnut oak and scarlet oak these species will persist their dominance of the future forest.

Consequently the reduction or increase in seedling density may not have a biologically significant impact on the future forest. Reduction in seedling densities in the Fishburn Forest will not result in a serious shortage of tree species. To foresters, better seedling growth in this situation may be preferable to an increase in seedling density. In general, this glaze event will not change the dominant forest types in the Fishburn Forest. The forest will remain an oak forest with white oaks and red maples dominant on fertile slopes, yellow poplar dominant on toeslopes and, chestnut oak and scarlet oak dominant on steeper backslopes (Rhoades 1995).

However within local very large gaps the forest will take a much longer time to recover, and the pattern of the forest landscape will be affected. Furthermore, the local dominance of Virginia pine and Table mountain pine in many places are results of past fire and human disturbances (Carter and Snow 1990, Della-Bianca 1990). The extremely poor representation of pines in gap seedling communities indicates a reduction of the species in future forests.

Summary

Glaze storms create different sized gaps in the forest canopy within different forest types and topographic categories. Different turnover rates, caused by different sized gaps sustain early seral stage forest stands, such as Virginia pine, on steep slopes, which were

more severely disturbed by glaze. Later seral stages, such as forest stands with white oak exist on toeslopes, which were less severely disturbed. The change in density of some species (black cherry, sourwood) within gaps, suggests that these species will persist in the forest as a result of glaze while the height increase of other species within gaps (scarlet and chestnut oak) ensures that they will continue to dominate the overstory. Glaze is an important factor in sustaining diversity in the Appalachian forests.

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Conclusions

This study determined that glaze had a significant impact on canopy trees. Approximately six percent of trees surveyed were severely damaged by the storm. Basal area loss was also six percent. Damage was significantly different between species and between topographic categories.

Steep slopes had the greatest damage and the most severely damaged species was Virginia pine. Trees on steep slopes were more likely to be damaged as they have uneven canopies, creating an unbalanced load. Species restricted to toeslopes were mostly undamaged, hickories and oaks were the least damaged species that grew on a variety of topographic categories.

Severely damaged large trees created gaps in the forest canopy. Gap size was very variable, 20- 14,000 m² and median gap size was 73 m². Gap size was effected by forest type, canopy tree damage and topography. The largest gaps occurred on steep backslopes where glaze damage was greatest.

Glaze storms are an important disturbance factor in the ridge and valley region of the Appalachian Mountains. Gaps created in the forest by the glaze storm of 1994, which had a small affect on species composition. The future forest in this area is unlikely to change significantly, as species composition while altered was altered slightly, in a manner unlikely to affect the future forest. The storm created good conditions for gap phase species establishment; however these gap phase species (black cherry, sourwood) were not present in sufficient quantities to take advantage of the gaps created. Instead other species, dominant already in the forest canopy (chestnut oak, scarlet oak) also benefited through the creation of gaps and these species will dominate the future forest. However the existence of earlier gap phase (blackcherry, sourwood) species indicates that these species will continue to be represented in the understory in small numbers and some may become large canopy sized individuals. On steep slopes, which were particularly susceptible to glaze damage, xeric species (Virginia pine) may continue to dominate. The frequency and size of disturbances due to glaze and the environmental conditions will ensure that only these hardy species will survive on these dry slopes. However fire is

important in the regeneration of Virginia pine and few conifer seedlings were found during the survey.

Species diversity in this area is particularly great and this may be due to glaze. The forest maintains itself in a continual cycle of disturbance and regeneration with a large variety and number of environmental niches resulting in high species diversity. Thus the forest remains in a steady equilibrium state where a variety of species is maintained through the environmental conditions brought about by a variety of topography features and the changes wrought by frequent disturbance due to glaze.

Further work

Further studies are needed in different areas of the country and around the world on the effects of glaze on forests. Succession and disturbance patterns are different in different forest communities and studies on the effects of glaze on other forest communities is needed. Few studies have made use of before and after data of the forest stand, most studies relying instead on reconstruction of the existing stand after a glaze storm. By utilizing permanent plots a clearer picture of glaze damage can be made. Finally, programs to reduce glaze damage should be further developed, practiced and studied.

Applications for forestry

A reduction in tree destruction due to glaze is advantageous to those forests that are intensively managed, either for recreation or timber. This study has shown that conifers as a whole are more susceptible to glaze and so in areas of the country where glaze is a very serious problem, conifers should be replaced by hardwoods. On steep slopes glaze destruction is more severe and should be expected, dominant trees of some species are more susceptible and should be removed. Chestnut oak and white oak seemed most resistant to glaze on steep backslopes.

However as this study has indicated susceptibility is very variable and is influenced by topography, species distribution and climate. Therefore an examination of conditions at the site is essential for reducing possible glaze storm losses.

Regeneration within select cut may closely mimic regeneration within small gaps caused by glaze openings in the forest. This study came to no strong conclusion regarding the effect of gap size on seedling regeneration within small gaps. Regeneration within small select cuts in the forest may be similar to regeneration within larger openings. Therefore smaller harvest areas, utilized to reduce visual impact, may be as beneficial to forest regeneration as larger openings.

VITA

The author, Michael P. Warrillow, was born in 1972 in Ilkley, Yorkshire in the United Kingdom. Michael attended Bartholomew school, Eynsham, Oxfordshire, attaining 10 G.C.S.E's and 3 A levels in Math, Biology and Chemistry. In 1995 he graduated from the University of Wales, Aberystwyth with a B.Sc. Hon. in Botany. Michael began working towards his Masters degree in Forestry at Virginia Polytechnic and State University in 1995. He conducted forest inventory for the Virginia Department of Forestry during 1998 as part of the U.S. Forest Services Forest Inventory and Analysis research program. Michael married Jennifer Warrillow (nee Smith) in 1993.