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Ice Storm Impacts on Forest Health: Monitoring the Growth and Mortality of Ice Damaged Trees in Francis Beidler Forest

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ICE STORM IMPACTS ON FOREST HEALTH: MONITORING THE GROWTH AND MORTALITY OF ICE DAMAGED TREES IN FRANCIS BEIDLER FOREST

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by
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ABSTRACT

Forests in the Southeast U.S. Coastal Plain are subjected to periodic disturbances such as fire, hurricane, ice storm, and drought. For floodplain forests, ice storms are among the most frequent and injurious disturbances that occur. Despite this, these storms have not been studied as often as other disturbances, so their ecological role remains unclear. This study takes place in Francis Beidler Forest, an original growth floodplain forest preserve administered by the National Audubon Society near Charleston, S.C. The study examined the impacts of an ice storm that occurred February 11th-13th, 2014 on 3,700 trees that reside in three forest community types along an increasing moisture gradient: upland, bottomland hardwood, and cypress-tupelo swamp. The objectives of the study were to monitor the immediate and long-term growth and mortality of trees in Beidler Forest in response to key factors related to the ice damage. Results imply that ice storm damage has a lasting impact on mortality in southern forests, with an increase from 3.4% mortality immediately after the storm to 13.1% four years later. Damage severity had a positive correlation with mortality ($p < 0.001$) and damage categories of uproot and snapped bole were more likely to perish than those with crown damage. Evergreen broadleaf and marcescent trees in the upland community were significantly more likely to perish than deciduous trees ($p < 0.001$). Small diameter trees were also more likely to perish than larger ones. The cypress-tupelo swamp is the community that is most resistant to ice storms, with significantly lower mortality ($p = 0.046$) in trees > 5cm DBH than the two drier communities, bottomland hardwood and upland. Trees with DBH >11cm are the most dynamic in changes in growth after the storm, with >30% each experiencing recovery and decline, while most smaller trees remain steady in post-storm growth rates. These results suggest while ice storms may be infrequent, their impact can have a lasting legacy on the remaining trees for years after an ice storm event.

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CHAPTER ONE

INTRODUCTION

Natural disturbances that have the highest impact on forests in the United States include fire, drought, invasive species, insect and disease outbreaks, hurricanes, windstorms, ice storms, and landslides (Dale et al 2001). In the southeastern United States, the most frequent and impactful forest disturbances are fires, hurricanes and ice storms. These disturbances, along with climate and topo-edaphic factors, have determined the composition, structure, and function of the forest communities in the southeast (Rogers 1996). However, most studies in the last two decades have focused on fires, and little attention has been given to the other two disturbances, especially ice storms.

Ice storms are the most damaging disturbances in temperate forests, and forests in the eastern US historically encounter the most ice storm damage in the world due to conditions that encourage freezing rain (Irland 2000, Changnon and Karl 2003). In the southeastern US, severe ice storms are predicted to impact forests once every 5-15 years (Bragg 2003, Wahlenberg 1960 and Schultz 1997). The impacts of these events on individual trees can be instant mortality, injury or delayed mortality. However, some trees have the capacity to recover from severe damage. In the following review, factors that impact the degree of ice damage, mortality and recovery are examined, focusing on the southeastern US. Most ice storm studies focused on the immediate effects of ice storms, and few examined the impacts of ice storms on the growth and mortality of trees over time (Amateis and Burkhart 1996, Brender and Romancier 1965, Bruederle and

Stearns 1985, Carvell let al 1957, Pile et al 2016, Wang et al 2016, Croxton 1939, Halverson & Guldin 1995, Lafon 2004, Mutz 1947). Most studies on ice storm impact have been conducted in northeastern and northwestern US and Canada or in loblolly pine plantations in the southeast US. There is currently a knowledge gap for ice storm effects on naturally occurring forests in the southeastern US. In order to address these gaps, trees were monitored for changes in growth and mortality every 2 years following an ice storm. Tree details including lifeform, damage type and damage severity were also recorded. The objectives of this research are to determine which factors have a significant impact on post-storm mortality and growth 4 years after a storm event and to assess how Beidler Forest has recovered from this ice storm damage.

CHAPTER TWO

LITERATURE REVIEW

Ice Storm Climatology

The U.S. weather bureau officially defines glaze as a ‘homogeneous transparent ice layer [that is] built up on horizontal as well as on vertical surfaces either from supercooled rain or drizzle, or rain or drizzle when the surfaces are at 32°F or lower” (Haynes 1947). A more modern definition from the National Weather Service states that an ice storm occurs after at least 0.6 inches of ice has accumulated (Irland 2000). Ice accumulation can result in weight stress to trees and cause damage or mortality. Damages can compound if ice residence time is increased due to a long duration of freezing air temperatures. This can cause additional damage to forests from persistent weight stress. Freezing rain events are often accompanied by additional wind, snow or rain that can exacerbate the effects caused by the glaze (Bragg et al 2002, Gay & Davis 1993, Lemon 1961). According to Bennet (1959), the highest degree of damage is often concentrated in small areas because of microclimate cells and localized forest traits.

A ‘glaze belt’ exists from northern Texas up through New England where ice storm events can be expected to occur once every 3 years (Bennet 1959). Although South Carolina is not located in this area, sites south of the glaze belt still experience ice storms about every 5-15 years (Bragg et al 2003, Changnon and Karl 2003). A study including both glaze and sleet events in the southeast suggests that South Carolina can expect from 0-3 glaze or sleet events per year. Both events decrease in likelihood as the coast and the equator are approached (Gay & Davis 1993). Since these areas may not be adapted to glaze events, any ice accumulation has the potential to cause major forest damages and potentially lead to changes in species composition and diversity. Ice storms can cause a shift toward more storm-resistant species, stem damage, and increased susceptibility to secondary damages such as pest and disease (Irland 200).

Factors affecting tree mortality

Ice storms can damage trees by causing crown damage, bending, snapping and uprooting. The results of these damages can range from minor injuries to instant mortality. Mortality most often occurs as a result of ice storm damage if the crown is severely damaged, the bole is snapped, or the tree is uprooted at a severe angle (Carvell 1957). If a significant portion of the crown is lost, the tree may not produce sufficient carbohydrates to survive due to lost leaf area and greatly decreased photosynthetic productivity (Bragg et al 2002). Minor damages along the stem and crown can cause long term mortality, as injuries may open the tree up to secondary damages such as fungal or insect invasion. Due to complex interactions between many factors such as tree health, vulnerability, and insect populations, an insect or disease infestation after an ice storm is not inevitable (Muntz 1947, 1948).

A study done on a southern loblolly pine after an ice storm showed that 28% of severely damaged trees (categorized as 70% or more of the crown lost or greater than a 60° angle bend in the stem) died by the end of the first growing season following the storm (Bragg et al 2002). Less than 2% of individuals with minor damage died after this period. In a follow up after 5 years on the same stand, mortality was 55% for trees with critical damage, 16% for those with major damage and <3% for trees with low to moderate damage. Growth was affected negatively by the intensity of the damage and positively by the initial diameter size of the tree (Bragg et al 2002).

Factors affecting damage

Biotic factors

Injury is caused in wood when the stress applied surpasses its structural integrity. 'Green' wood refers to wood that is cold, or less dense, and this type of wood has a lower resistance to breakage than warm wood from a tree of the same species (Cannell and Morgan 1989). Trees that are less brittle and have more pliable wood with thick branches that face downward are more likely to survive an ice storm without injury since they can bend and potentially shed ice rather than snap (Cannell and Morgan 1989, Smith 2000). There are several biotic factors that may affect a tree's ability to withstand damage from an ice storm. These factors include stem size, growth form, symmetry of the crown, foliage presence, canopy position and root depth (Irland 2000, Bruederle and Stearns 1985).

Stem Size and shape

Stem size has a very complicated relationship with damage, a topic in which many studies do not agree. There are three general outcomes of these types of studies; a positive relationship with size and damage, no relationship, or a complex relationship. This can be attributed to the fact that stem size can be measured by diameter at breast height (DBH) or height. Each can have different effects on wind resistance, and the morphological differences in crown shape and species also play a role. Furthermore, wood density may have more of an important effect than the size itself. Therefore, it is very difficult to assess the relationship shown between size and damage. It is often found in these studies that the smallest and largest trees survive, while the intermediately sized individuals face the most damage and are most likely to experience bole snap (Edwin and Everham 1996, Rebertus et al. 1997, Proulx and Greene 2001). A positive correlation was found between tree height, diameter and crown diameter with any damage in the Appalachian plateau (Boerner and Kooser 1988).

In *Tsuga canadensis* hardwood forests in the Adirondacks of New York, a model was used to simulate ice storms. The model showed that smaller diameter trees were more likely to experience severe bole damage (leaning, snapping, or uprooting) (Lafon 2004). Trees with stout boles were more resistant to minor or moderate damage, but they were also more likely to experience mortality from severe damage (Shepard 1975, Amateis & Burkhart 1996). Also, the probability of canopy damage had a positive correlation with tree size (Lafon 2004, Pisaric et al 2008).

Taper refers to the degree in which a tree decreases in diameter as it increases in height. Trees that have a greater taper in their trunks, or with buttresses such as in *Taxodium distichum* are more resistant to breakage of the main stem because of their strength and ability to hold more mass. Trees that have a lower taper and are spindlier can allow for greater bending, but also break more easily under heavy loads (Hauer et al 1994).

Crown shape, symmetry and flexibility

Individual trees with specific traits may have a higher chance of survival with less damage during a glaze event. The optimal traits are short trunks, fewer surfaces where ice can accumulate, strong wood, symmetrical crowns, good rooting conditions and local support. For example, *Pinus palustris* Mill. has longer needles and lower stem flexibility compared to *Pinus taeda* L., so *P. taeda* will tolerate glaze events better and incur less damage (Mckellar 1942, Wahlenberg 1960, Brender and Romancier 1965).

Crown shape also plays a role, as the excurrent form of many pines is favorable for survival in ice storms. An excurrent form allows trees to shed ice better than trees with a decurrent form, such as elms and oaks, which can be especially endangered by ice storms. A decurrent shape allows ice to accumulate on branches that extend perpendicular to the tree, which can cause limb breakage or toppling of the tree (Rogers 1924, Reed 1939, Van Dyke 1999, Bruederle and Stearns 1985).

Pile et al (2016) studied the shape of pine crowns in response to the same ice storm analyzed in this study that occurred in February 2014. Two crown shape ideotypes of *P. taeda* were compared, a narrow crown and a broad crown type. These ideotypes each allocated more carbon to different areas of the tree. Broad shaped ideotype trees experienced a higher percentage and more extreme crown damage than narrow shaped trees. Narrow ideotypes experienced significantly higher mortality due to bole snap than broad crown trees (Pile et al 2016).

Crown symmetry is important because of even distribution of weight of ice accumulation. If a crown is symmetric, the tree may remain straight, but if it is not more ice will accumulate on one side increasing the chances of bending, snapping, or uprooting in a single direction. In addition, if a tree has flexible, strong and thick branches it is more likely to bend and shed the ice accumulation than snap from it (Rogers 1924, Croxton 1939).

Foliage presence

Presence of foliage during ice storm events increases surface area for ice accumulation. Boerner and Kooser (1988) found that needle leaf trees experienced more severe damage compared to deciduous trees because of increased surface area for ice accumulation. Another recent study examined the ice storm in nine locations across SC in concern to winter morphology and ice damage. Broadleaf evergreen trees were the most susceptible lifeform to ice damage, followed by needle leaf evergreen, marcescent trees (trees that hold onto dead leaves during the winter) and deciduous trees being the least susceptible (Wang et al 2016). Overall, trees with foliage present in the winter have a greater surface area in general, which leaves them more susceptible to injury from ice, snow and wind unless their wood is exceptionally strong (Rogers 1923, Croxton 1939).

Canopy Layer

Trees in a forest stand may occupy different canopy positions. This has important implications for the resulting glaze damage due to different exposure to ice accumulation. Logically, a dominant canopy tree would receive the most ice accumulation because of its canopy exposure to freezing rain, and a suppressed tree or tree under the main canopy would receive the least due to its shelter from above trees. Wang et al (2016) found that overstory trees were more susceptible to crown damage than lower canopy layer trees, and experienced higher amounts of crown damage as well regardless of other variables such as lifeform and species. The intercepted glaze is not the only advantage of residing in the understory, as these trees also experience diminished winds, decreasing damages (Bruederle and Stearns 1985, Carvel 1957).

Life history strategies

Tree species exhibiting different life history strategies have been shown to experience different levels of ice damage. These strategies include stress tolerators, competitors and ruderals. To go along with their life history, the level of damage sustained decreased as the strategy went from tolerator to competitor. Stress tolerators experienced low damage, because of the importance of survival for slow growing, long living and low reproduction of trees in this category. Competitive species had high widespread damage, but low mortality. This is due to their competitive strategy which is quick growing but also quick recovery. Ruderal type trees had high damage and mortality due to their focus on reproduction rather than strength (Wonkka et al 2013). More research is needed on this topic.

Abiotic factors

The abiotic factors that may affect damage include ice accumulation, ice residence time, wind presence and intensity, topography, soil conditions and disturbance history.

Ice storm intensity

Ice storm intensity can be measured by ice accumulation, extent, residence time and associated wind or other precipitation. Ice accumulation can range from 0 to 15 cm and depends on many factors during the storm, mainly temperature fluctuation and duration (Lemon 1961). Ice storms can vary from little accumulations with minimal damage on the canopy to extremely severe where most trees are toppled. Loss of high proportions of the crown leads to decreased growth, but minor ice storms may even be beneficial as they will only trim trees of damaged branches and smaller limbs (Lemon 1961). Ice residence time is based upon many factors of tree form, elasticity and wood strength and is spoken about in the crown shape section. There have been severe ice storms in which trees in the high canopy layers are all killed, severely altering forest structure (Halverson & Guldin 1995, Carvell et al 1957).

The season in which the storm occurs is also important. Deciduous trees are less likely to be uprooted in winter seasons when they have shed their leaves since they will experience reduced wind drag and a higher likelihood of their roots being anchored in strong, frozen soils (Mayer 1989). A similar trend is seen with ice storms since damage is decreased with deciduous loss of leaves. This allows the trees to experience a lower weight of ice loading since the surface area is reduced, decreasing the intensity of the storm.

Roots, soil and topography

There is a complexity relationship between topography and tree damage from wind and ice. There have been many studies on which topographic factors affect wind intensity and damage. There have been many accounts of increased damage on windward slopes and ridges (Alexander 1964, Curtis 1943, Liegel 1984, Neustein 1968, 1971, Ruth & Yoder 1953, Smith 1946, Stoeckeler & Arbogast 1955, Webb 1958). Others have found evidence of decreased damage on leeward slopes and valleys (Andersen 1954, Webb 1958, Liegel 1984, Wunderle et al 1992). Any tree found on a steep slope is more likely to have an asymmetrical crown, have shallow soils, leading to shallow rooted plants and higher exposure to ice accumulation. Similar results are seen on forest edges because of their increased exposure to the elements both precipitation and wind, and decreased local support (Bruederle and Stearns 1985, Seischab et al 1993, Warrilow and Mou 1999). These conditions increase the probability of damage and mortality from ice.

For ice storms, the most susceptible area of the landscape seemed to be eastern facing aspects and steep slopes, while the safest area (where the least damage was recorded) was in the foothills and valley area (Warrilow and Mou 1999). Others found that canopy damage was most likely to occur on gentle slopes, and the probability of severe stem damage increased with an increasing slope (Lafon 2004).

Soil characteristics that prevent the establishment of deep strong tree roots could increase damages sustained. These characteristics can be hard, thin or high-water table soils or steep slopes (Smith 1946, Foster 1988, Bromely 1939, Trousdell et al 1965). The depth of soil is low in these scenarios, which can decrease the chance of deep root establishment by trees and increase chances for uprooting during an ice storm or wind events. Seischab (1993) reported shallow soil as a factor for increased uprooting in a New York Ice storm. The root anchoring capacity of different soil textures may also play a role, with significantly higher damage (30%) found in coarse-textured soils than in fine ones (5%) in a wind event, and these vulnerabilities would transfer to an ice storm (Trousdell 1965). Root crown diameter was not found to have a relationship with ice damage (Boerner and Kooser 1988).

Stand conditions

Regarding stand conditions, ice storm damage was found to be related to stand age, recent thinning and closeness to stand openings. Many studies show an increase in damage with an increase in stand age, but this cannot be confirmed because as stand age increase, many other factors may also increase such as stem size and exposure to tree pathogens (Irland 2000, Zhu et al 2015).

Recently thinned stands are especially susceptible to ice storm damage. Thinning removes support trees for the residual stems, which directly increases ice damage. After thinning, wind is capable of blowing more through the stand and increasing forces sustained to the trees, which indirectly increases ice damage (Bromley 1939, Liegel 1984, Nelson & Stanley 1959, Ruth & Yoder 1953, Wadsworth & Englerth 1959, Wilson 1976, Brender and Romancier 1960, Carvell 1957). One study also found that naturally occurring, less dense forests are more stable in wind events than thinned or naturally dense forests (Alexander 1964). The time it takes for stands to fully recover from thinning in order to withstand wind again is about 5 years (Cremer et al 1977, 1982). Natural or harvest related gaps may also increase damages in a stand, for the same reasons as thinning. Increased damage is also observed on trees located along the forest edges since their exposure to wind and ice is higher, they are more likely to have asymmetrical crowns and ice loading, and they lack local support (Foster 1988). Some studies show insignificant effects were found between spacing and density and ice damage (Amateis and Burkhart 1996), while others suggest densely crowded stands are more susceptible due to a spindlier form (lower taper) of trees and increased chances of trees toppling on each other (Hauer et al 1994).

Disturbance history

Anything that predisposes a tree to decreased vigor will increase its chance of damage or death through a disturbance event. These predisposing agents can include insect infestations, root canker, drought, root rot, or anything that weakens the wood or causes stress to the tree for an extended period of time. For example, in New England, it was found that fungus and insect infestations significantly increased hurricane damage to trees (Bromley 1939). There are many other studies confirming that the presence of fungi or pest will increase damage sustained by strong winds (Webb 1986, Hubert 1918, Trousdell 1955). The same outcome would also likely apply to ice storms.

Individual recovery and measurement

There are many different strategies for individual and species of trees to survive through damaging events. Trees can either resist damage originally, resprout or flower and fruit quickly thereafter. There is also evidence of trees recovering from damage such as straightening out after being severely bent.

Measuring damage and recovery

One way to measure recovery and damage is to monitor the changes in basal area or radial growth. Due to the order of resource allocation in trees, if a tree is severely stressed or damaged the radial growth is often reduced (Kozlowski & Pallardy 1997, Pedersen 1998, Dobbertin 2005). If radial growth decreases, not enough energy is present to heal injuries and produce secondary growth simultaneously. Once growth returns to rates similar to before the tree was injured, it can be determined recovered. When determining average growth before a disturbance, it is cited that ten years is enough to determine a pre-storm growth rate for an ice storm. (Nowacki & Abrams 1997, Smith & Shortle 2003). Damaged trees will likely experience decreased growth, but surrounding trees may grow more after a damage event due to increased light from openings in the canopy from crown damaged trees and those who have been toppled(Lafon & Speer 2002, Smith & Shortle 2003, Smolnik et al. 2006, Pisaric et al. 2008).

Resprouting

There are many species of hardwood and few species of pines that have adapted to top kill damages such as fire and browsing by resprouting. This vegetative regrowth can save individuals after severe damage such as snapped bole or severe breakage due to an ice storm or wind. Some studies show that shade tolerant species are more likely to sprout, which can change the structure of post-disturbance forests. These species are most likely to be important after a storm if the damage is not severe and there are no secondary disturbances such as disease or insect outbreak (Dallmeier et al 1991, Putz & Sharitz 1991, Lugo & Scatena 1995 Halverson & Guldin 1995). After an ice storm, some species that experience top kill can be seen resprouting to remain alive and repopulate the damaged area. Although large trees are more likely to be snapped, smaller trees can be snapped if they are hit by the toppling of larger canopy trees. Large trees sprout less, and this can reduce their ability to recover from damage (Kozlowski & Pallardy 1997)

Flower and fruit

Trees react to some levels of stress differently. Severe defoliation caused by an ice storm can lead to an unseasonal intense flower and fruiting from the tree. The increased fruiting can cause increased seed fall in disturbed areas, a study recorded almost double the seed fall in gaps after a hurricane than before (Lynch 1991, Synder & Synder 1979, Wiley & Wunderle 1994, Zamore 1981). This ability can increase future germination of that species and change the composition of the post-disturbance forest by increasing the proportion of young seedlings of the species that set seed extensively in response to disturbance.

Bending

There is evidence that small trees below 15 ft tall in the sapling stage can recover from bending at severe angles, but this declines as the tree grows. If a tree is bent at or near 60°, it is unlikely to recover (Barry 1993). Even if the tee is over 15 ft tall, if bending occurred during ice load it is likely to return to its normal state once the load is melted. The fact that it bent instead of broke is a good sign of structural integrity of the wood and a high chance of recovery. Highly problematic bends occur in the lowest 1/ 3 of the trunk and can cause lasting effects if internal cracks due to the bending (Hauer et al

1994). Bark damage may arise from over bending of the trunk in both young hardwoods and pines (Spaulding and Bratton 1946).

Paths to stand recovery

Forest stands as a whole can recover in four ways: regrowth, release, recruitment, or repression. These all can cause shifts in community composition and structure after a disturbance and depends on the type and extent of damage sustained.

Regrowth refers to the vegetative regeneration through resprouting of damaged trees. This can definitely alter stand dynamics as previous trees in the sapling stage will regrow from sprouts and will favor those that have this resprouting ability (Edwin and Everham 1996).

Release refers to trees in the understory that were released from suppression from the felling of larger trees during the disturbance. This can cause a shift in species dominance if the understory species composition did not match species composition in the canopy. A study done by Spurr (1956) showed that the canopy 10 years after a hurricane was dominated by those in the understory at the time of the event. Stand history is important here because if the understory is limited in biodiversity or richness, the stand has a higher chance to be recruited by pioneer species than released (Edwin & Everham 1996). After an ice storm, Lafon (2004) found a decrease in species richness in his study area, but evenness increased due to the demise of minor tree species entirely.

Recruitment refers to recovery by early successional species (pioneer) species. This is most likely to occur with low to moderate mortality and moderate structural damage. This will open up enough of the canopy for shade intolerant pioneer species to establish but not contribute too much litter to make seed establishment difficult (Yih et al 1991).

Repression occurs when secondary succession of trees and shrubs is suppressed through herbaceous or vine growth, or heavy litter. This occurs when non-woody plant growth explodes following a disturbance and woody plant growth cannot outcompete. These plants are able to grow quickly because of their protected location in the understory during the disturbance event (Wadsworth & Englerth 1959, Webb 1958, Whitmore 1974, Wood 1970).

Conclusion

Ice storms can have profound impacts on US forests. Many factors can impact how an area is damaged. The major factors include tree morphology, size, form and symmetry, foliage presence, wood strength, canopy status, local support and soil and topographic factors. Due to the complexity of factors involved in ice storm damage, it can be difficult to predict how an area will respond. Broad generalizations can be made, but specific damages will vary due to a multitude of variables.

Ice storms will continue to occur in the southeastern US, and more research is needed to understand the impact they have on forest health in this area. The following research is meant to fill some of those gaps concerning the effects of lifeform, damage category and damage severity on tree mortality and growth

CHAPTER THREE

MATERIALS AND METHODS

Ice Storm

The ice storm in this study occurred February 11-13, 2014, affecting 24 counties in South Carolina and leaving approximately 1.5 million acres of forestland damaged. The damage sustained to the timberlands of South Carolina cost about $360 million, second in damage costs only to Hurricane Hugo (South Carolina Forestry Commission 2014). The hardest hit areas in the southwestern part of South Carolina down through eastern Georgia (Figure 1) with ice accumulations of between 25.4 and 38.1 mm (SCFC 2014.) This study took place in Francis Beidler Forest in southeastern SC. Beidler Forest experienced between 9.9 and 19.6mm of ice accumulation during the February 2014 ice storm.

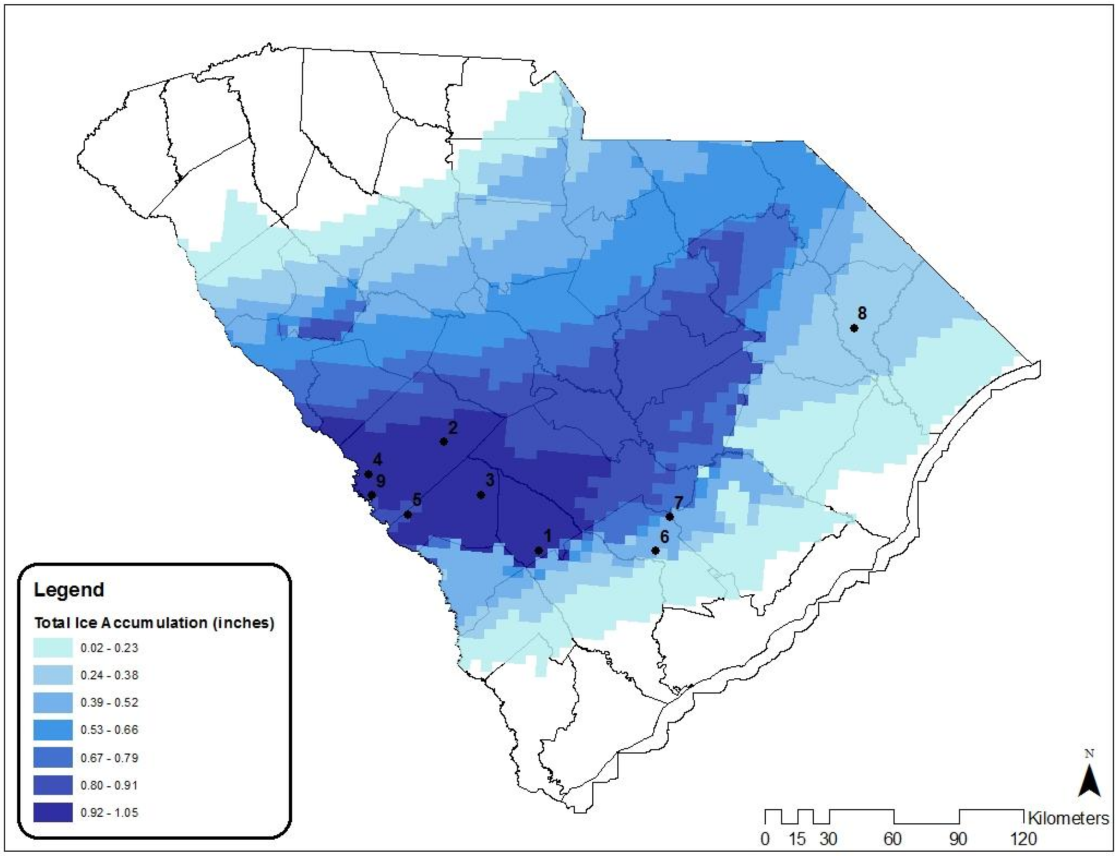

Figure 1 Levels of ice accumulation in South Carolina denoted by different colors from the 2014 ice storm (Credit: SCFC). The study site Francis Beidler Forest is 7.

Study Site

The Francis Beidler Forest (referred to as Beidler Forest subsequently) is a bottomland hardwood swamp located in the coastal plain of South Carolina in Berkeley and Dorchester counties (33°14′02″ N, 80°21′40″ W). Beidler Forest is a National Audubon Sanctuary in Four Holes Swamp and lies in the Edisto River Basin. Beidler Forest is referred to as an original growth forest and not a virgin forest because it is presumed that original settlers removed a tree here and there for clearing of primitive roads or for firewood. These removals did not affect the native ecosystem, leaving it to the term original growth forest (Porcher 1981). Beidler Forest is the largest original growth bald cypress (*Taxodium distichum (L.) Rich.)* and water tupelo (*Nyssa aquatica* L.) forest in the United States, at about 3,500 acres with trees averaging at around 1,000 years old (Brunswig and Winton 1978). Elevation at this study site is 0-60 ft above sea level, with average yearly temperatures at 17.8 °C. The lowest mean air temperature occurs in January at 11.2 °C and the highest mean air temperature occurs in July at 33.4 °C. Rainfall averages 1200 mm annually (NOAA Climatic Data Center). This site represents an area of moderate to heavy ice storm damage. The ice accumulation experienced here in 2014 was 9.9-20mm (SCFC 2014).

Data Collection

Three forest types were identified along a decreasing moisture gradient: cypress-tupelo swamp, bottomland hardwood, and upland forest. As part of a Hurricane Hugo assessment in 1994, four 20 m x 100 m (0.2 hectares) permanent plots were established in each of these types for a total of 12 plots. In each plot, woody stems > 2.5 cm diameter at breast height (DBH, 1.4 m above ground) were recorded by species and marked with an aluminum tag. Ingrowth of stems 2.5 cm or larger were tagged and identified to species during each data collection. The plots were re-measured about every 3 years until 2014, and then they were measured every 2 years. In this study, measurements from 2010, 2013, 2014, 2016 and 2018 were used. During each measurement, each tagged tree was identified into species, status was recorded as alive, dead or missing, and DBH was measured. Additional measurements were also taken in 2014 and 2018 as described below.

Post-ice storm measurement was conducted during the growing season after the 2014 ice storm. Only 11 plots were analyzed in the original measurement of damage from the ice storm due to extremely high water levels in plot 6, excluding it from the rest of the study.

Stand type, site type, GPS location and level of ice accumulation were recorded for each plot. Each stem with height >1.4 m was identified to species and its DBH was measured, including those killed or damaged by the ice storm. Because seedlings are very flexible and seldom suffer significant damage from ice storms, they were not measured in the study.

The status of each stem was first recorded in 2014 as alive and not damaged (N), alive and damaged (DM), or damage and dead (DD). For the trees that sustained damage from the ice storm, each stem was assigned into one of four damage types: CD = crown damage (the tree crown was injured but the tree remained upright; % crown loss was visually estimated in 5% increments); BB = bent bole (stem was significantly bent, and the vertical distance from tree top to the ground was measured); SB = snapped bole (a portion of upper main stem had been snapped off and most crown (>90%) was lost; the height from the ground to the snapping point was recorded); UR = uprooted (stem was partially or entirely uprooted). Trees sustaining several types of damage were assigned to the most severe damage type, with the priority of UR > SB > BB > CD. Trees were recorded as dead when there were no living buds, except stump sprouts. Trees were remeasured in 2016 and 2018 to record DBH growth and status changes (dead, alive or missing).

Additional data were recorded in the most recent study period in 2018 to assess individual tree health. These data included the presence of discolored or dead foliage, leaf tip or branch dieback, withered leaves, leaf miner evidence, the presence of insect galls, bores in the bark, cankers on the bark, and evidence of fungal mycelium or fruiting bodies on any part of the tree's bark or roots. The presence of potentially strangling vines, animal damage and any other visual health data was also recorded.

Increment borers were used to take cores of trees in 2018 to assess changes in growth since the storm and throughout the tree's life. In the three forest types, the most abundant living species were cored. Damage classes in consideration were minor crown damage and severe crown damage denoted in Table 1.1. Trees that were fully uprooted or snapped rarely survived, so they were not included. As a control, trees with no damage were cored to compare the growth rates between damaged and undamaged trees of the same species. Replicates were taken for each species and damage type in each habitat when possible. Cored species include *T. distichum*, *Nyssa sylvatica* Marshall*, Fraxiunus pennsylvanica* Marshall, *Quercus coccinea* Münchh, *Acer rubrum* L., *Quercus alba* L., *Quercus laurifolia* Michx and *N. aquatica*. These data were used to compare incremental growth among the moisture gradient, species and crown damage classes.

Table 1.1
Classification of crown damage only for trees that were cored for ring width analysis

Damage class	Crown damage %
0 Minimal	0-5
1 Minor	10-35
2 Major	40-90

Once collected, the samples were stored in plastic straws with holes cut in them for ventilation. Cores were mounted on wood with a curved groove cut in it to fit the core and securing with wood glue. Cores were then sanded with a full range of sandpaper from 80 to 800 grit incrementally using a DeWalt hand-held disc sander. Once smooth and cleaned of any residual dust, the rings were measured using a moveable stage microscope under magnification between 50x and 120x. Dates were assigned to each ring going back to 1989 when possible.

A 30 m transect was randomly established across each plot with standing water to record water level. The height of 30 live cypress knees (from the ground to the tip of the knee) and water level at the spot of each knee (from the ground to the water surface) was measured. The width of the transect was variable depending on the abundance of knees. For plots with only a few bald cypress trees, knees were randomly selected to be measured. Plots with many bald cypresses included plots 5, 7, 8, 9, 10 and 12. This measurement was to better understand the water level at the time of data collection (data not shown).

Data analysis

Using an approach similar to Bragg and Shelton (2010), an ice damage classification system was developed to estimate damage severity based on the types and degrees of damage (Table 1.2).

Table 1.2
Grouping of damage severity into three damage classes for all trees

Damage class	Crown damage %	Uproot angle from vertical°	Snap %
1 Minor	0-35	0-30	
2 Moderate	40-65	30-60	
3 Major	70-95	60-90	50-100

Three DBH size classes (<5, 5-10.9, and >11 cm) were assigned based on observed annual growth averages (Smith and Shirley 1984). These size classes were assigned from 2014 (the year of the storm) or 2013 if data was absent in 2014.

Lifeform was classified into two broader categories: winter broadleaf, including evergreen broadleaf (EB) and marcescent (M) species (species that hold onto their dead leaves throughout the winter, such as some species of oak), and deciduous (D) including both broadleaf and needle leaf deciduous trees. Evergreen coniferous (EC) trees were excluded because of their low frequency (only 59 individuals) and presence in only the upland community plots. These categories were condensed because evergreen broadleaf trees were absent in cypress community but were common in the other two forest types so they could not be excluded. An additional analysis was run in only the upland community because of the presence of all 4 tree lifeforms.

Analyses were conducted excluding trees where the status was noted as ‘missing’. These trees were not found in 2018. It is likely that some of these trees are dead, but without finding the aluminum tag it is not certain, so they are put in their own category as missing and excluded from the data analyses.

ANOVAs were used in Statistical Analysis Software (SAS) by the generalized linear mixed models (glimmix) to compare mortality to the variables; forest type, lifeform, damage category, damage severity and diameter size. When significance was found means were separated using least square means values. This model accounts for random (Gausian) effects which exist between the plots. Generalized linear mixed models were used because status is a binary discrete response. The alpha level of 0.05 was used for significance.

SAS was used to compare growth with the same variables (forest type, lifeform, damage category, damage severity and size) with the addition of species. ANOVA was used to compare mean annual basal area growth after the storm to these variables as well and the differences found in growth before the storm (2010-2014) and after the storm (2014-2018) using a proc glimmix model. Additionally, crown damage percentages were compared to basal area growth using the same model.

Based on changes in basal area growth from DBH measurements between 2014 and 2018, the recovery status of each alive tree was classified as in recovery (increase in growth), no change, or decline (decrease in growth).

Post-storm growth was broken down into two-year increments based on data collection dates, 2014-2016 and 2016-2018. Every tree's basal area was calculated for each measurement year in square meters using the equation below. Growth was calculated by taking the difference between the later year and the earlier year. After recovery statuses were assigned, ANOVA was run in SAS to see if the same variables in question (damage category, damage severity, lifeform, size and species) affected the recovery. This procedure was run as a multinomial assessment including all three categories, and again as a binary assessment excluding trees with no change to assess any relationship present.

$$BA=((\pi/4) * 10000) * DBH^2$$

$$BA=0.00007854 * DBH^2$$

BA is basal area per tree in square meters
DBH is the diameter at breast height in centimeters
π is the constant 3.1415

Cores were taken from 172 surviving trees with crown damage ranging from 0 to 90% to get a more precise measurement of annual radial growth. This information was used to evaluate whether the percentage of crown damage has an effect on annual growth. Crown damage classes are presented in Table 1.2. A radial growth index was calculated as the annualized mean radial increment for the 4 years after storm injury (2014-2017) divided by the annualized mean radial increment for the 4 years before the storm injury (2010-2013) to compare changes in growth between species and damage categories. A radial growth index value of about 1 indicates no change in growth rate, a value of < 1 indicates a decrease in growth rate and a value of > 1 indicates an increase in growth rate. Since data was collected in June of 2018, the year 2018 was not included in the analyses since the growing season had not finished and these rings were incomplete. The radial growth indexes and annualized mean increments were log transformed due to non-normal distribution and heterogeneity of variances to allow us to run statistical tests fitting the assumptions. ANOVA was used in JMP Pro14 to determine the relationship between growth index, crown damage and species. A significance level of 0.05 was used.

Tree health was analyzed using descriptive statistics because of the low frequency of observations.

Ring growth is weakly, but significantly, related to the temperature and precipitation during the growing season. Extreme events including hurricane and ice storm that show >1 standard deviation from the mean are also significant in changes to ring growth (Graumlich 1993). Data used in this study were obtained using the National Oceanic and Atmospheric Administration’s Climatic Data Center. The data are from a weather station located in Walterboro, SC which is 33 miles south of Beidler Forest. A two sample, two tailed t-test was used to determine whether or not climatic data (temperature and precipitation) were significantly different between the growing seasons before and after the ice storm, April through August during 2010-2013 and 2014-2017. These data were used to determine if any of the changes in growth were attributable to changes in precipitation and temperature.

Not included in this climatic data is the presence of hurricane Matthew, a category 1 hurricane that hit eastern SC in October of 2016. A walkthrough of the plots suggested minimal damage occurred that may have affected the damage data from 2014. Climate data is in the Appendix.

CHAPTER 4

RESULTS

Damage and Mortality

Ice damage related mortality is still experienced 5 years after the 2014 ice storm. Tree mortality increased from 3.4% initial mortality in 2014 directly after the storm to 10.1% cumulative mortality in 2016 and 13.1% cumulative mortality in 2018. This does not include the 5% of trees that were missing (unable to be located and measured but cannot be presumed dead). The following results are based upon cumulative mortality in 2018. For cumulative mortality in 2018, 63.2% of mortality was directly related to ice damages.

Damage category has a significant relationship with mortality ($p < 0.001$). Higher mortality occurs in trees experiencing snap and uprooting than those with crown damage or no damage (Table 2.1). The lowest probability of survival is in the snapped bole category (Table 2.2). Within the damage categories (CD, UR, SB and N), there was no difference in mortality for undamaged trees and those with crown damage ($p= 0.252$) while all other comparisons of damage category were significantly different ($p < 0.001$).

Table 2.1
ANOVA table for type and damage category effects on mortality

Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	p-value
Forest type	2	8	1.34	0.3156
Damage category	3	20	34.2	<.0001
Forest type*damage category	6	20	1.56	0.2095

Table 2.2
Mortality among damage categories. Values with different letters represent significant differences between mortality in damage categories at $\alpha = 0.05$

Damage Category	**Mortality (%)**
Crown Damage	9.3^{a}
No Damage	10.3^{a}
Uprooted	47.4^{b}
Snapped Bole	72.7^{c}

No interaction exists between forest type (upland, bottomland and cypress-tupelo) and damage category (p=0.209). Higher mortality occurs in upland and bottomland communities than cypress-tupelo (16.9% and 12.8% vs 7.8% respectively) although this relationship is not statistically significant among all trees (p=0.316), it is significant among trees >5cm DBH (p=0.0467). Only 4.3% of trees > 5cm DBH died in the cypress-tupelo community, while 11.2% and 15.2% in bottomland and upland. The cypress-tupelo community also had more undamaged trees (59.9%) than bottomland (40.6%) and upland (45.8%).

Lifeform does not significantly affect mortality overall, but significant interaction existed between lifeform and forest type (p=0.013) (Figure 2). When analyzed separately for each lifeform, forest type only affected mortality in winter broadleaf lifeform (p=0.014) where the upland community experienced the highest mortality and cypress community had the least. When analyzed separately for forest type, lifeform only affected mortality in the upland community (p<0.001) where broadleaf lifeforms were more likely to die than deciduous (Table 3). Winter broadleaf trees experienced 22.9% mortality while deciduous trees experienced 10.7%.

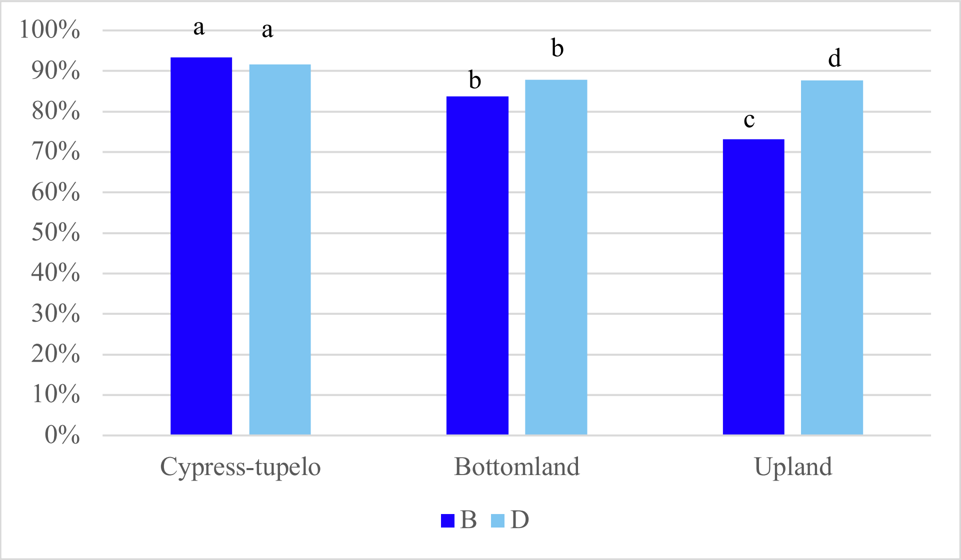

Figure 2 Living trees among forest type and lifeform in Beidler Forest in 2018. B represents both evergreen broadleaf and marcescent trees, and D represents deciduous trees. Values with different letters represent significant differences between mortality among lifeforms within each forest community at α =0.05.

Table 3
ANOVA tables for effect of forest type and lifeform on mortality

Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	p-value
Forest type	2	8	3.23	0.0938
lifeform	1	3443	2.49	0.1146
Forest type*lifeform	2	3443	4.34	0.0131*
Tests of Effect of Lifeform by Forest Type				
Sliced By Type				
Forest type	Num DF	Den DF	F Value	p-value
Bottomland	1	3443	2.42	0.1197
Cypress-tupelo	1	3443	0.16	0.6867
Upland	1	3443	47.29	<.001*
Tests of Effect of Forest Type by Lifeform				
Sliced By lifeform				
Lifeform	Num DF	Den DF	F Value	p-value
B	2	3443	4.26	0.0142*
D	2	3443	1.22	0.2959

Since the upland community had all four lifeforms (evergreen broadleaf, evergreen needle leaf, deciduous and marcescent) and had a significant relationship with mortality in the condensed lifeform categories, the impact of all four lifeforms on mortality was also analyzed for this community separately. No significant relationship was found ($p=.076$) although mortality decreased as winter surface area decreased and was highest in EB (32.3%) followed by EC (31%), M (18.1%) and D (12.7%).

Damage severity was evaluated using derived damage classes in the field (Table 1.2) and higher damage severity leads to a higher likelihood of mortality ($p < 0.001$). Mortality was 8.7% for those with minor damage, 15.8% for moderate damage and 49.9% for major damage. There was also a significant interaction between forest type and damage severity ($p < 0.001$). When analyzed by damage class, forest type only affected mortality in damage classes 1 and 3 ($p < 0.001$). When analyzed by type, damage severity was significant in all forest types (Table 4). Mortality was highest in damage class 3 of the bottomland community and lowest in damage class 1 in the cypress-tupelo community (Figure 3). These results account for random variation due to plots within forest community types.

Table 4

ANOVA tables for the effect of forest type and damage class on mortality

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	p-value
Forest type	2	8	1.61	0.2581
Damage Class	2	3498	137.7	<.0001*
Forest type*Damage Class	4	3498	5.67	0.0002*

Tests of Effect of Type by Damage Class

Sliced by Damage Class

Damage Class	Num DF	Den DF	F Value	p-value
1	2	3498	3.01	0.0495*
2	2	3498	1.13	0.3228
3	2	3498	10.43	<.001*

Tests of Effect of Damage Class by Type

Sliced by Type

Type	Num DF	Den DF	F Value	p-value
Bottomland	2	3498	71.84	<.001*
Cypress-tupelo	2	3498	16.26	<.001*
Upland	2	3498	89.81	<.001*

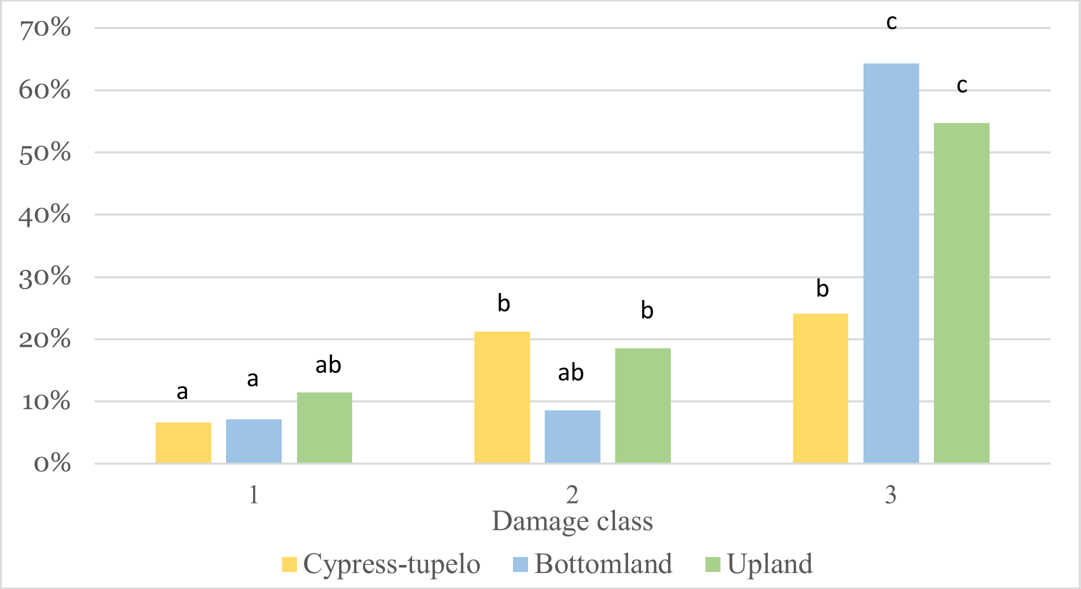

Figure 3 Cumulative mortality in forest types and damage severities at Beidler Forest in 2018 after a severe ice storm in 2014. Values with different letters represent the percent mortality is significantly different between forest types among damage classes at α =0.05. Damage classification is shown in Table 1.2

Diameter size significantly impacts mortality (p<0.001) with small trees being more likely to die than larger ones at 16.1% mortality, compared to 8.1% for medium trees and 2.8% for large. 69.8% of large and 69.3% of medium trees experienced crown damage compared to 30% of small trees. No interaction is present.

Forest type does have a significant impact on mortality (p=0.047) only in trees >5cm DBH with the probability of mortality significantly lower in the cypress-tupelo forest type than bottomland and upland (Table 5).

Table 5 Percent mortality in forest types for all trees and trees > 5cm DBH

	All trees (%)	**Trees > 5cm DBH (%)**
Cypress-tupelo	7.8	4.5
Bottomland	12.8	11.6
Upland	16.9	16.0

In total, 39 different species from 20 families were found in the 11 measured plots, but not all were present in each plot or forest type. After excluding missing trees and families with fewer than 10 individuals present, the 13 most common families were compared. The most resistant families to mortality were the Aquifoliaceae, Cupressaceae, Ulmaceae and Nyssaceae families (Figure 4). The most susceptible families to mortality were the Cornaceae and Pinaceae. The Lauraceae family has the highest overall mortality rate, at 92.7%, but these trees were highly affected by laurel wilt disease. The most overall damaged family was the Fagaceae family, while the least damaged family was the Oleaceae. Damage calculations included missing trees since the damage was assigned in 2014 when all individuals were accounted for.

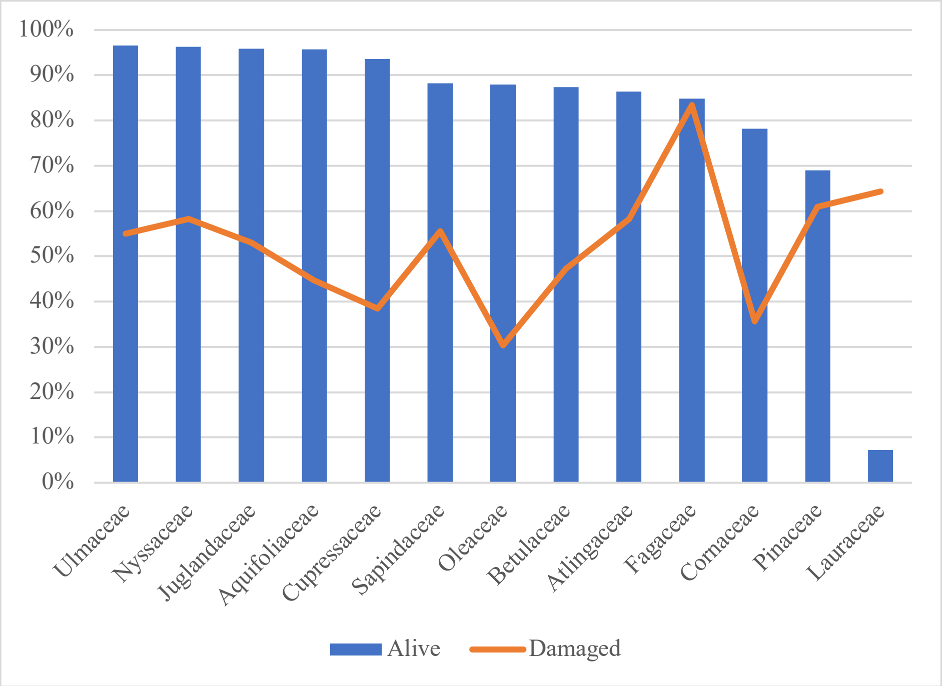

Figure 4 Proportions of living and damaged trees by family in Beidler Forest

Among major species present, *N. aquatica* and *Ilex opaca* Aiton were the most surviving trees, with mortality of only 2.0% and 2.4% respectively. The species with the highest mortality were *Q. laurifolia* and *Cornus foemina* Mill. with 17.3% and 20.0% mortality. The rest of the major species mortality and damage data is given in Table 6.

Table 6 Damage and mortality by species in Beidler Forest. N represents the number of individuals present per species.

Species	**Dead**	**Alive but Damaged**	**N**
Nyssa aquatica	2.0%	57.4%	201
Ilex opaca	2.4%	54.1%	248
Quercus coccinea	3.8%	58.9%	52
Taxodium distichum	6.3%	38.5%	158
Nyssa sylvatica	8.6%	60.8%	70
Ilex decidua	8.7%	22.0%	104
Acer rubrum	10.8%	61.5%	158
Fraxinus pennsylvanica	12.0%	30.0%	734
Carpinus caroliniana	12.6%	47.2%	713
Liquidambar styraciflua	13.6%	58.3%	198
Quercus alba	13.9%	77.6%	72
Quercus laurifolia	17.3%	88.7%	353
Cornus foemina	20.0%	33.3%	60
Pinus glabra	32.7%	58.9%	55
Persea borbonia	97.9%	65.3%	94

Growth

Growth was assessed for all trees using DBH measurements and calculating the mean annual basal area growth after the storm. Damage category, forest type, diameter size, species and lifeform all had a significant impact on growth ($p < 0.001$ for all) while damage severity did not affect growth ($p = 0.461$). Basal area growth differed between damage severities (0.0984 cm^2/year for damage class 1, 0.116 cm^2/year for damage class 2, and 0.040 cm^2/year for damage class 3) although it was not significant.

There was an interaction between forest type and size ($p < 0.001$) where forest type only influenced growth in large ($p<0.001$) diameter sizes. Growth was highest for large trees in the cypress community (Figure 5). An interaction was also present between species and forest type ($p < 0.001$), with type affecting growth only in black gum and cherrybark oak. The highest growth for black gum was in the cypress forest type and lowest growth was in the upland. For cherrybark oak the highest growth was found in the bottomland forest type and the lowest growth was in the upland (cherrybark oak was not present in the cypress community).

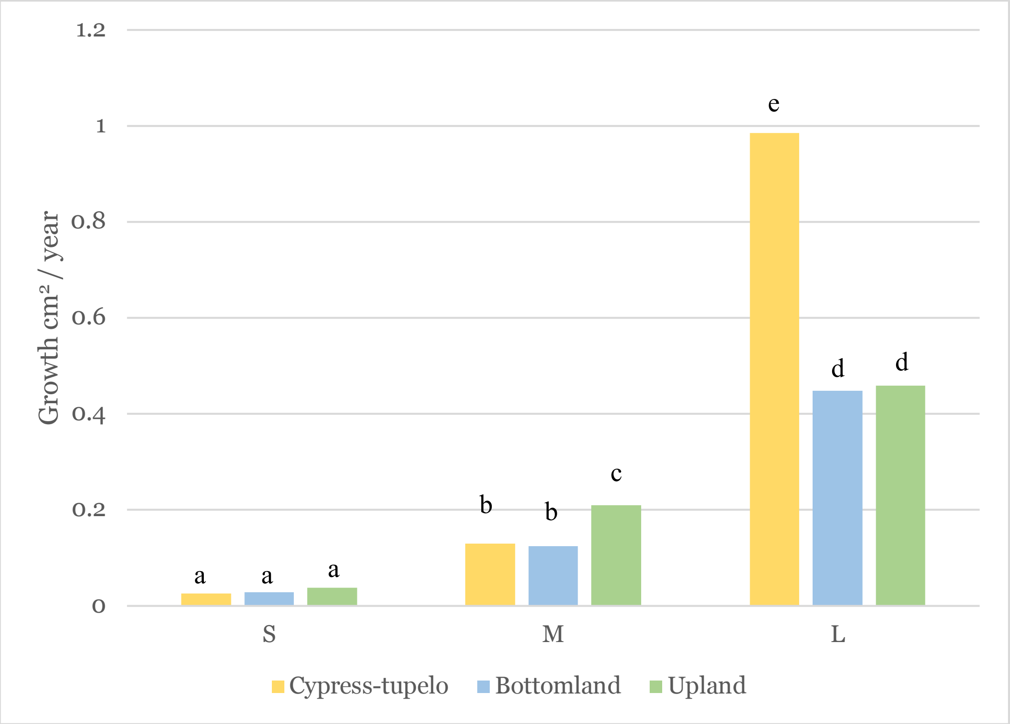

Figure 5 Mean annual basal area growth among forest types and damage classes are compared at Beidler Forest in 2018. Values with different letters represent that mean annual growth is significantly different from sizes and damage categories. Significance is set at α =0.05

The upland community had the lowest mean growth (0.0791 cm^2/year) while cypress community had the highest mean growth (0.174 cm^2/year). Bottomland was 0.138 cm^2/year. Also, broadleaf lifeforms had higher growth than deciduous lifeforms (Figure 6).

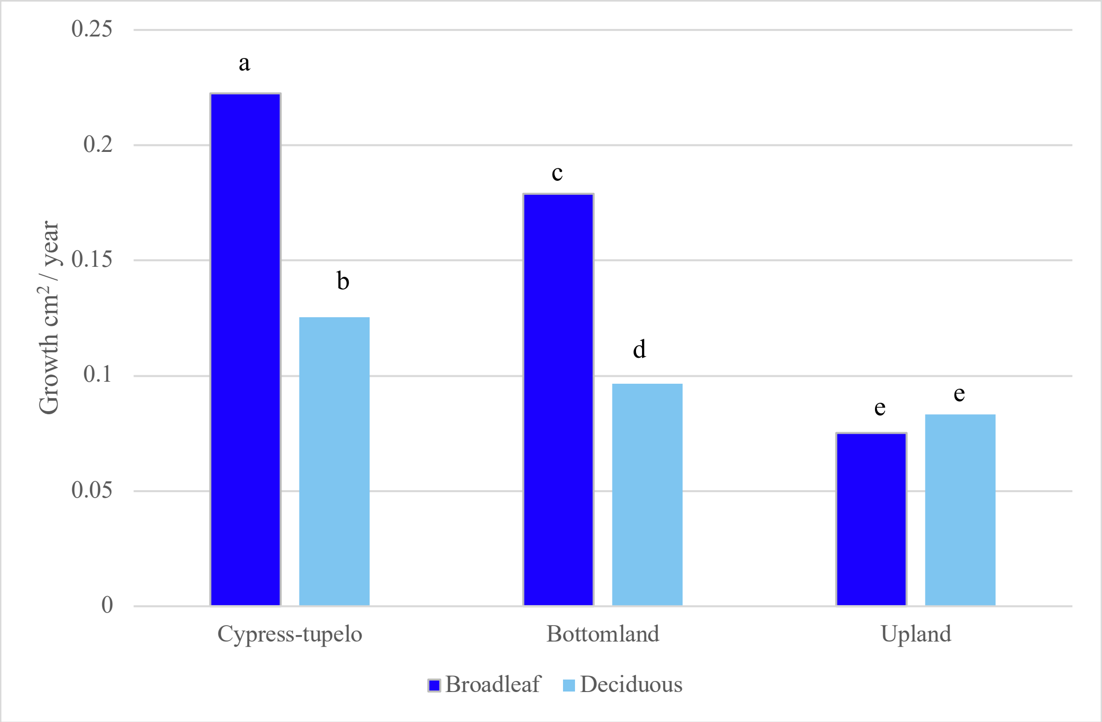

Figure 6 Mean annual basal area growth among forest types and lifeforms are compared at Beidler Forest in 2018. Values with different letters represent mean annual growth is significantly difference between lifeforms within each forest type at α=0.05

Damage category significantly impacts growth (p > 0.001) in a decreasing trend where CD > N > SB (Figure 7). Uprooted trees were excluded because too few had any measurable growth, or imprecision in DBH measurement showed negative growth. Crown damage percentage was also compared to basal area growth, but no relationship was found (p = 0.354).

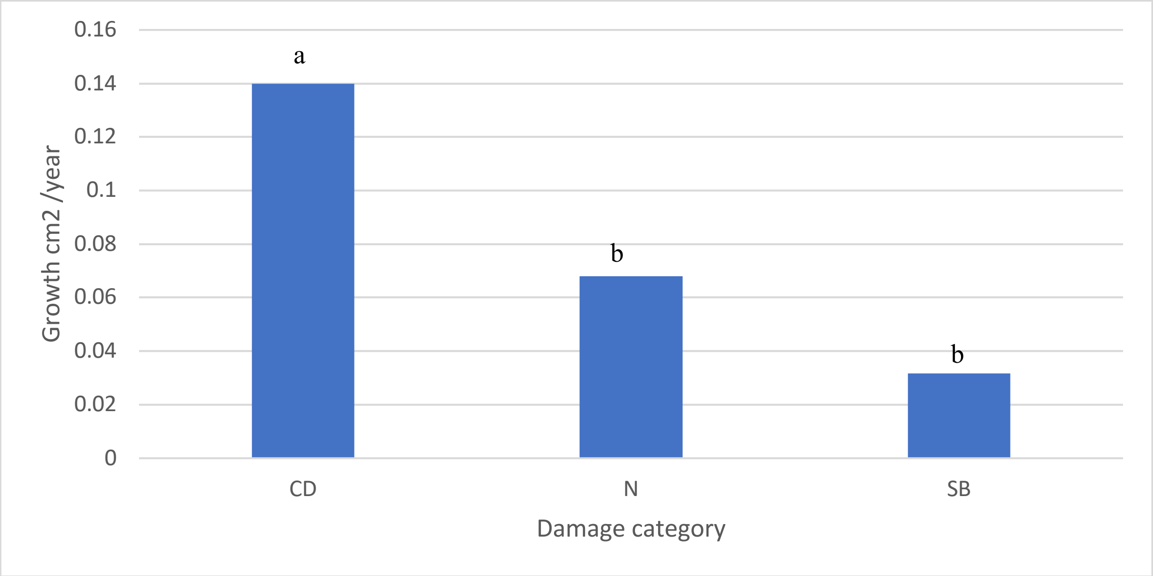

Figure 7 Mean annual basal area growth among damage categories at Beidler Forest in 2018. CD is Crown damage; N is no damage and SB is snapped bole. Values with different letters represent mean annual growth is significantly different between the damage categories at α=0.05

Some trees were cored for analysis. Although visual differences are seen between some of these trees from varying crown damage categories (Figures 8.1 and 8.2), no significant relationship between crown damage percentage and radial growth was found. Neither species nor crown damage class has a significant impact on the log-transformed mean radial growth for the cored trees from 2014-2017 (Table 7).

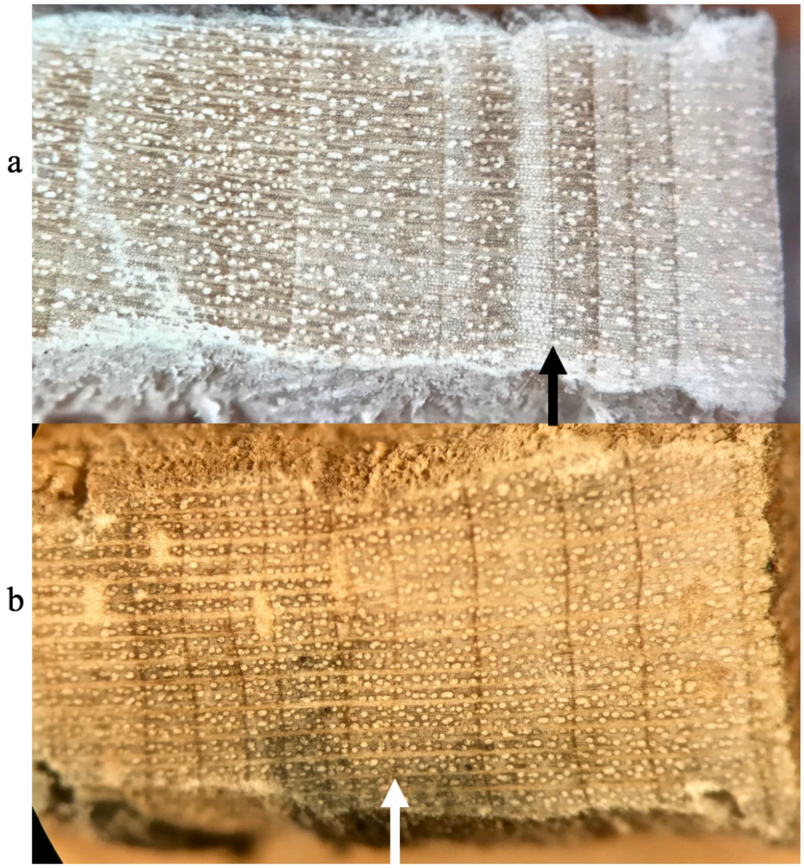

Figure 8.1 *Quercus laurifolia* with high crown damage (a) and *Acer rubrum* with low crown damage (b) are compared. b shows an increase in radial growth after the 2014 ice storm indicated by the arrow, while a shows a decrease.

Figure 8.2 *Nyssa sylvatica* with low crown damage (c) and *Quercus alba* with high crown damage (d). Both show a decrease in radial growth after the 2014 ice storm indicated by the arrow.

Table 7
ANOVA table for crown damage severity and species effects on mean radial growth 2014-2017

Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	P value
crown damage	2	2	0.104	0.902
species	6	6	2.051	0.063
crown damage%*species	12	12	1.267	0.245

Climate

Climate was not found to be significantly different for temperature (p = 0.813) and precipitation (p = 0.917) between the pre- (2010-2013) and post- (2014-2017) storm period as a result of a two tailed two sample t-test. This suggests that the climate is likely not responsible for changes in growth during the study period. Climate data are in the Appendix.

Recovery

Overall, 14.2% of surviving trees are in decline, while 65.3% experienced no change and 20.5% are in recovery since the storm in 2014. The forest type with the most trees in decline is the bottomland community at 18.9%. Interestingly, the bottomland community also has the highest number of recovering trees at 22.2% (Table 8).

Table 8
Recovery status among forest types in Beidler Forest in 2018

	Bottomland	**Cypress-tupelo**	**Upland**
Decline	18.9%	10.6%	14.3%
No change	59.0%	71.9%	64.2%
Recovery	22.1%	17.4%	21.6%

75.7% of undamaged trees had no changes in growth, while only 51.5% of trees with crown damage remained steady in growth (Table 9). In reference to lifeform, winter broadleaf species were 20.5% in decline and 22.2% in recovery, while deciduous trees were only 12.6% in decline and 19.6% in recovery (Table 10). The species with highest recovery rates are *N. sylvatica* 53.6 % and *Pinus glabra* 37.5 %, while those in most decline are *Q. alba* 32.7% and *N. aquatica* 36.9%. Species recovery is reported in Table 11.

Table 9

Recovery status among damage category in Beidler Forest in 2018

	Crown damage	**No damage**	**Snapped Bole**
Decline	21.15%	9.14%	9.09%
No change	51.52%	75.65%	54.55%
Recovery	27.33%	15.21%	36.36%

Table 10

Recovery status among lifeform groups in Beidler Forest in 2018

	Broadleaf	**Deciduous**	**Evergreen Conifer**
Decline	20.5%	12.6%	5.9%
No change	57.3%	67.8%	52.9%
Recovery	22.2%	19.6%	41.2%

Table 11
Recovery status among major species in Beidler Forest in 2018

Species	Decline	Recovery
Acer rubrum	14.6%	30.1%
Carpinus caroliniana	11.2%	20.9%
Cornus foemina	0.0%	5.4%
Fraxinus pennsylvanica	6.1%	12.5%
Ilex decidua	3.4%	11.4%
Ilex opaca	11.7%	11.2%
Liquidambar styraciflua	20.3%	22.0%
Nyssa aquatica	36.9%	29.2%
Nyssa sylvatica	17.9%	53.6%
Persea borbonia	100.0%	0.0%
Pinus glabra	6.3%	37.5%
Quercus alba	32.7%	21.2%
Quercus coccinea	23.3%	25.6%
Quercus laurifolia	26.0%	33.2%
Taxodium distichum	17.6%	24.3%

Diameter size had a significant impact on recovery ($p = 0.028$) with large trees having the highest probability of decline. 42.2% of large trees were in decline, with only 31.5% medium and 7.7% small. 47.4% of large trees were also in recovery, compared to 40% medium and 13.5% small. As trees grow larger, their likelihood of both decline and recovery increases. Small trees are the most likely to experience no change (78.79%).

No significant relationship with recovery status was found between forest type ($p=0.535$), damage category (only CD and N) ($p=0.131$), or lifeform ($p=0.158$). Not enough trees were present to analyze the impact of damage severity on recovery status since many trees in categories 2 and 3 had already died, and similarly not enough trees were present in damage categories of SB and UR to analyze recovery.

Forest Health

Due to the height variation of individual trees, the visual health data was skewed toward smaller trees since visual estimations of foliar damage were difficult for taller trees. Overall, 6.1% (184 of 3032) of surviving trees had some sort of implication to their health. <2% of these trees were specifically insect and fungus related. The other category included bark and foliar problems. The most health problems were found in damage class 1 at 5.3% of that category. Moderate damage had 4.6%, while severe only saw 2.7% since most of those trees had already died. The bottomland community had the fewest records of tree health problems, at 2.8%. The cypress forest type had 7.7% and bottomland 4.2%. In reference to lifeform, 5.7% deciduous, 3.4% evergreen broadleaf and 3.2% marcescent trees had health problems.

CHAPTER 5

DISCUSSION

Since ice storms can be expected in the southeast every 5-15 years, impacts on forest health may be severe. Since ice storms are mostly studied in the north and in pine plantations, little is known about the long-term impact of ice storms in naturally occurring forests in the southeast. This study fills a knowledge gap on the effects of ice storm damage on growth and mortality in southern forests, especially related to damage category, diameter size, lifeform and damage severity.

Damage and Mortality

Ice storm damage can have lasting effects on the mortality of southern forests. Tree mortality increased by at least 10% four years after the ice storm hit. The mean annual mortality for a forest in the southeastern US is less than 1% (Klos et al 2009).

Tree mortality from damage was dependent upon the category of damage sustained from the ice storm, and the forest type in trees > 5 cm DBH. Root-sprung trees and snapped trees were more likely to perish over time than those with crown damage due to the loss of water and nutrient uptake ability in the case of those uprooted, and loss of photosynthetic area for those with snapped bole. Crown damage, the most common type of damage sustained from an ice storm, does not impact the probability of mortality. Trees with crown damage are capable of recovering in four years after a storm event.

Forest type due to moisture gradient had a significant relationship with mortality because of the difference of species and their traits. The cypress-tupelo community showed to be most resistant to ice storm damage because of dominant species such as *T. distuchum* showing storm resistant traits such as narrow, symmetrical crowns, deciduous leaves and strong buttressed stems. The dominant species in the bottomland and upland forest types such as *Q. laurifolia* had qualities associated with higher susceptibility to ice damage such as asymmetry, winter phenology with larger surface area (marcescent and evergreen broadleaf trees) and sprawling crowns. There are exceptions to this rule, however, since other dominating species in the bottomland and upland communities should be resistant to ice damage and include *Carpinus caroliniana* and *Ilex opaca*. The cypress community also has fewer species (10) than the bottomland (16) and upland (23). Mortality in the drier forest types may largely be from their non-dominating species, those that are most susceptible to ice storms. The ice storm may serve as the periodic successional disturbance necessary to replace these susceptible species with more resilient ones. Differing stand conditions or other factors may also be involved, and more research is needed to understand why the cypress community is most resistant to ice storm mortality.

The forest community may also respond to disturbances as a function of the species that occupy the site and their life history strategies. The cypress-tupelo represents a community with highly resistant species that sustained low damage and mortality and very little recovery response (Table 7). This may be due to the abundance of trees here relying on stress tolerating life history strategy, where long life is valued (Wonkka et al

2013). The upland type had significant damage and mortality and high response following the ice storm and represents a community resilient to disturbance. The bottomland hardwood community may be the most susceptible community to disturbances with high damage and low response. These communities may have more competitive species where recovery is important, but high damage is sustained. The results indicate that cypress-tupelo community is the most resistant to ice storms, which may help explain the dominance of this community in waterlogged sites across the coasts of the Atlantic Ocean and the Gulf of Mexico where ice storms may occur.

Trees with broader winter foliage have a greater surface area, which allows them to be more susceptible to injury from ice and wind unless their wood is exceptionally strong (Rogers 1923, Croxton 1939). Lifeform was designated based on winter foliage (winter broadleaf including marcescent and evergreen broadleaf, or deciduous) and had a significant impact in the upland community, which was the only community where evergreen broadleaf trees were common (346 individuals). Evergreen broadleaf trees were not found in the cypress community and only 35 individuals were found in the bottomland community. Since the evergreen broadleaf lifeform has the largest surface area, more ice can accumulate on those trees during an ice storm, which increases weight and can lead to higher damage related mortality. The resulting mortality in the upland community was also consistent with results from Wang et al (2016) where lifeform significantly impacted mortality and had a negative correlation with surface area, where EB > EC > M > D.

Logically, as damage severity increased in Beidler Forest, tree mortality also increased. Trees are more likely to die from severe damage than minor damage. Interestingly, forest type had an impact on mortality when damage severity was minor or severe. In minor damage, the upland community was most likely to experience mortality while bottomland and cypress were the same. For severe damage, bottomland and upland forest types were far more likely to experience mortality while mortality in the cypress type was consistent with that of moderate damage. The bottomland type had the highest mortality from severe damage, which means this forest type may have a higher threshold for damage related mortality, but once that is passed it experiences high mortality rates. The cypress community showed the most resistance to mortality at high damage severity (Figure 3).

The major species with the highest ice related mortality (excluding *P. borbonia* due to the spread of laurel wilt disease leading to over 96% mortality) were *Q. laurifolia, Q. alba* and *C. foemina. Q laurifolia* is a semi-evergreen or marcescent species with a broad crown. These two traits alone can cause *Q. laurifolia* to experience high ice accumulation and stress on the limbs. It is susceptible to breakage although it has a symmetrical, dense and oval-shaped crown. *C. foemina* is a deciduous tree but with a broad branching habit causing high breakage potential. *Q. alba* is deciduous but has an irregular spreading crown of moderate density. Both oak species also have the highest percentage of damage among living individuals for the same reasons. *I. decidua and F. pennsylvanica* have the lowest percentage of damage among living individuals, due to their deciduous lifeforms, symmetrical crowns and resistance to branch breakage. Species attribute data was compiled in Wang et al 2016.

I. opaca and *N. aquatica* were the most surviving. This is interesting because of their opposing strategies of surviving ice damage. American holly has a symmetrical, dense, and conical crown and is resistant to branch breakage which leads to its high survivability during ice events. *N. aquatica* is deciduous, with low crown density and an open crown, allowing ice to pass through instead of accumulating on its surfaces.

A positive correlation with diameter size and damage was found, consistent with Boerner and Kooser (1988), Lafon (2004) and Pisaric et al (2008). Smaller trees are more likely to die from severe damage as consistent with Lafon (2004) and were consistent in mortality and damage among forest types. Other studies found that both small trees and large trees are the most surviving (Edwin and Everham 1996, Rebertus et al. 1997, Proulx and Greene 2001) with intermediate sized trees experiencing the highest mortality, which was not replicated in this study. Future research could include tree height as an additional measure of size to compare with damage.

Although topography has shown to affect tree damage and mortality from ice storms (Warrilow and Mou 1999, Lafon 2004, Seischab et al 1993) in mountainous regions, Beidler Forest is generally flat. Therefore, topography data were not collected in the study but can be important in understanding ice storm damage in areas with more varied terrain.

Growth

Diameter size and growth rate had a positive correlation in this study, which is consistent with Bragg et al (2010). A significant negative relationship between growth and damage severity was also found several studies (in Bragg et al 2003, Pisaric et al 2008) but was not found to be significant in this study. Surprisingly, the damage category impacted growth in a positive way with the highest annual growth rates found in trees that sustained crown damage in all forest types. This is an unexpected result but may be due to microclimates in ice storms. Bennet (1959) noted that ice storms often have microclimate cells that lead to high destruction in small forest areas. This variation is also due to localized forest traits. The result of high growth in crown damaged trees may be due to the probability of these trees being in the vicinity of other crown damaged trees, which can open up the canopy and increase sunlight availability. This change in light abundance must have been large enough to overcome the loss of photosynthetic area from crown damage and increase growth in these trees. Crown damage percentage was not found to have any relationship with annual basal area growth.

Changes in more precise radial growth were analyzed through cores. Like with basal area growth, no significant impact on radial growth was found from varying crown damage intensity. Smith and Shortle (2003) found decreased radial growth after an ice storm in several species correlated with increased crown damage. Although species differences were accounted for, no correlations were found in this study. Some cores showed visual decreases in growth after the storm, and some increased. Due to the high percentage of trees with crown damage (41.81%), the amount of light intercepted by the canopy changed dramatically after this ice storm. Increases in growth could be due to damaged or dead surrounding trees opening up resource gaps through sunlight, water or nutrients. The sample size for cored trees was smaller than anticipated, which may have impacted the results. The limited sample size was due to a low number of alive trees with severe crown damage at a suitable diameter size to core.

The detection of crown damage may be difficult after a storm, as estimations are made without seeing the intact full crown, only with what is left. Dense canopies can also make the estimation of crown damage difficult particularly for large trees over 100 feet in height since the canopy of a single tree may overlap with other trees. This can lead to less precise estimations of crown damage.

When analyzing growth, measuring the diameter at breast height can be an imprecise representation of actual tree growth over time. When measuring trees in wetlands such as swamps, this can be due to changes in water level which may change the appearance of DBH to the measurer, or bark growth. For large buttressed trees, the true DBH can be difficult to obtain since it must be measured above the buttress, with a ladder in deep water. Nails were placed at the location of DBH measurement for buttressed trees in this study, which should have been helpful. In the future, installing a dendrometer on each tagged tree would be recommended for monitoring diameter growth over time, but may be impractical due to a large number of trees in the study.

Recovery

Assessing long term changes in growth showed that while the majority of trees experience no changes in growth rate as time goes on, more are in recovery than decline. Large diameter trees were the most impacted by the ice storm for growth changes, and this may be due to their position in the canopy. Large diameter trees are likely dominant canopy trees, intercepting the most ice during a storm event. They also will experience the most wind during the ice storm. Changes in canopy light due to crown damage after an ice storm may allow some trees to take advantage of the change in light availability. Since large trees also grow more each year, more minute changes in growth were detectable compared to smaller trees. Living small trees were almost entirely unaffected due to their position in the canopy providing protection, low growth rates and general stem flexibility. Canopy position should also be evaluated in the future along with diameter size.

Forest health

Anything that predisposes a tree to decreased vigor would increase ice damage and mortality, so evaluating this factor both before and after storm events would be beneficial in future studies.

Forest health was difficult to monitor at Beidler Forest due to the size of some trees and the density of the canopy. Recorded forest health data included any ailments observable from the forest floor and may have omitted foliar abnormalities in larger trees. A more thorough examination of forest health may be beneficial in the future to assess the exposure to insect, fungus and disease after ice damage. The data can only imply that forest health problems are more common in lower damage classes since the higher damage class individuals had a higher probability of dying.

It is difficult to isolate factors that affect ice storm damage when they are so interconnected. Species have several morphological and intrinsic factors affecting susceptibility and can confound with other variables such as size and lifeform.

CHAPTER SIX

CONCLUSION

Although ice storms are not studied frequently in the south, their periodical occurrence can have lasting impacts on forest mortality. Four years after the February 2014 ice storm, trees in Beidler Forest are still experiencing damage related mortality and some are still experiencing declining growth rates. The cypress-tupelo forest type is the most resistant to ice storm damage, with the lowest proportion of mortality and damage. The highest mortality was found in severe damage categories (such as snapped bole and uprooted) and high damage severities. Small diameter trees had the highest probability of mortality. Species resistant to ice storm will persist as ice storms occur, and those that are more susceptible will decline in frequency as long as these storms continue to occur. Although these storms are only expected about every 5-15 years in the southeast, their impacts can have long-lasting effects on the health of these forests.

APPENDIX

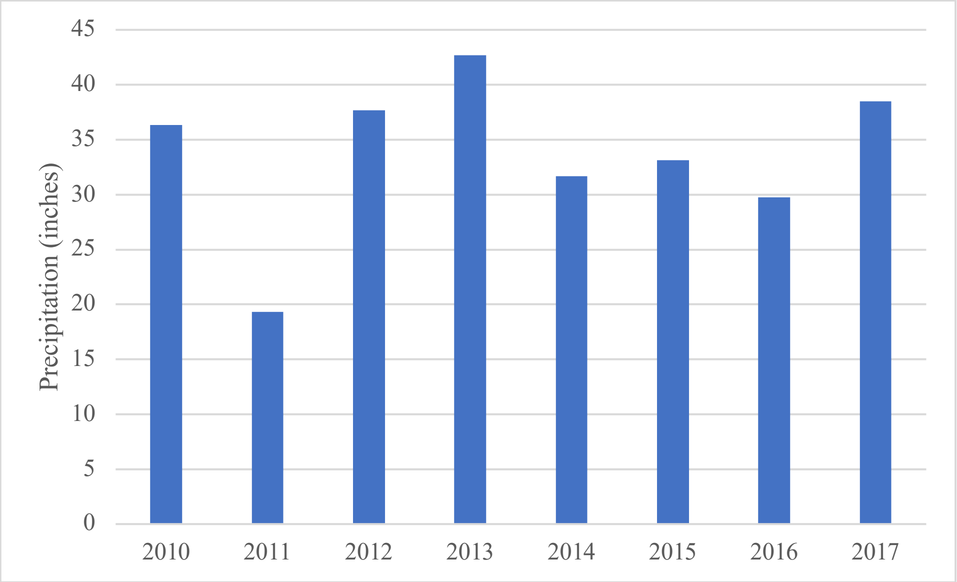

Figure 9 Total annual growing season (April-September) precipitation near Beidler Forest

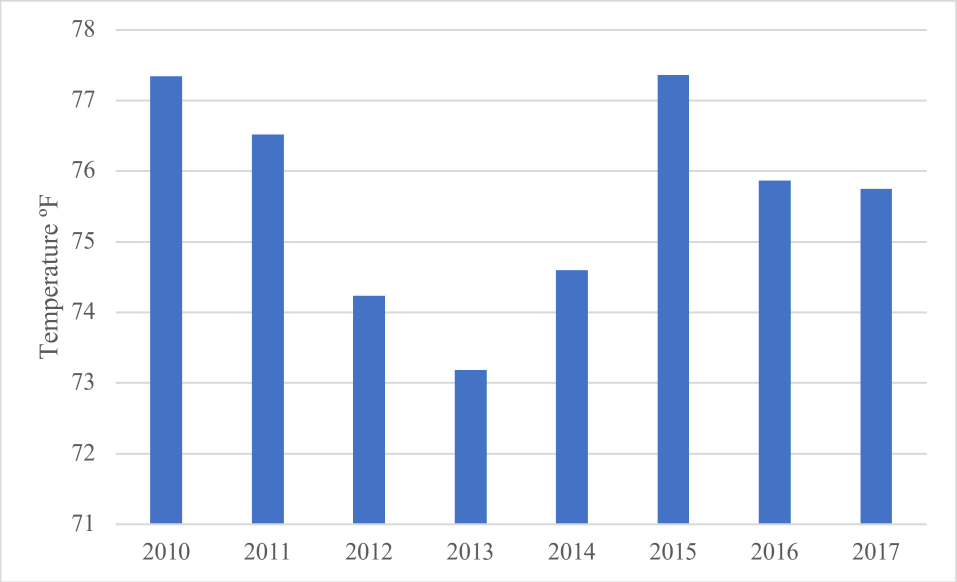

Figure 10 Average annual growing season (April-September) temperature near Beidler Forest

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