OAK REGENERATION PATTERNS AND STAND DYNAMICS IN BURNED AND UNBURNED FOREST STANDS IN SHAWNEE STATE FOREST, OHIO, USA

A Thesis
by
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Abstract

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The primary goal of this thesis was to compare oak (*Quercus spp.* L.) regeneration, canopy class distributions, and forest stand dynamics following a glaze ice storm to *Quercus spp.* regeneration, canopy class distributions, and forest stand dynamics following a severe wildfire. Additionally, tree ring research was used to examine forest disturbance history of the study site from 1930-2001 and to analyze the growth-climate relationship of *Quercus spp.*

Quercus spp. regeneration was higher in the burned stands than the unburned stands. The dominant canopy trees of both stands were *Quercus* *spp.* However, the suppressed and intermediate trees were mostly red maple (*Acer rubrum* L.), tulip poplar (*Liriodendron tulipifera* L.), and black gum (*Nyssa sylvatica* Marshall). This indicates that fire improved the competitive status of *Quercus spp.* regeneration, whereas the ice storm improved the competitive status of shade-tolerant species. Age-diameter data revealed that *Quercus spp.* has not been able to successfully recruit to an intermediate canopy class since the 1940s. The disturbance history revealed several decades where disturbances were frequent, and other decades when disturbances were absent. However, there were no stand-wide disturbance events. Most events were minor (>25% increase in radial growth) disturbances, but there were also several major (>50% increase in radial growth) disturbances. These disturbances were unable to facilitate *Quercus spp.* regeneration. Analysis of the climate-growth relationships revealed that *Quercus spp.* were most responsive to drought conditions. Also, the growth-climate relationships of *Quercus spp.* showed the highest responses were in the early period (1913-1945) during open-stand conditions following logging. Growth-climate relationships were lower in the late period (1979-2011) which suggested a temporal shift in climate response.

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Dedication

This thesis is dedicated to my grandmother, Elizabeth Brown.

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Chapter 1: Introduction

1.1 Decline of Oak Regeneration

Throughout the 20th century and into the present there has been a decline in the frequency of white oak (*Quercus alba* L.) and other oak species (*Quercus spp.*) to reach the advance regeneration stage of forest development within eastern deciduous forests (Abrams 1992, Dyer 2001, Abrams 2003). Although *Quercus spp.* can regenerate following clear-cutting and subsequent timber harvesting (Potzger and Friesner 1934), they are unable to reach the advance regeneration stage and recruit to a mature size class because they are lacking a competitive advantage against more mesophytic and shade tolerant species such as maples (*Acer spp.* L.) and beech (*Fagus grandifolia.*) (Lorimer 1984, Nowacki and Abrams 2008). This has led to an increase in maple and beech abundance, a phenomenon termed “mesophication” by Nowacki and Abrams (2008 pp. 123). *Quercus spp.* seedlings require more light than mesophytic species following disturbance events to reach larger size classes (Lorimer et al. 1994).

While many forest disturbance events are responsible for allowing light to reach the understory and altering growing space within the forest, fire is capable of altering forest composition more than any other event (Oliver and Larson 1996, Frelich 2002). Forest fires are disturbance events that burn the forest understory and in severe cases the overstory. Fires not only burn vegetation, but they alter the soil characteristics and local nutrient cycling beneath the forest floor (Dress and Boerner 2001). Fires can spread most quickly and intensely on xeric sites when the leaf litter is dry. Fire intensity refers to the heat a fire is capable of emitting, typically measured in British Thermal Units (BTU). Fire severity is the damage and mortality resulting from a forest fire. Fires spread slower and less intensely on mesic sites when the soil is wet. The microsite-specific fuel loads and leaf litter content can create a myriad of localized fire intensities and severities even within small watersheds (Trammell et al. 2004). The variability of microsite fire intensities within the landscape determines the severity of the fire. Additionally, fire frequency affects the intensity, severity and resulting forest regeneration. An alteration of fire frequency changes the effects of forest fires on the landscape (Boerner et al. 2004, Green et al. 2010, Arthur et al. 2012, Greenberg et al. 2012).

The fire regime of the Central Hardwoods Region (CHR) has undergone significant changes during the past 400 years (Brose et al. 2001). Prior to European settlement, fire was periodically ignited by Native Americans (Delcourt and Delcourt 1997) to drive wild game, aid in hunting, help with navigation, and many other advantageous tribal practices (Williams 1989). Also, fire was naturally ignited by lightning and able to spread at low intensities throughout forests without being hampered by human development, agriculture, and roads (Banks 1960). Fire history research typically involves the use of lacustrine charcoal sediment (Clark and Royall 1995, Delcourt and Delcourt 1997) or fire-scarred tree cross sections (Shumway et al. 2001, Swetnam and Brown 2011). Fire-history studies throughout the United States suggest a marked suppression of fire since the late 19th century (Abrams 1985, Guyette and Cutter 1991, Sutherland 1997, Shumway et al. 2001, Cocke et al. 2005, Allen et al. 2008). Following European settlement, the disturbance regime and subsequent fire frequency throughout the eastern deciduous forests was significantly altered (Abrams 1992, Sutherland 1997, Brose et al. 2001, Shumway et al. 2001, Hutchinson et al. 2008).

The decline of *Quercus spp.* regeneration in the mixed-oak forests of the eastern United States can be attributed to the 20th century suppression of periodic low-intensity fires (Abrams and Downs 1990; Abrams and Nowacki 1992; Brose et al. 2001; McEwan et al. 2007) and is referred to in the literature as the "oak and fire" hypothesis (McEwan et al. 2011 pp. 244). This decline can be attributed to causes other than fire suppression, which led McEwan et al. (2011) to propose the "multiple interacting ecosystem drivers hypothesis," (MIEDH). The MIEDH suggests that the decline of *Quercus spp.* regeneration also can be attributed to the chestnut blight (*Cryphonectria parasitica* Murrill.) of the 1930s (Hart et al. 2008, van de Gevel et al. 2012), extinction of the passenger pigeon (*Ectopistes migratorius* L.), a large increase in white tailed deer (*Odocoileus virginianus*), and changing drought dynamics that promoted mesophytic species (McEwan et al. 2011). Several management objectives and considerations such as the forest disturbance regime must be addressed for fire to help improve *Quercus spp.* regeneration (Arthur et al. 2012).

1.2 Forest Disturbance Regime in the Central Hardwoods Region

Forest disturbances are events that alter the growing space, resource availability, and biophysical characteristics of a forest (Oliver and Larson 1996). The disturbance regime of any forest ecosystem includes the combination of events, their severity, their frequency, their seasonality, and organic/inorganic chemical characteristics (Watt 1947, Busing 1995, Oliver and Larson 1996, Frelich 2002, Woods 2004). Forest disturbance events typically result in tree injury or mortality which alters the growing space and light availability within a forest (Oliver and Larson 1996, Frelich 2002). Disturbance events are important drivers of forest succession (Clinton 1994) and biodiversity (Loehle 2000). Examples of forest disturbance events include glaze ice storms (Whitney 1980), forest fires (Fule et al. 2005), insect outbreaks (Swetnam et al. 1985), acid deposition (Haines et al. 1980), and high wind events (Knapp and Hadley 2011). Forest disturbance events such as windstorms can occur in various forest environments, but their frequency and magnitude are specific to particular disturbance regimes and respective individual ecosystems (Watt 1947). While fire has been shown to be more frequent in forests of the arid western United States (Fule et al. 2005, Swetnam and Brown 2011) than it is in the eastern United States (Sutherland et al. 1997, Shumway et al. 2001) it is still a natural component of the forest disturbance regime in the CHR. Fire history research has shown that fires occur periodically with predictable return intervals (Sutherland 1997). Other disturbances can occur at random intervals without predictable return intervals.

Glaze ice storms occur at random intervals, resulting in widespread tree mortality, and damage to the canopy (Lemon 1961, Lafon et al. 1999, Weeks 2009). The glaze ice storm is one of the most severe natural disturbance events in the CHR. Glaze ice storms subject the landscape to a wide variety of damage severity. They exhibit topographic (Lafon et al. 1999, Stueve et al. 2007), species specific (Smolnik et al 2006), and hydrologic (Millward et al 2010) damage heterogeneity across the landscape. Glaze ice storms coat the stems of trees and woody shrubs with ice (Lemon 1961). The weight of the ice snaps large and small stems and uproots many trees (Lafon 2004). Damage to the forest canopy from the ice storms can be severe. Lafon et al. (1999) found 30%-60% of basal area was removed during an ice storm in 1994 in southwest Virginia.

Dendroecological analysis suggests that most trees are subject to declined ring widths in years following ice storm damage, while others can show an increase in radial growth due to decreased competitive pressures (Lafon 2002). When dominant canopy-forming trees lose limbs to a glaze ice storm, the intermediate and suppressed trees can absorb more light in years following the storm. The increase in light enables the trees to allocate more resources to growth. Although ring width variations do not directly represent primary growth the of the forest stems, they do provide a relative scale to understand species-specific responses to ice storm damage (Smolnik et al 2006). Smolnik et al. (2006)

also noted that the species showing signs of recovery were those that were able to generate more epicormic branches following severe pruning due to glaze ice, which favored tulip poplar (*Liriodendron tulipifera* L.) recovery in the forests of Delaware. Like other disturbance events, ice storms tend to impact select species within the forest.

The different damage patterns influence the species assemblages that recover following the ice storm. The influence of aspect on glaze ice storms results in greater mortality and canopy damage on eastern aspects than on western aspects (Warrillow and Mou 1999, Lafon 2007, Stueve et al. 2007). The damage difference between aspects has a considerable impact on the species compositions even within a small watershed (Lafon 2004). Even though glaze ice storms influence forest compositions, they cannot be actively altered by forest managers to promote selected species regeneration. Their frequency, intensity, and severity are naturally determined. However, forest managers can alter other disturbance events such as prescribed fire and selective logging to promote the regeneration of selected species.

1.3 Prescribed Fire and Oak Regeneration

Prescribed fire has been shown to alter forest compositions. Like ice storms, select species can respond with greater growth and regeneration rates than others. Studies in the CHR suggest that prescribed fire improves white oak regeneration (Arthur et al. 1998, Brose and van Lear 1998, Blankenship and Arthur 2006, Iverson et al. 2008, Brose 2010, Hutchinson et al. 2012a, Hutchinson 2012b). Several studies have applied prescribed fire to forest stands to compare oak regeneration before and after the treatments (Hutchinson et al. 2005). Following a prescribed fire, the density of all seedlings and saplings is significantly reduced in the understory (Hutchinson 2005). Within the understory *Acer rubrum* seedling survival is less than that of the *Quercus spp.* following prescribed fire (Green et al. 2010). *Quercus spp.* is given a slight competitive advantage because it is able to resprout quicker and incur less damage from prescribed fires than mesophytic species such as *Acer spp.* and *Fagus spp.* (Brose and van Lear 1998). During the spring growing season after the fire, soil temperatures increase quicker than unburned sites (Iverson and Hutchinson 2002). The acorns from *Quercus spp.* trees that occupy the seedbank and their fine root biomass from that survive fire are thus able to initiate growth earlier in the growing season than the *Acer spp.* (Dress and Boerner 2001).

Studies of the effects of fire combined with anthropogenic disturbance events that cause canopy gaps are limited to recent research (Iverson et al. 2008). The first study to compare *Quercus spp.* regeneration in natural canopy gaps that were subjected to prescribed fire to natural canopy gaps that were left unburned found that prescribed fire promoted *Quercus spp.* regeneration (Hutchinson et al. 2012a). Other studies have applied shelterwood timbering combined with prescribed fire to promote *Quercus spp.* regeneration. Fire concurrent with other disturbances is important for *Quercus spp.* regeneration (Brose and van Lear 1998, Hutchinson et al. 2005). Disturbances that remove portions of the canopy increase light availability to the understory which increases the growth of suppressed trees. Openings within the canopy are necessary for understory recruitment to the canopy and increase the effectiveness of prescribed fire (Hutchinson et al. 2005).

1.4 Canopy Gap Dynamics

Canopy gaps are openings within a forest canopy caused by disturbance events and individual tree mortality that allow light to reach the apical meristems of the understory trees and the lateral meristems of the overstory trees (Runkle and Yetter 1987). Canopy gap size is highly variable and influenced by disturbance type and age structure of the forest stand. Once light reaches the respective portions of the trees the canopy gap begins to close laterally from the overstory trees and apically from the understory trees (Runkle 1985). The rate of canopy gap closure is dependent on the gap size and forest productivity (Dickinson et al. 1993). Canopy gap closure occurs in one growing season in small gaps in productive environments, but takes decades in large canopy gaps in less productive environments (Runkle 1985). Because seedlings and saplings in the forest understory require light to recruit to larger size classes, canopy gap formation helps catalyze their accession toward the overstory. Canopy gaps are widely studied because their compositions are indicative of the future forest overstory and they exhibit future forest compositions of a particular stand (Barden 1979, Barden 1981, Runkle 1981, Runkle 1985, Runkle and Yetter 1987, Hart and Kupfer 2011).

Canopy gaps yield different physiological contributions to trees within a gap relative to their age, diameter, position within the gap, and size class (Barden 1979, Canham 1988).

Following canopy gap formation, understory trees allocate increased energy toward apical meristems (Runkle and Yetter 1987) and dominant overstory trees allocate increased energy toward lateral meristems due to the amount and direction of increased light availability (Canham et al. 1990). The increase in light availability increases the photosynthetic rate of the trees and results in greater amounts of carbohydrates in both the understory and overstory trees (Montgomery and Chazdon 2002). The carbohydrates are used to increase the rate of radial (secondary) tree growth. All tree species exhibit different growth responses relative to gap formation characteristics. Tree species' response to gap formation varies with seasonality, topography, disturbance type, mortality of gap forming species, gap area, and collateral mortality (Hart and Grissino-Mayer 2009). Understory and overstory trees are capable of exhibiting a significant increase in radial growth for over five years following canopy gap formation (Rubino and McCarthy 2004).

1.5 Forest Disturbance History

Release events can be used to reconstruct forest disturbance history (Lorimer 1980). Widespread release events throughout a forest stand are indicative of disturbance events and can be analyzed to determine the disturbance history of a forest stand (Lorimer 1980, Hart et al. 2011). Release events enable dendroecologists to date the year of canopy gap formation and canopy accession dates (Black and Abrams 2003, Speer 2010, Buchanan and Hart 2011). Radial growth release patterns between trees in a forest stand can identify canopy gap ages. Releases also can be used to identify years of stand-wide (>25% of the tree ring series detects a disturbance event) disturbance events (Nowacki and Abrams 1997, Black and Abrams 2003, Rubino and McCarthy 2004) such as ice storms (Lafon 2004), windstorms (Knapp and Hadley 2011), and selective diseases (van de Gevel et al. 2012). The analysis of all the stand-wide forest disturbance events within a forest is referred to as the disturbance history (Lorimer 1980). Trees exhibit differential release timing, magnitude, and duration following disturbances (Canham 1989, Hart et al. 2012). The disturbance history of a forest captures the frequency and relative severity of disturbance events within a stand. The frequency of these events helps to inform land managers about how often to expect particular disturbance events and how they will affect different tree species (Lorimer 1980).

1.6 Forest Succession

Forest succession is the term used to describe the change in forest compositions, age-structure, and stand dynamics over time (Shugart and West 1980). Forest succession patterns are affected by disturbance events (Henry and Swan 1974). All species within the forest have different tolerances for drought, shade, and disease. Forest disturbances favor some species and injure other species. Some shade intolerant species such as *Quercus spp.* and *Liriodendron tulipifera* require high light and are able to establish in open-canopy or deforested areas to initiate forest regeneration following a disturbance (Boring and Swank 1984). However, once the canopy is established and available soil moisture becomes higher, the early successional trees become competitively overwhelmed by mid-successional trees.

The early successional trees do not become completely eliminated (Oliver and Larson 1996); they establish less frequently following the establishment of the mid-successional trees (Egler 1954). Mid-successional trees are able to dominate the canopy for much longer periods of time and are typically more shade-tolerant than the early successional species (Barden 1981). Late-successional trees that replace the mid-successional are even more shade tolerant (McCormick and Platt 1980). Late-successional trees are often replaced by mid-successional trees following forest disturbances (Barden 1979). Disturbances can change the number and species of trees occupying a particular growing space at all phases of succession. When disturbances result in tree mortality and significant pruning of scaffold limbs, such as in the case of the ice storm (Lafon 2004), new growing space becomes available. The newly-formed available growing space in a forest is referred to in the literature as a canopy gap (Bray 1956, Runkle 1981, Young and Hubbell 1991).

1.7 Goals of this thesis

This project compares regeneration, canopy class distributions, and basal area between unburned canopy gaps and burned stands in Shawnee State Forest, Scioto County, Ohio. There has not been a study that compared regeneration within a burned forest stand to canopy gaps within an unburned portion of nearby stands until Hutchinson (2012a). This is important because canopy gaps are fundamental points where regeneration takes place within a forest (Barden 1981, Runkle 1981, Hart and Kupfer 2011). Additionally, this project analyzes long-term forest stand dynamics by examining the age-diameter relationship, disturbance history, and growth-climate relationship in Shawnee State Forest. This thesis will provide information about the structure, age, and future succession of Shawnee State Forest as it recovers from the glaze ice storm of 2003 and the wildfire of 2009.

1.8 Research Questions

1. How do the seedling and sapling regeneration dynamics in burned and unburned stands differ?

2. How do the canopy class distributions differ between burned and unburned stands?

3. Is there a difference in the distribution of basal area between classes and species in burned and unburned stands?

4. How has the overall diameter and age-structure changed in Shawnee State Forest during the past 90 years?

5. What does the disturbance history reveal about the frequency, magnitude, and extent of disturbance events in the forest?

6. Have disturbance events altered the growth-climate relationship of *Quercus spp.* during the past 100 years?

Chapter 2: Study Area

2.1 Geography

This research project was conducted in Shawnee State Forest, Scioto County, Ohio. Shawnee State Forest (38°44’21.6816”N; 83°13’36.9438”W) is located approximately 8 kilometers west of Portsmouth, Ohio. This region was left unglaciated and referred to as the Allegheny Plateau of southern Ohio (Figure 1). Forests of the study area are regionally classified as part of the Central Hardwoods Region of the eastern United States. Shawnee State Forest is managed by the Ohio Department of Natural Resources Division of Forestry. It comprises 25,700 ha, making it the largest state forest in Ohio. Approximately 3,000 ha are designated as unmanaged wilderness (Ohio Department of Natural Resources 2006). The Division of Forestry applies three basic management strategies for individual watersheds in Shawnee State Forest: clear-cut harvesting, selective-cut harvesting, and no harvesting prior to 1940 (Summerville and Crist 2002).

Elevation of the study area varies from 138 to 322 meters. Valleys within the study site are deeply incised and the adjacent slopes leading up to the ridge tops are often steep (17-25 degrees). However, the vegetation is continuous from the valleys to the ridge tops because there are very few large bedrock outcrops. The complexity of slope gradients and aspects within the study area result in a wide-range of hydrologic and climatic variability at the landscape scale. This complexity promotes high biodiversity of woody and non-woody vegetation communities.

Forests of the Allegheny Plateau of southern Ohio are classified as mixed mesophytic (Braun 1950). Common woody species from the study site are listed in (Table 1). The most common dominant canopy trees in the study site are *Quercus rubra*, *Quercus alba*, *Acer rubrum*, *Liriodendron tulipifera*, *Acer saccharum*, *Prunus serotina*, *Juglans nigra,* and *Carya ovata* , (Griffith et al. 1993). The understory is primarily composed of *Sassafras albidium, Acer rubrum,* and *Viburnum dentatum*. Shawnee State Forest is at the understory re-initiation phase of forest development (Oliver and Larson 1996).

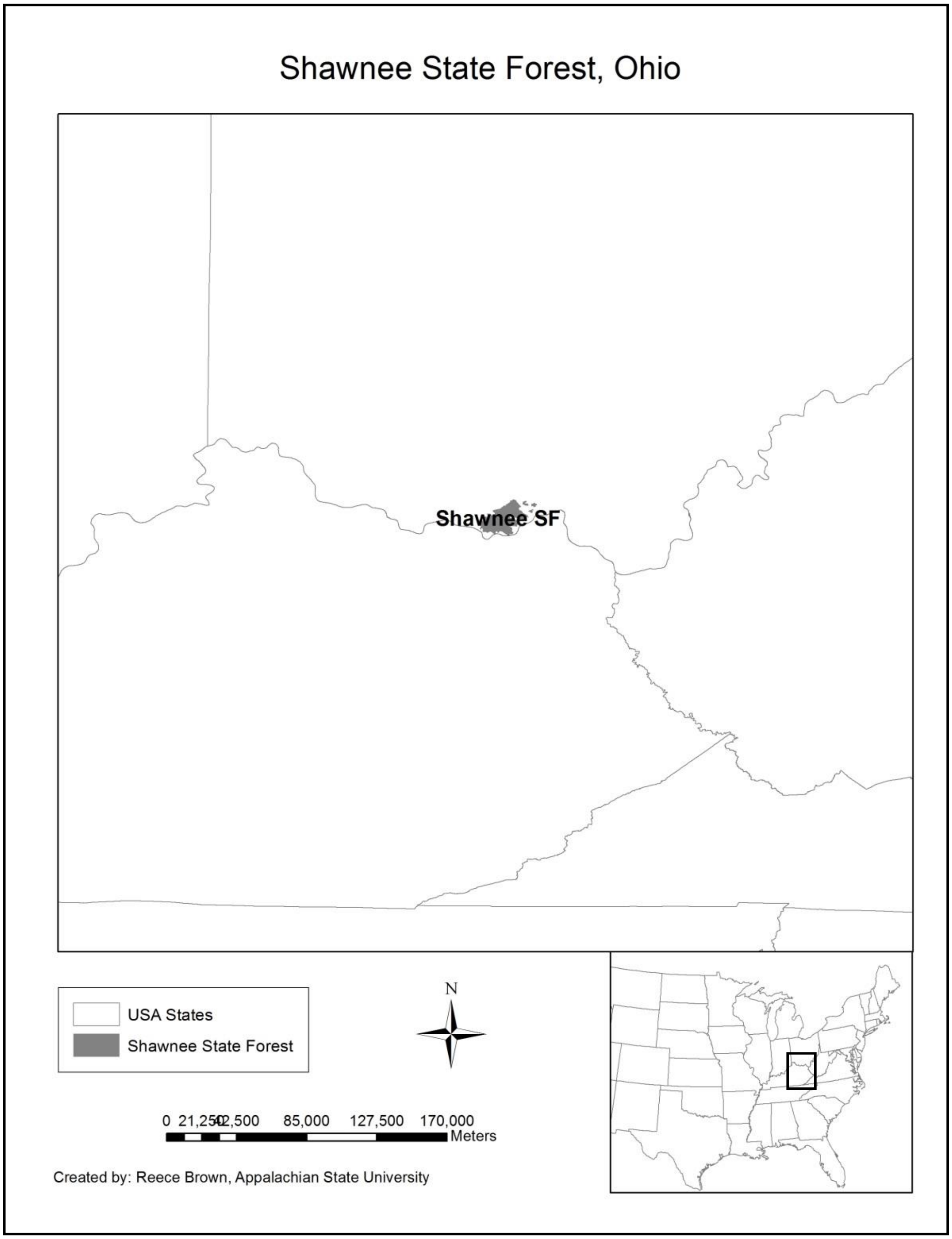

Figure 1. Map of the study area. Shawnee State Forest, Scioto County, Ohio**.**

Species	Common name
Acer rubrum L.	Red maple
Acer sacharum L.	Sugar maple
Amalanchier arborea Michx.	Downy serviceberry
Carpinus caroliniana Walter	Musclewood
Carya glabra Nutt.	Pignut hickory
Carya ovate Nutt.	Shagbark hickory
Carya tomentosa Nutt.	Mockernut hickory
Castanea dentate Marshall	American chestnut
Celtis occidentalis L.	Hackberry
Cercis canadensis L.	Eastern redbud
Fagus grandifolia Ehrh.	American beech
Fraxinus americana L.	White ash
Fraxinus pennsylvanica Marshall	Green ash
Hamamelis virginiana L.	Witch-hazel
Ilex opaca Aiton	American holly
Kalmia latifolia L.	Mountain laurel
Liriodendron tulipifera L.	Tulip poplar
*Magnolia tripetala*L.	Umbrella magnolia
Nyssa sylvatica Marshall	Black gum
Oxydendrum arboretum L.	Sourwood
Pinus rigida Mill.	Pitch pine
Pinus virginiana Mill.	Virginia pine
Populus grandidentata Michx.	Big-tooth aspen
Prunus serotina Ehrh.	Wild black cherry
Quercus alba L.	White oak
Quercus prinus L.	Chestnut oak
Quercus rubra L.	Red oak
Quercus velutina Lam.	Black oak
Rhus glabra L.	Smooth sumac
Rhus typhina L.	Staghorn sumac
Sassafras ablidium L.	Sassafrass
Vaccinium spp. L.	Blueberry
Viburnum dendatum L.	Blackhaw viburnum

Table 1. List of woody plants sampled in this study of Shawnee State Forest, Scioto County, Ohio.

2.2 Geology and Soils

The local bedrock formations are all sedimentary and composed of undivided Bedford shale, Berea sandstone and Sunbury shale Devonian to Mississippian age (Hodson et al. 1940). Unlike southeastern and southwestern Ohio, Scioto County lacks carbonate bedrock systems, but borders the Brush Creek limestone deposits of Pennsylvanian age that are located just to the west and northwest in Adams County (Carlson 1994). Most of these units represent transgression and regression sequences and form the northwestern portion of the Appalachian Basin (Busch and Rollins 1984, Carlson 1994). Regression sequences are represented by ripple marks preserved within the sandstone/shale units, while the transgression sequences are represented by the Brush Creek limestone that was deposited during Pennsylvanian time (Busch and Rollins 1984). Soils of the ridges and steep slopes that make up about 90% of the study area are poorly-drained loam to silty clay and are classified as members of the Shelocta-Brownsville association. Soils in the lower elevations and river valley are primarily loam and are classified as Berks channery silt loam and Skidmore silt loam (Hodson et al. 1940, USDA 2012).

2.3 Climate

The climate of southern Ohio is classified as humid continental (Midwestern Regional Climate Data Center 2005). The study site is located in United States Climate Division #9. U.S. Divisional Climate Data averages from 1900-2012 (http://www.esrl.noaa.gov/psd/cgi-bin/data/timeseries/timeseries1.pl) indicate that July is the warmest month, and January is the coolest. July receives the most precipitation, and February receives the least (Table 2).

	Temperature (°C)	Precipitation (cm)
January	-0.2	8.5
February	1.0	7.3
March	6.2	10.1
April	11.7	9.4
May	17.1	10.6
June	21.6	9.9
July	23.7	11.3
August	22.9	9.5
September	19.3	7.9
October	12.8	6.5
November	6.6	7.4
December	1.4	8.1
Total		**106.5**

Table 2. 1900-2012 averages of temperature and amount of precipitation each month for Ohio Climate Division 9.

2.4 Severe Forest Disturbances

Shawnee State Forest has undergone some significant forest disturbances during the past decade. The combination of these disturbances occurring within Shawnee State Forest is the primary reason that this site was chosen for the study. During February 2003, Shawnee State Forest was subjected to a severe glaze ice storm which extensively pruned tree limbs and uprooted thousands of trees (ODNR 2006). The ice storm was described as "the most severe ice storm to affect forests in the state of Ohio" (video interview with Hamilton 2012). Six years later, during April 2009, nearly 800 hectares of Shawnee State Forest experienced an unintentional wildfire, which was deemed as arson (ODNR 2009). The burn scorched thousands of canopy-forming trees and removed almost all of the understory in its path. Burn severity was the worst on the xeric sites and decreased slightly in the mesic sites. Due to the ice storm severity just six years prior, there was a large build-up of fuel to amplify the intensity of the fire. The ice storm and fire have altered the forest compositions of Shawnee State Forest.

Chapter 3: Methods

3.1 Field Methods

3.1.1 Forest stand dynamics and regeneration within unburned canopy gaps

During June, July, and August of 2012, seven large, greater than 30cm diameter at breast height (dbh; height = 1.37m), uprooted *Quercus spp.* trees were located that formed canopy gaps in Shawnee State Forest, Scioto County, Ohio (Table 3). Gaps were found on various slope positions, aspects, and gradients to analyze forest stand dynamics and understory regeneration. The base of the uprooted tree was used to establish the plot center for a 0.05ha circular plot. A GPS was used to record the latitude and longitude of each point for cartographic representation. At the plot center, the slope position was recorded as lower, middle, or upper based on relatively defined moisture gradients and tree assemblages. Also at each plot center, the aspect and slope were measured to the nearest degree with a Brunton Compass. Each plot was divided into four quadrants. Once the plot was established and the four quadrants were delineated, all woody seedlings and saplings were identified by species and tallied to quantify their occurrence and analyze understory regeneration within each gap. Seedlings were defined as stems <1m in height, and saplings were defined as stems >1m in height and < 5cm dbh. All stems >5cm dbh were identified by species and assigned a canopy class (overtopped, intermediate, codominant, and dominant) to analyze each tree's dominance based on the direction and amount of light reaching the majority of their leaves (Oliver and Larson 1996). An increment core was extracted from at least ten overtopped and intermediate trees within each gap to date the year of canopy gap formation and to understand the age-diameter relationship of various understory trees. At least five codominant and dominant *Quercus spp.* within each plot were cored to reconstruct disturbance history of the greater Shawnee State Forest and to analyze their radial growth response to climate. Vines and non-woody vegetation were excluded from analysis.

3.1.2 Forest stand dynamics and regeneration within the burned area

In July and August of 2012, five 0.05ha (8m x 62.5m) transects were delineated at random points within the burned area of Shawnee State Forest to analyze forest stand dynamics and regeneration 3.5 growing seasons after the wildfire (Table 3). The understory was exposed to amounts of light similar to canopy gaps within the unburned portion of the forest because the fire was severe enough to remove significant portions of the canopy. Therefore, it would not be acceptable to compare the burned area to closed canopy stands in the unburned portion of the forest. Plots within the burned section of the forest had to be transects rather than circular plots because of the extremely dense understory of green briar *Smilax spp.* and other vines. Transect apexes were randomly located and aligned perpendicular to the slope contour to capture various slope positions and gradients. The aspect was recoded for each transect. Within each transect all woody seedlings and saplings were identified and tallied, using the same procedures as within the unburned canopy gaps, to quantify their occurrence and analyze regeneration dynamics within each gap. Increment cores were extracted from dominant and codominant *Quercus spp.* trees to analyze forest disturbance history. Considering that the year of gap formation was 2012, cores were not extracted from understory trees to date the year of gap formation.

	Aspect	Gradient	Position	North	West
Gap#1	N56°W	22°	Middle	38°47.46	83°07.75
Gap#3	S63°E	17°	Lower	38°42.04	83°10.85
Gap#4	N41°W	12°	Upper	38°48.24	83°09.01
Gap#5	N63°E	16°	Upper	38°48.29	83°08.47
Gap#6	S55°W	26°	Upper	38°47.55	83°07.74
Gap#2	N70°W	23°	Lower	38°42.05	83°09.06
Gap#7	N75°W	16°	Middle	38°43.49	83°10.73
Burned #1	S28°E	16°-20°	Transect	38°41.70	83°12.05
Burned #2	N23°W	18°	Transect	38°41.72	83°12.03
Burned #3	S33°E	19°	Transect	38°41.66	83°12.09
Burned #4	S55°W	18°-22°	Transect	38°41.62	83°12.13
Burned #5	N46°E	17°	Transect	38°41.97	83°13.71

Table 3. Topographic variables and coordinates (WGS84) of canopy gaps in the unburned stand and transects in the burned stand.

3.1.3 Disturbance history

Dominant and codominant *Quercus spp.* cored in and out of plots in the burned and unburned stands were used to analyze stand-wide disturbances in Shawnee State Forest. *Quercus spp.* increment cores have been widely used to reconstruct forest disturbance histories because they lack absent rings, have similar growth patterns within the genus, and have clearer ring boundaries than other species (McCarthy and Bailey 1996, Rubino and McCarthy 2004, Hart et al. 2011). The dbh and canopy class of each tree was recorded. One increment core was extracted from each tree (Buchanan and Hart 2011).

3.2 Laboratory Methods

3.2.1 Regeneration composition

Regeneration layer composition was analyzed by computing species richness (number of species), density (stems*hectare^{-1}), and relative density ([(stems*hectare^{-1})/total hectares sampled]*100) for all seedlings and saplings in the unburned canopy gaps and burned portion of the forest. The distribution across unburned and burned regeneration layers was compared using a non-parametric independent samples Mann-Whitney U Test.

3.2.2 Canopy class distribution

Canopy class distributions of all trees >5cm dbh were analyzed by computing species richness, density (number of each species hectare^{-1}), relative density, dominance (basal area = m^{2}*hectare^{-1}), and relative dominance (Hart et al. 2008, van de Gevel et al.

2012). The canopy classes also were used to compare the difference between burned and unburned stands. The distribution of each canopy class, selected group, and abundant individuals were compared across burned and unburned stands using an Independent Samples Mann-Whitney U test.

3.2.3 Basal area

Basal area was calculated for each species, group, and canopy class to compare the difference of each in burned and unburned stands. Basal area values were obtained using (Thomas and Roesch 1990):

$$\text{Basal area} = \text{dbh}^2 * 0.00007854$$

An Independent Samples Mann-Whitney U test was used to examine the difference in distribution of each variable across burned and unburned stands.

3.2.4 Tree ring analysis

All increment cores were mounted with glue, air dried, and sanded with progressively finer grit sand paper to reveal the cellular structure of the wood (Speer 2010). The increment cores measured for disturbance history and growth-climate relationships were placed beneath a stereozoom microscope and visibly cross-dated using the list-year method to assign a calendar year to each ring (Yamaguchi 1991). Cores were scanned using an Epson Expression 1000 XL scanner at 1200 dots/inch. The image scans were opened as TIF files using WinDendro software (Windendro Version

2004b for Tree Ring Analysis. *Regent Instruments Inc.* Chicontimi, Quebec, Canada), individual rings were measured to the nearest 0.001mm, and then statistically verified using program COFECHA (Holmes 1983). In COFECHA, a 40-year segment lagged 20 years was used to compare segments within the tree ring series and master chronology. Segments with low correlations were visibly re-examined to verify calendar date assignments. If an error was found, the core was re-measured correctly. The tree ring series used in the growth-climate relationship was detrended using program ARSTAN. A negative exponential curve was applied to minimize effects of stand dynamics and physiological consequences of tree growth (Speer 2010).

3.2.5 Age-diameter relationship

Age/diameter data were obtained from increment cores and dbh from the 12 closest trees to plot center that were >5cm dbh. The inner-most year on each core with pith or significant growth ring curvature near pith was used as the date of establishment for each tree. Cores without significant curvature were discarded from this portion of analysis. These establishment dates were plotted with dbh to analyze patterns of tree size and establishment periods.

3.2.6 Disturbance history

The increment cores of codominant and dominant *Quercus spp.* were used to analyze disturbance history. Stand-wide and localized release events were quantified by detecting radial growth releases in *Quercus spp.* increment cores (n=56) using a 10 year running (20 year window) median method (Rubino and McCarthy 2004). Growth increases greater than 25% were recorded as minor releases and 50% growth increases were recorded as major releases (Nowacki and Abrams 1997). Releases must have lasted a minimum of five years to be considered in the disturbance history. When >25% of the trees recorded a release it was considered to be a stand-wide release (Nowacki and Abrams 1997). All other releases were considered to be localized.

3.2.7 Growth-climate relationship

Climate data were obtained from the National Oceanic and Atmospheric Administration Divisional Climate Data Set (NOAA 2013). The master *Quercus spp.* chronology (1897-2011) was truncated by 16 years based on limited sample depth (<10) and diminished running r-bar (<0.85) (Speer 2010). The remaining 99 year chronology was split into three equal periods. The truncated series (1913-2011) was compared with concurrent and lagged monthly temperature, precipitation, and Palmer Drought Severity Index (PDSI; Palmer 1965). The highest correlations between growth and climate of the 99 year series were identified. The series was split into early (1913-1945), middle (1946-1978), and late (1979-2011) to identify temporal stability of the growth-climate analysis.

Chapter 4: Results

4.1 Seedling and Sapling Regeneration Dynamics

The density and species richness of seedlings were significantly less in the burned stand (Table 4). Seedlings (stems <1.5m height) showed differences in density (seedlings ha^{-1}), richness, and composition between stands (Table 5). Specifically, the densities of *Acer rubrum* and *Quercus alba* seedlings were significantly less in the burned stand. However, the relative densities (%) of *Quercus alba* and *Quercus spp.* seedlings were not significantly different between stands, but greater in the burned stand (Figure 2).

Sapling densities and species richness were different between burned and unburned stands, but not statistically significant (Table 6). The densities of *Acer rubrum*, *Quercus alba*, *Quercus spp.*, and *Quercus spp.* + *Carya spp.* saplings were not significantly different between stands. However, the densities and relative densities of *Quercus alba* and *Quercus spp.* saplings were greater in the burned stand (Figure 2). Species richness was 24 in the burned stand and 25 in the unburned stand.

Distribution Across Burned and Unburned	Significance	H_o Decision
Total Seedling Density	0.017	**Reject**
Total Sapling Density	0.588	Retain
Total Seedlings + Saplings	0.003	**Reject**
Seedling Species Richness	0.048	**Reject**
Sapling Species Richness	0.268	Retain
Total Species Richness	0.073	Retain
Quercus alba seedling Density	0.032	**Reject**
Quercus alba sapling Density	0.548	Retain
Quercus alba seedling Relative Density	0.310	Retain
Quercus alba sapling Relative Density	0.314	Retain
Quercus spp.* Seedling Density	0.421	Retain
*Quercus spp**. Sapling Density	0.390	Retain
Quercus spp.* Seedling Relative Density	0.413	Retain
Quercus spp.* Sapling Relative Density	0.089	Retain
Quercus spp. and *Carya spp*.**Seedling Density	0.041	Retain
Quercus spp. and *Carya spp*.** Sapling Density	0.128	Retain
Quercus spp. and *Carya spp*.** Seedling Relative Density	0.222	Retain
Quercus spp. and *Carya spp*.** Sapling Relative Density	0.095	Retain
Acer rubrum Seedling Density	0.025	**Reject**
Acer rubrum Sapling Density	0.885	Retain
Acer rubrum Seedling Relative Density	0.032	**Reject**
Acer rubrum Sapling Relative Density	0.997	Retain

Table 4. Results from the Independent Samples Mann-Whitney U Test for differences in the distribution of regeneration layer dynamics between unburned and burned stands in Shawnee State Forest, Scioto County, Ohio.**Quercus spp.* includes *Q. alba*, *Q. prinus*, *Q. rubra*, and *Q. velutina*. ***Carya spp.* includes *C. glabra*, *C. ovata*, and *C. tomentosa*

Seedling	Density		Relative Density	
Species	Burned	Unburned	Burned	Unburned
Acer rubrum	64	1400	5.8	25.9
Acer sacharum	0	3	0.0	0.1
Amalanchair arborea	8	117	0.7	2.2
Carpinus caroliniana	4	0	0.4	0.0
Carya glabra	12	11	1.1	0.2
Carya ovata	0	57	0.0	1.1
Carya tomentosa	40	46	3.6	0.8
Castanea dentata	0	0	0.0	0.0
Celtis occidentalis	60	0	5.4	0.0
Fagus grandifolia	0	3	0.0	0.1
Fraxinus americana	20	26	1.8	0.5
Kalmia latifolia	0	14	0.0	0.3
Liriodendron tulipifera	8	274	0.7	5.1
Magnolia tripetala	0	0	0.0	0.0
Nyssa sylvatica	12	57	1.1	1.1
Oxydendron arboreum	0	49	0.0	0.9
Pinus rigida	0	6	0.0	0.1
Prunus serotina	0	46	0.0	0.8
Quercus alba	44	460	4.0	8.5
Quercus prinus	504	489	45.5	9.0
Quercus rubra	24	946	2.2	17.5
Quercus velutina	68	374	6.1	6.9
Rhus glabra	8	0	0.7	0.0
Rhus typhina	20	3	1.8	0.1
Sassafras ablidium	40	189	3.6	3.5
Vaccinium spp.	0	251	0.0	4.7
Viburnum dendatum	172	586	15.5	10.8
Total	**1108**	**5405**	**100.0**	**100.0**

Table 5. Density (stems ha^{-1}) and relative density of all seedlings in burned and unburned stands of Shawnee State Forest, Scioto County, Ohio.

Sapling	Density		Relative Density	
Species	Burned	Unburned	Burned	Unburned
Acer rubrum	472	417	20.5	14.7
Acer sacharum	4	34	0.2	1.2
Amalanchair arborea	40	363	1.7	12.7
Carpinus caroliniana	0	23	0.0	0.8
Carya glabra	20	57	0.9	2.0
Carya ovata	20	37	0.9	1.3
Carya tomentosa	80	63	3.5	2.2
Castanea dentata	8	0	0.3	0.0
Celtis occidentalis	40	0	1.7	0.0
Cercis canadensis	0	9	0.0	0.3
Fagus grandifolia	8	26	0.3	0.9
Fraxinus americana	32	40	1.4	1.4
Fraxinus pennsylvanica	0	3	0.0	0.1
Hammamelis virginiana	0	14	0.0	0.5
Ilex opaca	0	3	0.0	0.1
Kalmia latifolia	20	63	0.9	2.2
Liriodendron tulipifera	140	429	6.1	15.1
Magnolia tripetala	0	3	0.0	0.1
Nyssa sylvatica	144	103	6.3	3.6
Oxydendron arboreum	108	131	4.7	4.6
Populus grandidentata	4	0	0.2	0.0
Prunus serotina	16	63	0.7	2.2
Quercus alba	120	40	5.2	1.4
Quercus prinus	232	14	10.1	0.5
Quercus rubra	36	34	1.6	1.2
Quercus velutina	40	46	1.7	1.6
Rhus glabra	8	0	0.3	0.0
Rhus typhina	68	0	3.0	0.0
Sassafras ablidium	636	451	27.7	15.9
Viburnum dendatum	4	380	0.2	13.4
Total	**2300**	**2846**	**100.0**	**100.0**

Table 6. Density (stems ha^{-1}) and relative density of all saplings in burned and unburned stands of Shawnee State Forest, Scioto County, Ohio.

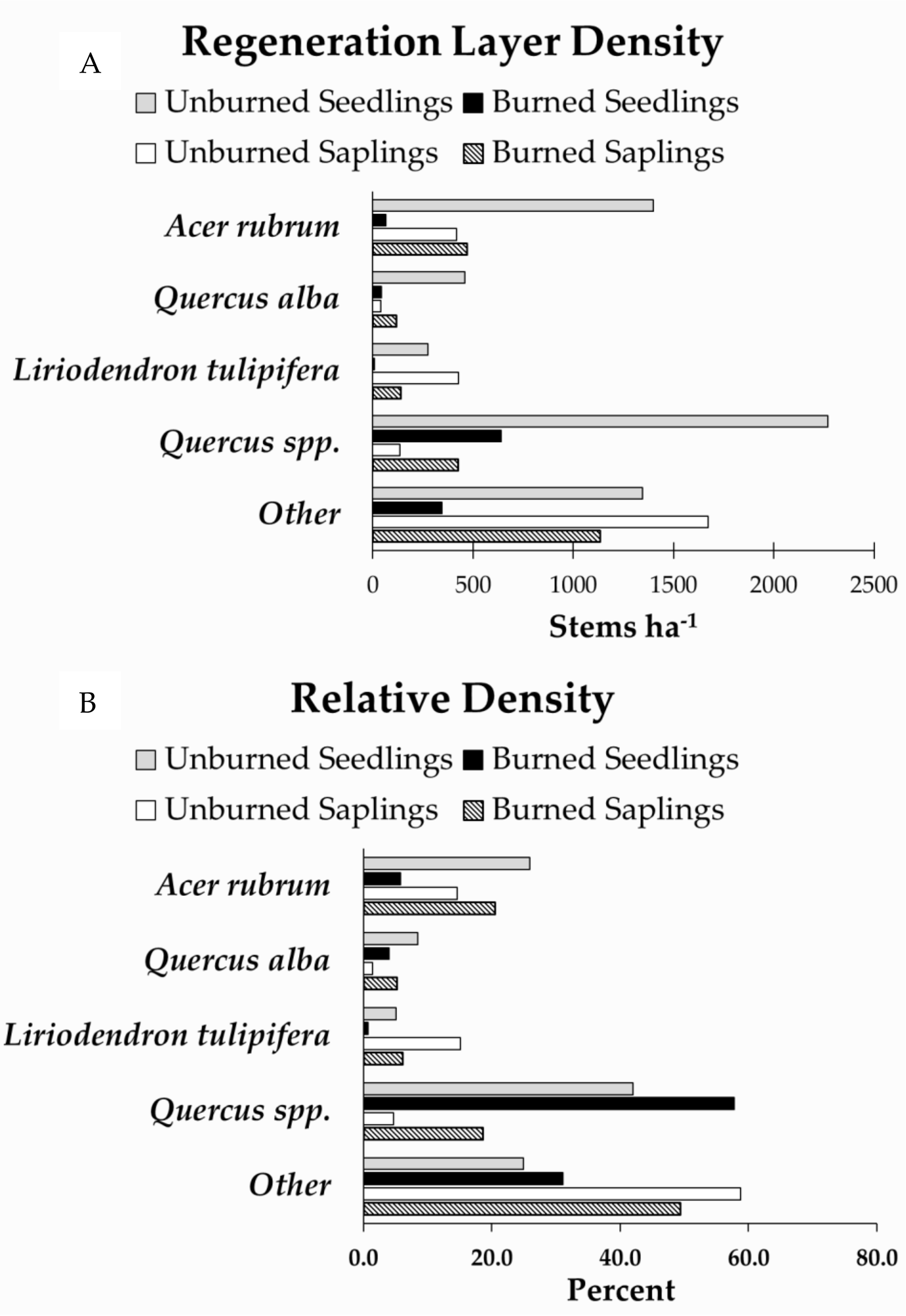

Figure 2. A: Density (stems ha^{-1}) and B: Relative Density (%) of selected seedlings and saplings in unburned and burned stands of Shawnee State Forest, Scioto County, Ohio.
Quercus spp. includes *Q. alba*, *Q. prinus*, *Q. rubra*, and *Q. velutina.*
**Carya spp. includes C. glabra, C. ovata, and C. tomentosa

4.2 Canopy Class Distributions

There were differences in the composition of each canopy class in both the burned and unburned stands. The only significant difference between stands was the intermediate trees ha^{-1} had a higher density in the unburned stand (Table 7). The burned stand contained less total trees ha^{-1} in the suppressed, intermediate, and codominant classes than the unburned stand (Table 8). However, the burned stand contained more dominant trees ha^{-1}. Species richness was nine in the burned stand and 19 in the unburned stand.

The density of each species varied between canopy classes in the burned stand (Table 8). *Sassafrass albidium* had the highest density in the suppressed class, *Acer rubrum* had the highest density in the intermediate class, *Quercus prinus* had the highest density in the codominant class, and *Liriodendron tulipifera* had the highest density in the dominant class of the burned stand.

The unburned stand had more species in each canopy class than the burned stand (Table 8). *Nyssa sylvatica* L. was the most abundant tree ha^{-1} in the suppressed and intermediate classes, *Liriodendron tulipifera* was the most abundant tree ha^{-1} in the codominant class, and *Quercus rubra* was the most abundant tree ha^{-1} in the dominant class).

The relative canopy class distribution shows that the burned stand was primarily composed of codominant and dominant trees, and the unburned stand was primarily composed of intermediate and codominant trees (Figure 3B). The midstory (suppressed +

intermediate) of the burned and unburned stands was primarily composed of Fagus spp. + Acer spp. (Figure 3C). The overstory (codominant + dominant) of the burned stand was primarily composed of *Quercus spp*., while the overstory of the unburned stand was primarily oak-hickory and *Liriodendron tulipifera* (Figure 3D).

Distribution Across Burned and Unburned	p-value	H_o Decision
Fagus spp. + *Acer spp*. SU+IN	0.343	Retain
Carya spp. SU+IN	0.432	Retain
Liriodendron tulipifera SU+IN	0.268	Retain
Quercus spp. SU+IN	0.998	Retain
Quercus spp. + *Carya spp*. SU+IN	0.432	Retain
Fagus spp. + *Acer spp*. CO+DM	0.106	Retain
Carya spp. CO+DM	0.106	Retain
Liriodendron tulipifera CO+DM	0.755	Retain
Quercus spp. CO+DM	0.876	Retain
Quercus spp. + *Carya spp*. CO+DM	0.639	Retain
Fagus spp. + *Acer spp*. SU+IN %	0.876	Retain
Carya spp. SU+IN %	0.432	Retain
Liriodendron tulipifera SU+IN %	0.268	Retain
Quercus spp. SU+IN %	0.999	Retain
Quercus spp. + *Carya spp*. SU+IN %	0.432	Retain
Carya spp. CO+DM %	0.106	Retain
Fagus spp. + *Acer spp*. CO+DM %	0.106	Retain
Liriodendron tulipifera CO+DM %	0.639	Retain
Quercus spp. CO+DM %	0.53	Retain
Quercus spp. + *Carya spp*. CO+DM %	0.53	Retain
Suppressed	0.202	Retain
Intermediate	0.018	**Reject**
Codominant	0.432	Retain
Dominant	0.343	Retain
Total (all trees >5cm dbh)	0.073	Retain
Suppressed %	0.343	Retain
Intermediate %	0.106	Retain
Codominant %	0.997	Retain
Dominant %	0.106	Retain

Table 7. Results from the Independent Samples Mann-Whitney U Test for differences in the distribution of canopy between unburned and burned stands in Shawnee State Forest, Scioto County, Ohio. Canopy classes were based on the direction and amount of intercepted light. Ranked in order from lowest class to highest class, SU: Suppressed, IN Intermediate, CO: Codominant, DM: Dominant.

	Suppressed		Intermediate		Codominant		Dominant	
Species	Bu.	Un.	Bu.	Un.	Bu.	Un.	Bu.	Un.
Acer rubrum	0	3	28	40	12	11	0	0
Acer saccharum	0	0	0	6	0	14	0	6
Amelanchair arborea	0	0	0	3	0	0	0	0
Carpinus caroliniana	0	3	0	3	0	0	0	0
Carya glabra	0	0	0	0	0	3	0	3
Carya ovata	0	0	0	3	0	0	0	0
Carya tomentosa	0	0	0	3	0	9	0	0
Fagus grandifolia	0	6	0	9	0	3	0	0
Fraxinus americana	0	0	0	0	0	0	3	0
Liriodendron tulipifera	0	9	0	46	20	89	20	11
Nyssa sylvatica	0	11	12	60	16	37	14	0
Oxydendron arboreum	0	0	0	20	4	6	0	0
Pinus virginiana	0	0	0	0	0	0	0	3
Prunus serotina	0	0	0	0	0	3	0	0
Quercus alba	0	0	0	6	12	37	3	3
Quercus prinus	0	0	4	0	40	14	11	11
Quercus rubra	0	0	0	0	0	0	0	14
Quercus velutina	0	0	0	0	8	3	9	3
Sassafras albidium	4	0	20	29	8	0	0	0
Ulmus rubra	0	0	0	3	0	0	0	0
Total	**4**	**31**	**64**	**229**	**120**	**229**	**60**	**54**

Table 8. Canopy class distributions (trees ha^{-1}) of burned (Bu.) and unburned (Un.) stands in Shawnee State Forest, Scioto County, Ohio. Canopy classes determined by direction and amount of light reaching each tree. Ranked in order from lowest class to highest class, SU: Suppressed, IN Intermediate, CO: Codominant, DM: Dominant.

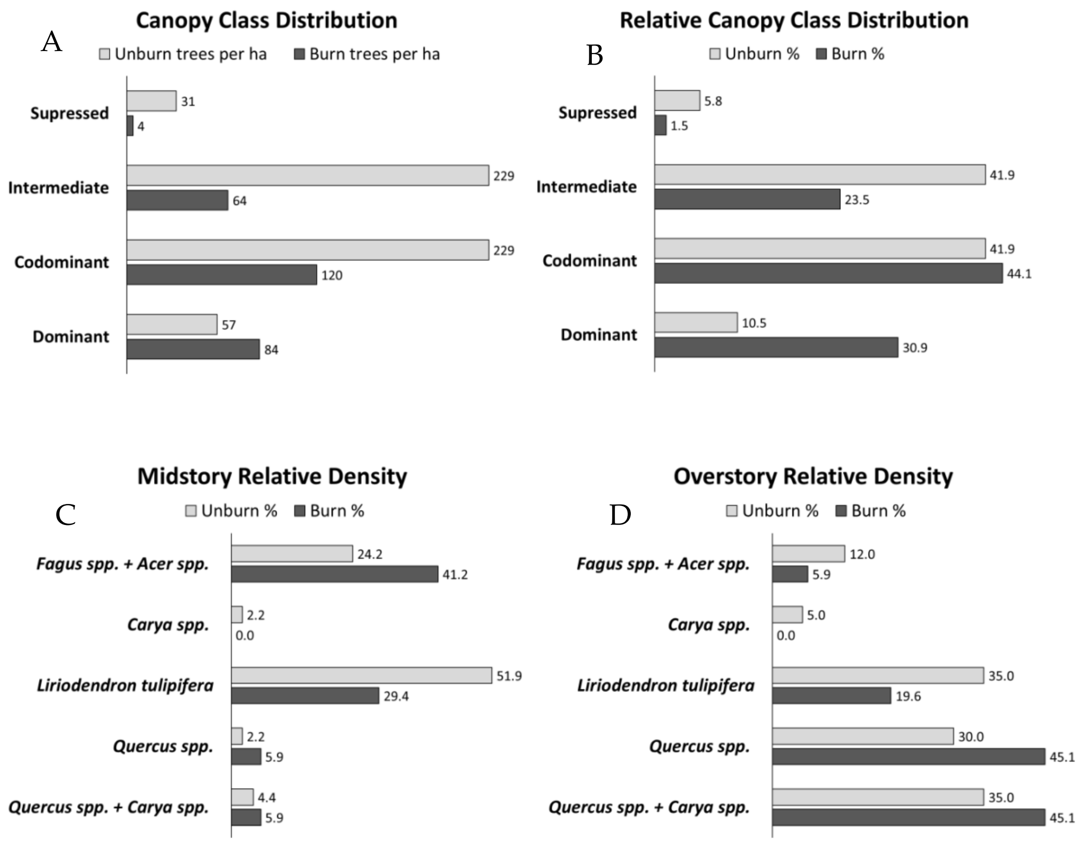

Figure 3. Canopy class distribution and relative densities of selected species and groups in Shawnee State Forest, Scioto County, Ohio. A: canopy class distribution of all tree (stems >5cm dbh) densities in unburned and burned sites. B: relative densities (Canopy class % of total trees in each site) of each canopy class. C: Midstory (suppressed + intermediate) relative densities of select individuals and groups. D: Overstory (codominant + dominant) relative densities of select individuals and groups.

4.3 Basal Area

The total basal area (m^2 ha^{-1}) was not significantly different between burned and unburned stands (Table 9). The total basal area in the burned stand was 24.8500 m^2 ha^{-1} and 15.4461 m^2 ha^{-1} in the unburned stand. *Carya spp.* had significantly greater dominance (basal area) in the burned stand. The *Acer spp.* + *Fagus spp.* group and *Carya spp.* had significantly less relative basal area in the burned stand. The most dominant trees in the burned stand were *Liriodendron tulipifera*, *Quercus prinus*, and *Quercus velutina* (Table 10). The most dominant trees in the unburned stand were *Quercus alba*, *Quercus rubra*, and *Quercus prinus*. *Liriodendron tulipifera* showed a much greater difference in dominance between stands than other groups and individuals, with greatest dominance in the burned stand (Figure 4). The *Quercus spp.* + *Carya spp.* group had the greatest relative dominance in both burned and unburned stands (Figure 4B).

There were many differences in the distribution of basal area between canopy classes and stands, but only two of them were significant. The burned stand contained significantly more basal area in the dominant class than the unburned stand (Table 9). The unburned stand contained significantly higher relative basal area in the intermediate class. Basal area of the burned stand decreased with canopy class positions (Table 11).

Distribution Across Burn and Unburn	Significance (p)	H_o Decision
Liriodendron tulipifera	0.268	Retain
Acer spp. + *Fagus spp.*	0.202	Retain
Carya spp.	0.017	**Reject**
Quercus spp.	0.999	Retain
Quercus spp. + *Carya spp.*	0.755	Retain
Total Basal Area	0.268	Retain
Relative *Liriodendron tulipifera*	0.432	Retain
Relative *Acer spp*. + *Fagus spp.*	0.048	**Reject**
Relative *Carya spp.*	0.048	**Reject**
Relative *Quercus spp.*	0.073	Retain
Relative *Quercus spp.* + *Carya spp.*	0.073	Retain
Suppressed	0.23	Retain
Intermediate	0.106	Retain
Codominant	0.999	Retain
Dominant	0.03	**Reject**
Relative Suppressed	0.202	Retain
Relative Intermediate	0.03	**Reject**
Relative Codominant	0.268	Retain
Relative Dominant	0.106	Retain
Basal Area of trees >25cm dbh	0.268	Retain

Table 9. Results from the Independent Samples Mann-Whitney U Test for differences at the 95% confidence level for the distribution of dominance (basal area: m^2 ha^{-1}) between unburned and burned stands in Shawnee State Forest, Scioto County, Ohio.

Unburned Stand Species	Density	Relative Density	Dominance	Relative Dominance	Relative Importance
Liriodendron tulipifera	154.29	28.27	0.52	9.67	18.97
Quercus alba	45.71	8.38	1.14	21.34	14.86
Nyssa sylvatica	108.57	19.90	0.24	4.49	12.19
Quercus rubra	14.29	2.62	1.07	19.99	11.30
Quercus prinus	25.71	4.71	0.90	16.90	10.80
Acer rubrum	57.14	10.47	0.32	5.95	8.21
Quercus velutina	5.71	1.05	0.49	9.23	5.14
Acer saccharum	25.71	4.71	0.14	2.66	3.69
Oxydendron arboreum	25.71	4.71	0.09	1.70	3.21
Sassafras albidium	28.57	5.24	0.03	0.56	2.90
Fagus grandifolia	17.14	3.14	0.06	1.21	2.17
Carya tomtentosa	11.43	2.09	0.10	1.81	1.95
Carya glabra	5.71	1.05	0.14	2.53	1.79
Pinus virginiana	2.86	0.52	0.07	1.30	0.91
Carpinus caroliniana	5.71	1.05	0.01	0.10	0.57
Carya ovata	2.86	0.52	0.02	0.33	0.43
Prunus serotina	2.86	0.52	0.01	0.11	0.32
Amelanchair arborea	2.86	0.52	0.00	0.07	0.30
Ulmus rubra	2.86	0.52	0.00	0.05	0.29
Total	**544.00**	**200**	**11.58**	**200**	**200**

Burned Stand Species	Density	Relative Density	Dominance	Relative Dominance	Relative Importance
Liriodendron tulipifera	48	17.65	2.52	43.46	30.55
Quercus prinus	60	22.06	1.48	25.64	23.85
Nyssa sylvatica	48	17.65	0.24	4.07	10.86
Quercus velutina	20	7.35	0.71	12.35	9.85
Acer rubrum	40	14.71	0.18	3.12	8.91
Sassafras albidium	32	11.76	0.05	0.79	6.28
Quercus alba	16	5.88	0.22	3.87	4.88
Fraxinus americana	4	1.47	0.38	6.65	4.06
Pinus virginiana	4	1.47	0.00	0.07	0.77
Total	**272**	**100**	**5.79**	**100**	**100**

Table 10. Density (stems ha^{-1}), relative density (%), dominance (basal area: m^{2} ha^{-1}), relative dominance (%), and relative importance (average relative density and relative dominance) of all trees (stems >5cm dbh) in burned and unburned stands of Shawnee State Forest, Scioto County, Ohio.

	Dominance		Relative dominance	
Canopy Class	Burn	Unburned	Burn %	Unburned %
Dominant	15.415	6.705	66.6	43.9
Codominant	6.997	6.793	30.2	44.5
Intermediate	0.726	1.668	3.1	10.9
Suppressed	0.015	0.107	0.1	0.7
Total	24.85	15.446	100	100

Table 11. Dominance (basal area: m^2 ha^{-1}) and relative dominance (%) of each canopy class in burned and unburned stands of Shawnee State Forest, Scioto County, Ohio.

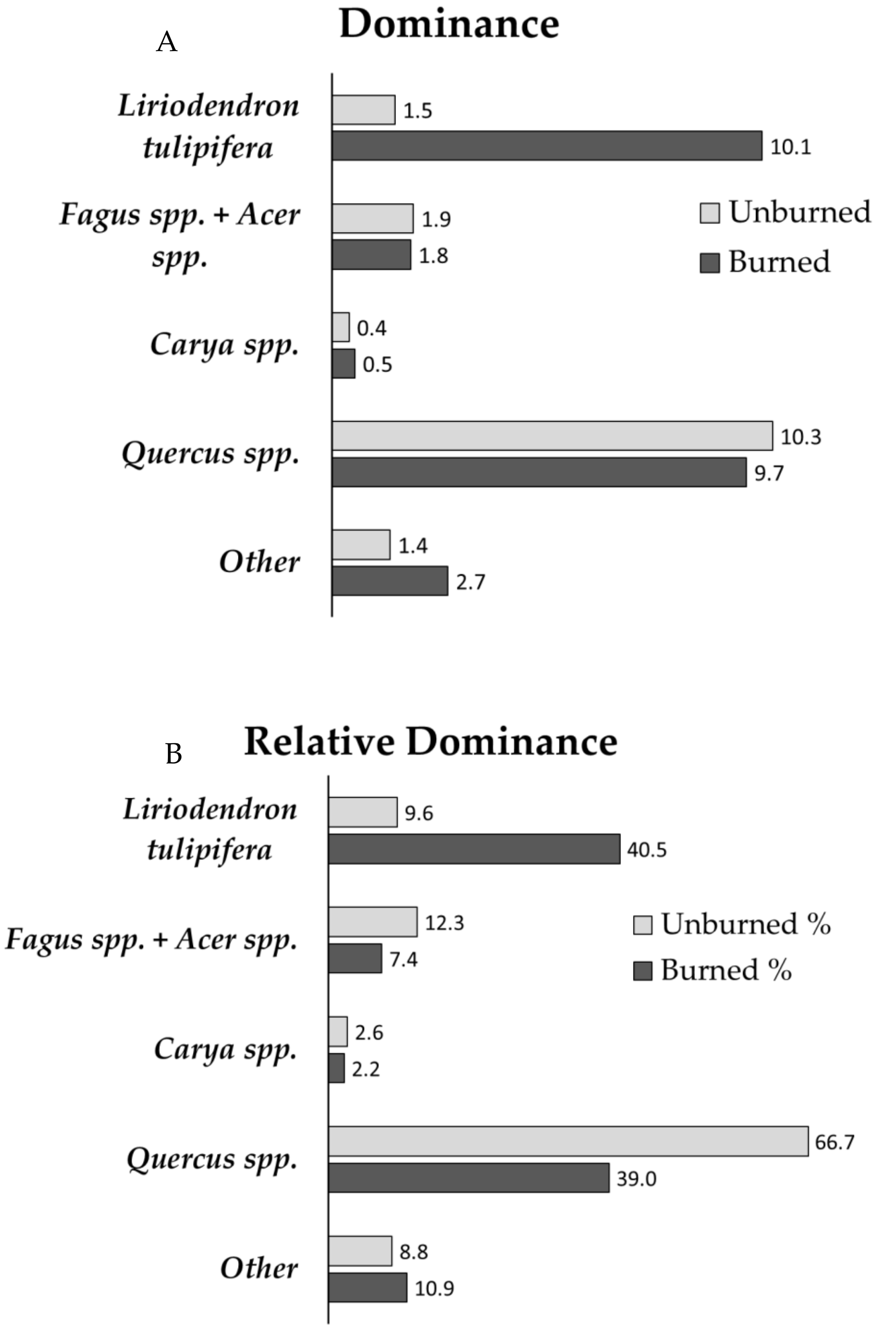

Figure 4. A: Dominance (basal area: m^2 ha^{-1}), B: Relative Dominance (%) of select species and groups in unburned and burned stands of Shawnee State Forest, Scioto County, Ohio. Other includes species listed on Table 7.

4.4 Diameter and Age Structure

The diameter-age relationship showed that most of the large trees (dbh > 20cm) were *Quercus spp.* and had inner-most dates between 1890 and 1940 (Figure 5). The period between 1940 and 2000 was when most of the shade-tolerant species (*Acer spp.*, *Nyssa sylvatica*, *Oxydendron arboreum*) were able to establish. This establishment period was dominated by *Acer spp.*, *Carya spp.*, *Nyssa sylvatica*, and *Oxydendron arboretum*. The final period, 2000 to the present, was when most of the *Liriodendron tulipifera* was able to establish. More specifically, the ice storm of 2003 created favorable conditions for *Liriodendron tulipifera* establishment (Figure 5). Most trees in the plots were in small (<20 cm dbh) classes rather than large (>20 cm dbh) classes (Figure 6). *Acer spp.* + *Fagus spp.*, *Liriodendron tulipifera*, *Nyssa sylvatica* comprised the bulk of the smaller size classes. *Quercus spp.* comprised the bulk of the larger size classes.

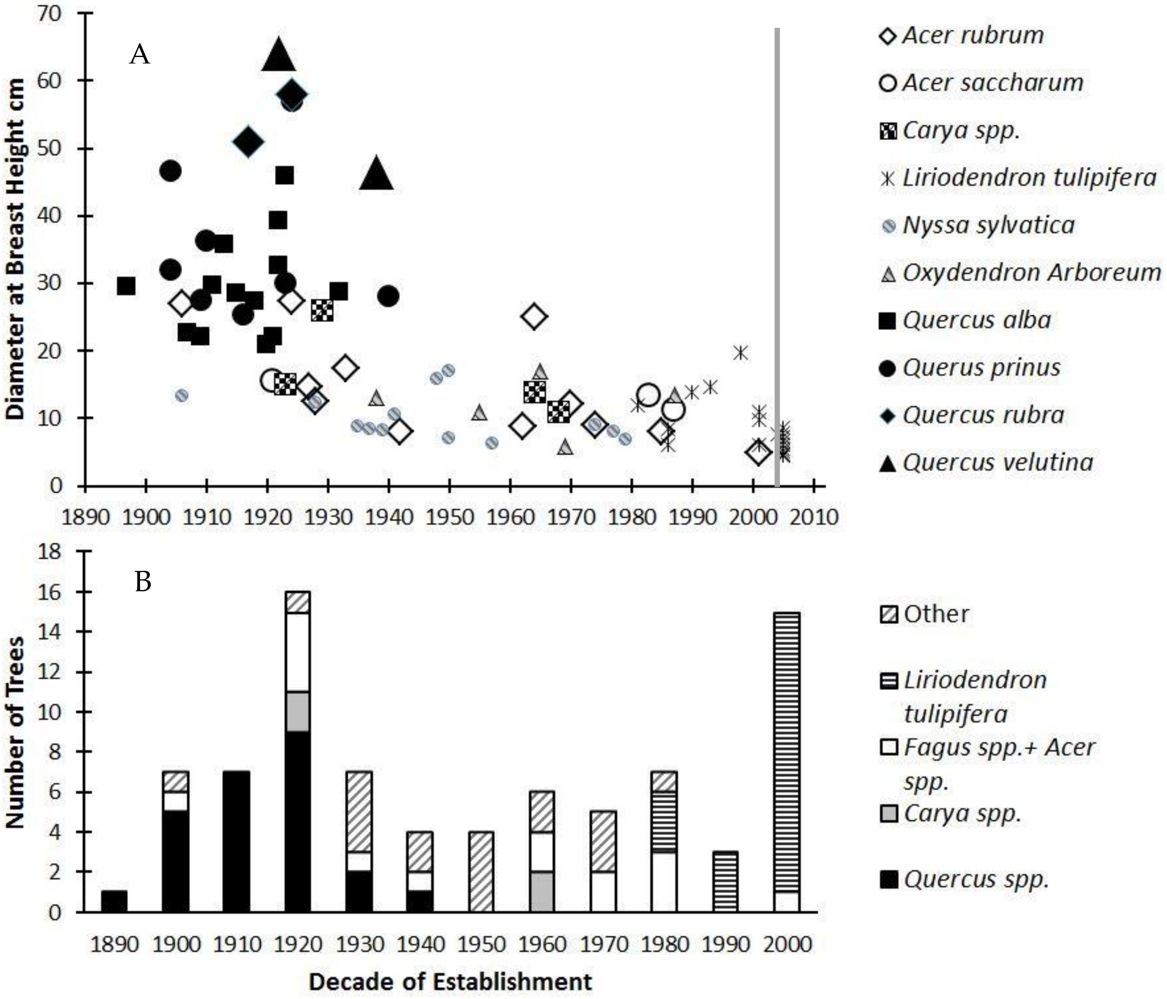

Figure 5. **A:** Diameter-age relationships for 82 trees (stems >5cm dbh) in 7 plots throughout the unburned stand of Shawnee State Forest, Scioto County, Ohio. B: Number of trees that established in each decade between 1890 and 2010. Gray line indicates the ice storm of 2003.

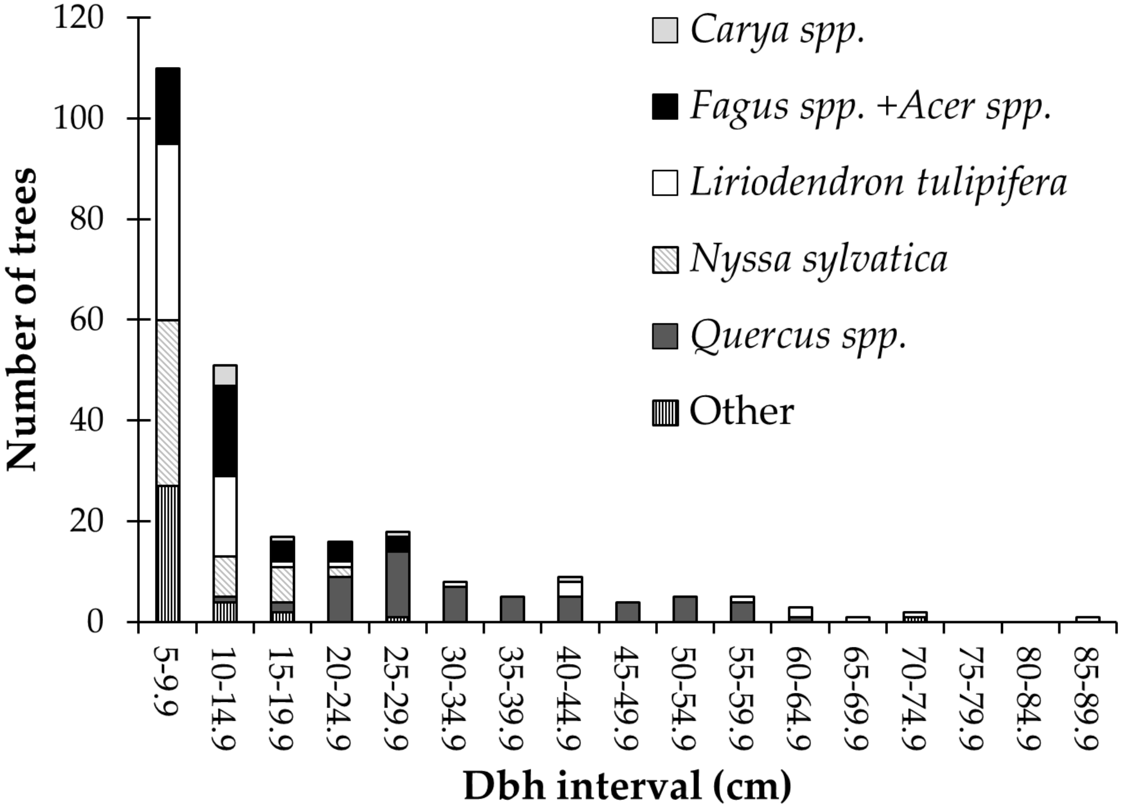

Figure 6. Number of trees (> 5cm dbh) ha^{-1} for selected species within each 5cm dbh interval for 260 trees in Shawnee State Forest, Scioto County, OH. Other species listed on Table 7.

4.5 Disturbance History

The 53 *Quercus spp.* (*Q. alba* n= 37, *Q. prinus* n= 8, *Q. rubra* n= 6, *Q. velutina* n= 2) increment cores detected a total of 78 release events between 1935 and 2001 (Figure 7). 49 of the cores (89%) detected at least one release event, 24 (43%) detected at least two, and five (9%) of the cores detected three events. Releases were clustered around the 1940s, 1960s, mid 1980s and late 1990s into 2001. The year 1999 had the greatest number of releases in the disturbance history. There were a total of 34 release years in the disturbance history. The longest period without any releases was between 1989 and 1997. The average, median, and standard deviation of the release event durations were 7.95, 7.5, and 4.09 respectfully. 58 (74%) of the release events were identified as minor (>25% increase and sustained for 5 years), and 20 (25%) were identified as major (>50% increase and sustained for 5 years). There were no stand-wide disturbances (>25% of trees experiencing a release in a given year) detected.

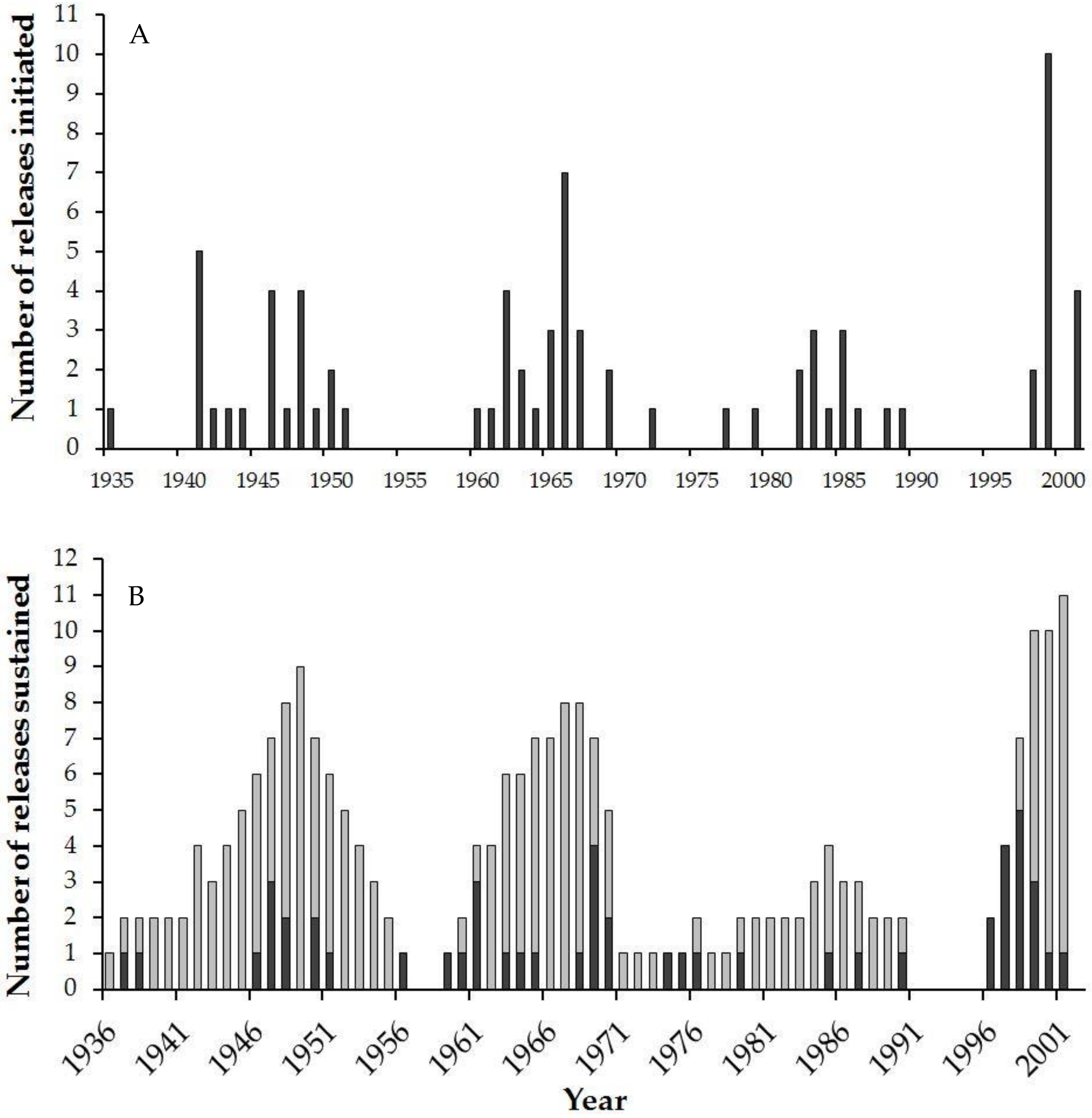

Figure 7. Releases identified using a 10 year running median from 53 *Quercus spp.* individuals in Shawnee State Forest, Scioto County, Ohio. A: Release initiation years. B: Releases and number of years sustained.

4.6 Growth-Climate Relationship

The same *Quercus spp.* chronology (n= 53, 1897-2011) that was used to reconstruct disturbance history was also analyzed for growth-climate relationships (Table 12). This chronology had an interseries correlation of 0.577 and a mean sensitivity of 0.269. Program COFECHA identified 25 out of 231 40-year segments as possible problems. The segments were re-examined using a stereozoom microscope, but no dating errors were found. The *Quercus alba* chronology (1897-2011) from 33 individuals (n=33) had an interseries correlation of 0.553 and a mean sensitivity of 0.288 and had lower correlations with growing season climate variables than the *Quercus spp.* chronology. Therefore, the *Quercus spp.* chronology was used to examine growth climate relationships because of its' higher sample size and greater correlation with climate.

The early, middle, and late growing periods exhibited differential responses to growing season climate variables. The early and middle periods showed higher correlations to climate variables than the late period. The highest correlation was between the early period and PDSI (Table 13). The late period had no statistically significant correlations between growth and PDSI. Correlations between growth and precipitation were lower and less frequent than PDSI. The highest correlation between growth and precipitation was in the middle period, and there were no significant correlations in the late period (Table 14). Correlations between growth and temperature were higher than precipitation, but less frequent. The correlation between growth and temperature had higher values in the late period than PDSI and precipitation (Table 15).

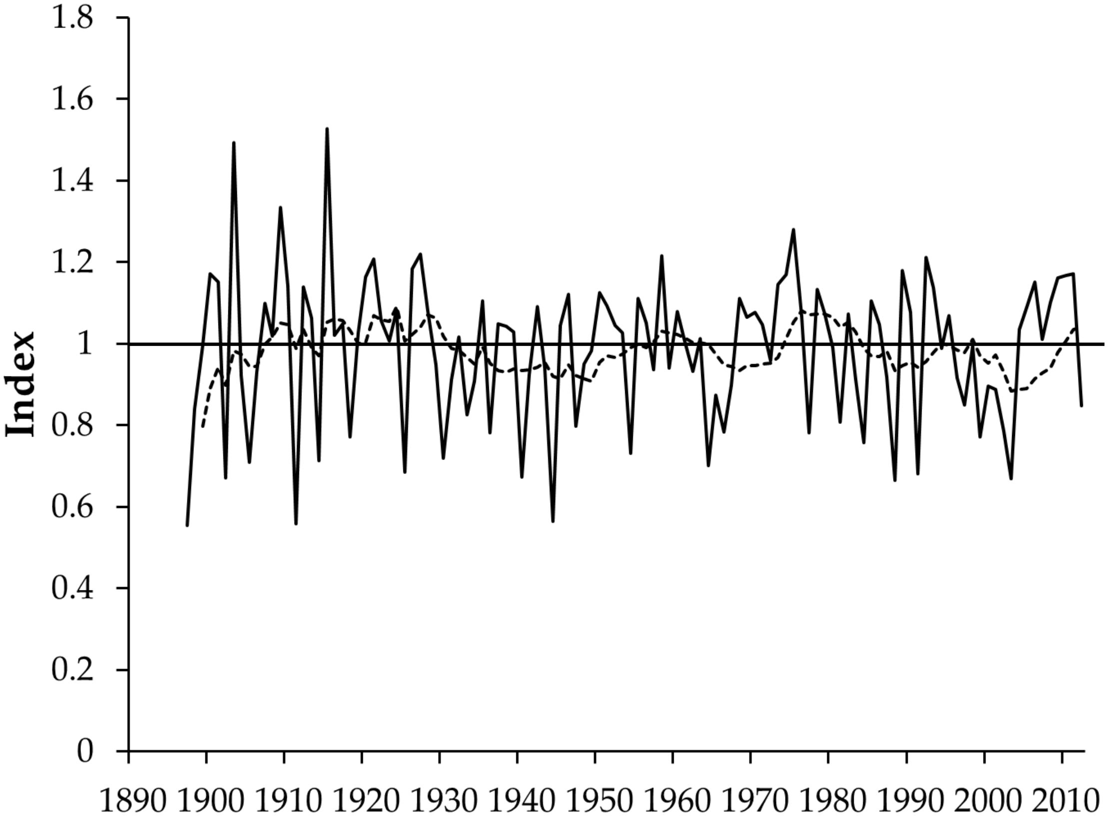

Table 12. Ring-width index (solid line) chronology of *Quercus spp.* chronology (n= 53) from Shawnee State Forest, Scioto County, Ohio. Dashed line is a 10-year moving average.

	Correlation with PDSI			
Month	Complete	Early	Middle	Late
Jan	**.276****	**.381***	**.403***	.073
Feb	**.234***	.339	.330	.054
Mar	**.263****	**.401***	.342	.086
Apr	**.231***	.267	.284	.210
May	**.327****	**.483****	**.404***	.222
Jun	**.424****	**.575****	**.606****	.251
Jul	**.431****	**.643****	**.403***	.270
Aug	**.411****	**.642****	**.349***	.261
Sep	**.391****	**.658****	**.324**	.201
Oct	**.374****	**.567****	**.387***	.227
Nov	**.344****	**.545****	.320	.202
Dec	**.340****	**.561****	.273	.175
Lag Jan	-.066	.086	.376*	.064
Lag Feb	-.056	.116	.307	-.007
Lag Mar	-.070	-.030	.155	.005
Lag Apr	-.029	-.020	.156	-.081
Lag May	.112	-.067	.252	-.093
Lag Jun	.080	-.076	.343	-.046
Lag Jul	.023	-.104	.139	.038
Lag Aug	-.038	.153	.076	.084
Lag Sep	-.002	.140	.099	.051
Lag Oct	.042	.292	.201	.013
Lag Nov	.059	.304	**.345***	.000
Lag Dec	.050	.305	**.456****	-.003

Table 13. Correlations between growth and PDSI for complete chronology (1913-2011); early (1913-1945), middle (1946-1978), and late (1979-2011) periods. Lagged months indicate previous year variables. Bold-faced values indicate statistically significant correlations ($p < 0.05$). * Significant at the 0.05 level. **Significant at the 0.01 level.

	Correlation with precipitation			
Month	Complete	Early	Middle	Late
Jan	.194	.318	.079	.126
Feb	-.022	-.124	.083	-.032
Mar	-.045	-.036	-.125	.015
Apr	-.061	-.059	-.259	.095
May	.142	.204	.256	.082
Jun	.355**	.308	.556**	.275
Jul	.263**	.542**	.013	.199
Aug	.055	.003	.065	.110
Sep	.122	.335	.096	-.015
Oct	.083	.008	.208	.136
Nov	.007	.265	-.171	-.106
Dec	.061	.183	-.004	.006
Lag Jan	-.200*	-.101	.180	.069
Lag Feb	.020	.006	.028	.082
Lag Mar	-.070	-.448**	-.313	.103
Lag Apr	.037	.036	-.054	-.138
Lag May	.178	-.308	.234	-.119
Lag Jun	-.002	-.139	.282	.036
Lag Jul	.018	-.110	-.175	.137
Lag Aug	-.094	.378*	-.006	.228
Lag Sep	.031	.052	.066	.008
Lag Oct	.081	.323	.264	-.132
Lag Nov	.041	.218	.341	-.041
Lag Dec	-.021	.321	.366*	-.027

Table 14. Correlations between growth and precipitation for complete chronology (1913-2011); early (1913-1945), middle (1946-1978), and late (1979-2011) periods. Lagged months indicate previous year variables. Bold-faced values indicate statistically significant correlations ($p < 0.05$). * Significant at the 0.05 level. **Significant at the 0.01 level.

	Correlation with temperature			
Month	Complete	Early	Middle	Late
Jan	.102	.132	.095	.088
Feb	-.037	.105	.083	-.294
Mar	.031	.013	.031	.075
Apr	-.079	.059	-.328	-.021
May	-.126	-.352*	-.010	-.040
Jun	-.252*	-.527**	-.188	.043
Jul	-.121	-.265	-.088	.005
Aug	-.140	-.494**	.019	.065
Sep	.035	-.024	-.053	.212
Oct	.077	.129	.031	.038
Nov	.054	.179	.023	.022
Dec	-.093	-.081	-.137	-.075
Lag Jan	-.130	-.044	.137	-.228
Lag Feb	-.026	-.107	.129	-.405*
Lag Mar	.086	-.114	-.051	.005
Lag Apr	.211*	.022	.002	.124
Lag May	-.063	.017	.028	-.038
Lag Jun	-.074	-.162	-.139	.127
Lag Jul	-.148	-.066	.144	-.140
Lag Aug	.016	-.130	.310	-.046
Lag Sep	-.159	.131	.086	.008
Lag Oct	-.159	.249	-.036	.069
Lag Nov	.211*	.168	-.087	-.040
Lag Dec	.060	.023	.145	-.140

Table 15. Correlations between growth and temperature for complete chronology (1913-2011); early (1913-1945), middle (1946-1978), and late (1979-2011) periods. Lagged months indicate previous year variables. Bold-faced values indicate statistically significant correlations ($p < 0.05$). * Significant at the 0.05 level. **Significant at the 0.01 level.

Chapter 5: Discussion

5.1 Seedling and sapling regeneration

Shade-intolerant saplings (*Quercus alba*, *Quercus spp.* and *Quecus spp.* + *Carya spp*) and *Quercus spp.* seedlings had greater relative densities in the burned stand of Shawnee State Forest. The greater relative density increased their competitive status relative to shade tolerant saplings and seedlings (*Acer spp.*, *Fagus grandifolia*). *Quercus spp.* seedlings and saplings have important physiological adaptations that enable them to gain a competitive advantage over other species following fire. *Quercus spp.* that are killed are able to resprout vigorously from carbohydrate reserves stored in the roots (Dey et al. 1996). Fire is the only natural disturbance capable of clearing multiple hectares of understory at a time (Oliver and Larson 1996). This form of disturbance enables *Quercus spp.* to gain a competitive advantage over other seedlings and saplings that are not able to resprout as vigorously (Hutchinson et al. 2012b).

Prescribed fire research typically involves sampling an area prior to burning (e.g., Brose and van Lear 1998). The burned stand was not sampled prior to the 2009 wildfire and *Quercus spp.* regeneration could have already had an elevated competitive status. However, this study actively sampled a much greater area (m^2) per treatment than other similar studies (Table 16). Additionally, these studies did not examine regeneration in canopy gaps. Hutchinson et al. (2012b) conducted a study approximately 130 km northwest of Shawnee State Forest in the Vinton Experimental Forest (VEP), Vinton County, Ohio. They found fire improved the competitive status of shade-intolerant species in canopy gaps, and they were able to sample the canopy gaps prior to fire. Furthermore, results from Hutchinson et al. (2012a) suggest that fire improved the competitive status of shade-intolerant species regeneration during the 13 year study with several prescribed fire regimes.

The increased competitive status of shade-intolerant species regeneration was not a direct result of fire. The reduction of seedlings, suppressed trees and intermediate trees in the burned stand suggest that fire altered other stand dynamics that may have indirectly improved shade-intolerant regeneration. Results from studies of prescribed fire suggest that factors such as understory density reduction and shelterwood removal helped promote shade-intolerant regeneration (Brose and van Lear 1998, Hutchinson et al. 2005., Iverson et al. 2008, Brose 2010). The burned stand had significantly fewer seedlings ha^{-1}. This enabled *Quercus spp.* to have a greater relative density in the burned stand, and decreased the relative density of *Acer rubrum* seedlings. Fire also reduced the number of saplings, suppressed canopy class trees, and intermediate canopy class trees. This reduction allowed more growing space to be available for shade-intolerant regeneration. The high severity of the 2009 wildfire also resulted in mortality of many large codominant trees. The burned stand only contained 120 codominant trees ha^{-1}, whereas the unburned stand contained 229.

This reduction in overstory trees allowed increased light to reach the understory, which is similar to the way shelterwood harvests promote the same process.

Management goals for prescribed fire have been outlined in several studies (e.g., Brose et al. 2001, Abrams 2005, Arthur et al. 2012), and these goals are oriented to decrease the total density of the understory to improve the competitive status of *Quercus spp*. Ideally, this should result in a lower % of *Acer rubrum* and a higher % of *Quercus spp.* Additionally, thinning the overstory to increase the light availability in the understory also gives *Quercus spp.* a competitive advantage. Although these goals were developed for prescribed fires as a best case scenario, this study of a high intensity out-of-control wildfire represents a worst case scenario for land managers. However, most of the results from this study are favorable when placed into the context of management goals for prescribed fire (Table 17). This study found that fire helped accomplish 14 out of 16 management goals to improve *Quercus spp.* regeneration (Table 17).

Study	Location	Seedling/sapling area sampled (m^2) per treatment
Arthur et al. (1998)	Kentucky	120
Blankenship and Arthur (2006)	Kentucky	200
Brose and van Lear (1998)	Virginia	300
Barnes and van Lear (1998)	Virginia	225
Hutchinson et al. (2005)	Ohio	Seedling:1350; Sapling: 2812
This study	Ohio	2500

Table 16. Seedling and sapling area (m^2) sampled in five other fire-oak regeneration studies in Kentucky, Ohio, and Virginia.

Management goals for prescribed fire to improve oak regeneration/competitive status	This study Unburned	 Burned
Increase the relative density (%) of *Quercus alba* saplings	1%	5%
Increase the % of *Quercus spp*. Saplings	5%	18%
Increase the % of *Quercus spp*. + *Carya spp*. Saplings	10%	24%
Decrease the % of *Acer rubrum* saplings	15%	21%
Increase the % of *Quercus alba* seedlings	9%	4%
Increase the % of *Quercus spp*. Seedlings	42%	58%
Increase the % of *Quercus spp*. + *Carya spp*. Seedlings	44%	63%
Decrease the % of *Acer rubrum* seedlings	26%	6%
Increase the density (stems ha^{-1}) of *Quercus alba* saplings	40	120
Increase the density of *Quercus spp*. Saplings	134	428
Increase the density of *Quercus spp*. + *Carya spp*. saplings	291	548
Decrease the density of *Acer rubrum* seedlings	1400	64
Decrease the total density of all seedlings	5405	1108
Decrease the total density of all saplings	2845	2300
Decrease the number of suppressed canopy class trees	31	4
Decrease the number of intermediate canopy class trees	229	64

Table 17. Common management goals for prescribed fire (Brose et al. 2001, Abrams 2005, Arthur et al. 2012) in mixed-oak forests and results from this study of a severe wildfire in Shawnee State Forest, Scioto County, Ohio.

5.2 Canopy class distribution

The lack of suppressed, intermediate and codominant trees in the burned stand indicates that the 2009 wildfire was severe. The fire altered growing space and increased light availability to the understory. Although the canopy class distributions indicate that growing space had been altered and light availability was greater in the burned stand, the unburned canopy gaps were the only comparable sites in the rest of the forest where growing space had undoubtedly been altered. The unburned canopy gaps were subjected to the severe ice storm of 2003, and many other disturbance events identified in the disturbance history (Figure 7).

Because canopy class distributions were composed of stems larger than saplings (trees >5cm dbh), trees that were killed by the wildfire were not able to reach that stage in four growing seasons. The mortality of saplings caused by the wildfire of 2009 was relatively undetectable because they were able to regrow during the past four growing seasons, and a similar total density as the unburned canopy gaps (Table 6). However, the trees that were sampled in the canopy class distribution were larger, and those that were killed have not had enough time to grow back to trees >5cm dbh. Some of these trees >5cm dbh are adapted to survive fire better than others, and thus were not killed (Oliver and Larson 1996). The higher relative density of *Liriodendron tuplipifera* in the midstory (suppressed+intermediate) of the unburned canopy gaps indicates that it is less adapted to withstand fire than other disturbance events. The glaze ice storm of 2003 favored the establishment of *Liriodenron tulipifera* in the unburned canopy gaps (Figure 5), but the wildfire of 2009 reduced its' density. The intermediate classes of *Nyssa sylvatica* and *Oxydendron arboreum* also showed a higher mortality in the burned stand. *Quercus spp*. is able to compartmentalize wounds from fire better than other species (Smith and Sutherland 1999). The increased relative density of *Quercus spp.* in the midstory and overstory (codominant and dominant) (Figure 3) of the burned stand indicates that it was more fire tolerant than other species (Abrams 2005).

The canopy class distributions of the unburned canopy gaps represent the most likely successional trajectory of Shawnee State Forest, which is similar to other studies that have found *Quercus spp.* in the codominant and dominant canopy classes, but a lack of *Quercus spp*. in the suppressed and intermediate classes (McCarthy and Bailey 1996, McCarthy et al. 2001, Hart et al. 2008, van de Gevel et al. 2012). *Quercus spp.* saplings in the burned stand are likely to recruit to larger size classes within the next decade because of decreased competition and their ability to resprout vigorously from root-stalk (Dey et al. 1996). Conversely, *Quercus spp*. in the unburned canopy gaps are less likely to recruit to the higher size classes due to their lack of abundance, decreased relative density, restricted light availability, and increased competition in the understory.

5.3 Basal area

The basal area was greater in the burned stand than in the unburned stand. This result was not expected, but may have been caused by a small number of very large trees being included in the sample. For example, a *Liriodendron tulipifera* individual in the burned stand had a dbh of 85.2 cm and basal area of 0.5674 m^2 ha^{-1}, and there were five other very large *Liriodendron tulipifera* individuals with dbh > 50 cm in the burned stand. Trees sampled in the burned stand may have had greater basal area due to the changes in nutrient availability and decreased competition after the fire. Research at the VEF suggests that fire increases the Ca^{2+} availability and raises the soil pH (Boerner et al. 2004). Soils of the study site are very acidic (3.6-4.5 pH) so it is likely that the rise in pH following the 2009 wildfire made unavailable nutrients become available (McCleary et al. 1989). Additionally, canopy class distributions show decreases in the suppressed, intermediate, and codominant classes which reduced competition for water and nutrients. This combination of increased nutrient availability and decreased competition likely increased the basal area in the burned stand.

5.4 Diameter-age relationship

The overall pattern of tree establishment is similar to Hart et al. (2008) and van de Gevel et al. (2012). Large *Quercus spp.* established in the earliest period and smaller shade-tolerant species (*Acer spp.*, *Nyssa sylvatica*, *Oxydendron arboreum*) established consistently throughout the most recent 70 years. The recruitment of shade-tolerant species throughout the last 100 years is also consistent with a nearby study (McCarthy et al. 2001). The largest cohorts established during the 1920s and 2000s. The large number of *Quercus spp.* that established in the 1920s were most likely the result of logging cessation within those stands during the early 1900s. Conversely, the cohort of *Liriodendron tulipifera* that established during the 2000s was the result of the 2003 glaze ice storm.

The diameter class distribution (Figure 6) shows the inverse-J distribution typical of a regenerating forest (Hart et al. 2008). Most of the trees in the forest were *Acer spp.*, *Liriodendron tulipifera*, *Nyssa sylvatica*, and *Oxydendron arboreum* between five and 19.9 cm dbh. These trees will likely become the future dominant and codominant trees in Shawnee State Forest as the mature *Quercus spp*. die-out. This same process is underway at a nearby old-growth forest (McCarthy et al. 2001).

5.5 Disturbance history

The disturbance history highlights the temporal frequency and spatial magnitude of disturbances prior to the ice storm of 2003 and the wildfire of 2009. The 10-year running median method that was used in other studies (Rubino and McCarthy 2004, Hart et al. 2011) was not able to capture the ice storm of 2003 because there were not 10 years of growth to analyze after it. Despite not capturing the ice storm of 2003, the disturbance history did capture 78 release events between 1935 and 2001. The majority of the increment cores (70%) used to reconstruct disturbance history were from the unburned canopy gaps. This indicates that the most of the disturbance events in the forest were most likely from the unburned stand and specifically within the canopy gaps sampled. Therefore, the unburned canopy gaps had been subjected to numerous disturbance events prior to the ice storm of 2003.

Although the disturbance history does not directly analyze the difference between unburned canopy gaps and the burned stand, it does explicitly verify that periodic disturbances have occurred in the canopy gaps since 1935. This is important because it verifies that the type of disturbance is responsible for influencing species assemblages in the forest. Regardless of the frequency and magnitude of the disturbances in the history, each disturbance type has different effects on the biotic and abiotic processes within the forest that ultimately effect the composition (Oliver and Larson 1996).

5.6 Growth-climate relationship

PDSI had the highest correlation with radial growth in this study and in a nearby study (Rubino and McCarthy 2000). PDSI takes into account soil moisture and temperature, variables that are both responsible for driving drought stress (Speer 2010). The early period trees had stronger relationships with climate variables than the middle period, late period, and complete chronology. This indicates that there was an age-related shift in climate response of *Quercus spp*. Another study of *Quercus spp.* found a greater growth-climate relationship in the younger trees (Haavik et al. 2011). Conversely, (Copenheaver et al. 2011) found a greater growth-climate relationship in the older trees.

The age-related shift in climate response has been attributed to causes such as increased CO^2, changing climate, insect outbreaks, fire suppression, chronic N deposition, and changes in tree physiology (Szeicz and MacDonald 1994, Bond 2000, Copenheaver and Abrams 2003, Carrer and Urbanati 2004, Voelker et al. 2006, Copenheaver et al. 2011, Haavik et al. 2011). The shift in growth-limiting climate variables throughout the life cycle of *Quercus spp*. also has been identified in central Virginia where it was linked to physiological changes that occur with tree age, and a shift in growth-limiting resources (Copenheaver et al. 2011). CO^2 enrichment throughout the last 150 years has increased the growth of *Quercus spp.* and *Pinus echinata* in Missouri (Voelker et al. 2006). The gypsy moth (*Lymantria dispar* L.) has reduced growth and increased mortality rates of *Quercus alba* throughout its' range, and likely decreased the climate response during favorable growth periods (Muzika and Liebold 2011).

Additionally, there also was a shift in the seasonality of the relationship. Younger trees (1913-1945) had a higher response to September climate variables than older trees (1979-2011). The relationships between climate and radial growth of the younger trees extended later into the growing season whereas the strongest relationships in the complete chronology were in July/August.

Results from this study suggest that the age-related shift in climate response could be caused by the increased magnitude and frequency of disturbances as the forest matured (Oliver and Larson 1996). The disturbance history from this study indicates that disturbances influence growth, and were also frequent throughout the development of the forest (Hart et al. 2011). Disturbance events are able to alter tree growth because they increase the light availability and decrease the competition for below-ground resources (Runkle and Yetter 1987, Canham et al. 1990, Montgomery and Chazdon 2002).

Furthermore, individual drought years and/or high precipitation years were only able to alter ring widths for 1-2 growing seasons. On the contrary, disturbance events in this study altered radial growth for the following ten years, and many of these releases were sustained for 12 years or more. This indicates that long-term ring width releases are more indicative of gap-phase dynamics rather than climate.

Chapter 6: Conclusion

This study investigated the disturbance history and effects of two recent severe disturbances on stand dynamics in Shawnee State Forest, Scioto County, Ohio. Several large scale and many localized disturbances in the unburned canopy gaps failed to improve the competitive status of *Quercus alba* and *Quercus spp* seedlings and saplings. The lack of *Quercus spp.* in the suppressed and intermediate canopy classes indicates that fire-free disturbances are unlikely to allow their regeneration. The fire uniquely altered growing space and light availability in such a way that improved their competitive status. Although the burned stand also lacks *Quercus spp*. in the suppressed and intermediate classes, there have only been four growing seasons prior to this study. It took at least eight growing seasons for the youngest trees in this study to reach 5cm dbh. The canopy class distributions also suggest that *Quercus spp*. is relatively fire-tolerant, while *Liriodendron tulipifera* is more tolerant of fire-free disturbances.

6.1 Major Conclusions

1. The higher relative densities of *Quercus alba*, *Quercus spp*., and *Quercus spp.* + *Carya spp.* saplings in the burned stand suggest that fire is important for regeneration.

Even though other disturbance events altered growing space and species compositions throughout the past 65 years, fire was unique in respect to *Quercus spp.* regeneration. Despite the high severity of the 2003 ice storm, regeneration in the unburned stand was less than in the burned stand. This suggests that fire is a unique disturbance event, and that these species must rely on it for regeneration.

2. The basal area was greater in the burned stand than in the unburned stand, but only because of several large *Liriodendron tulipifera* individuals.

There was greater total basal area in the burned stand, which could also indicate that many of the trees were growing faster following the fire. This is unlikely since these trees were measured just four growing seasons after the fire. Even though the results do not suggest that fire will increase basal area, they do suggest that a reduction in basal area is less likely following fire. Most of the mortality in the burned stand was in the suppressed and intermediate classes, which contribute very little to the overall basal area of the stand.

3. Diameter-age relationships show that *Quercus spp.* has not been able to establish since the early 1940s, and that the last severe disturbance of 2003 promoted the establishment of *Liriodendron tulipifera*.

Quercus spp. remained absent from the cohorts that established following several disturbances after the 1930s. This suggests that *Quercus spp.* is unlikely to establish in the absence of fire. Shade-tolerant (*Acer spp.*, *Fagus grandifoolia*, *Oxydendron arboreum*, *Nyssa sylvatica*) trees were able to establish in every decade since the 1920s. Most of the trees in the forest (68%) were less than 20 cm dbh, which is indicative of a regenerating forest.

4. The disturbance history detected a total of 33 years with disturbance events between 1935 and 2001, indicating disturbances have likely played a role in species composition shifts.

Most of the release years were clustered during the 1940s, 1960s, 1980s and late 1990s. The high frequency of release events in these decades indicates that these were the periods that were most affected by disturbances. As the stand matures, the magnitude of disturbance is likely to have greater impacts on species compositions in the forest. Also, more stand-wide disturbance events are likely to occur. These events influence species composition as well as the growth-climate relationship of *Quercus spp.*

5. The growth-climate relationship of *Quercus spp.* is highest in the early period and lowest in the later period.

Trees in the early period (1913-1945) had a greater frequency of significant relationships with climate variables than the late period (1979-2011). Drought conditions were the most growth-limiting, but the correlation decreased through time. The frequency and magnitude of disturbances likely influenced the climate-growth relationship in the late period. Although tree physiology changes throughout the tree's life cycle, disturbance events in this study clearly altered decadal trends in tree growth at several periods throughout the disturbance history. Severe droughts were only capable of reducing growth for 1-2 years, whereas the disturbances influenced growth for at least 10 years, and in many cases 12-15 years. The combination of the high frequency of disturbance events recorded in 1999, and the ice storm of 2003 likely decreased the growth-climate relationship in the late period.

6.2 Future research and improvements

This research helps to bridge an important literature gap between the paleoecological history of fire and contemporary effects of fire in southern Ohio. This type of methodology could be used to help bridge that same gap in other regions. Future research should continue to analyze forest stand dynamics and disturbance history within the site, and examine the contemporary role of fire. Additional research in Shawnee State Forest should examine the stand dynamics of another fire that burned in 2003. This stand would likely have a longer temporal component and enable some *Quercus spp.* regeneration to be evident in the canopy class distributions.

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Vita

Reece M. Brown was born in Portsmouth, OH where he attended Notre Dame Elementary. He graduated from Northwest High School in nearby McDermott, OH. He earned a Bachelor of Science in Natural Science at Shawnee State University in Portsmouth, OH. His undergraduate research project was awarded the John C. Johnson award for first prize in the Poster Competition at the Regional Beta Beta Beta Honors Biological Society Meeting in Cadillac, MI in April of 2010. He ran three years of Cross Country for Shawnee State where he was voted co-captain and received the award for "Most Improved Runner."

In August of 2011 he began studies toward a Master of Arts degree in Geography at Appalachian State University in Boone, NC. His assistantships and research interests were rooted in the Appalachian Tree Ring Lab. He presented posters of his research at the Southeastern Division of the Association of American Geographers conference in Asheville, NC and at the North American Forest Ecology Workshop in Bloomington, IN. He was also a graduate administrative assistant for the Appalachian State University Cross Country team.

The M.A. was awarded in August, 2013. Following graduation Mr. Brown took an assistant coaching position at his undergraduate alma mater Shawnee State University. He plans to coach cross country and track at the collegiate level for the years to come.