

DECADAL-SCALE TRENDS IN FOREST SUCCESSION AND CLIMATIC
SENSITIVITY IN A RED SPRUCE-FRASER FIR FOREST AT ROAN MOUNTAIN,
PISGAH AND CHEROKEE NATIONAL FORESTS

A Thesis
by
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ABSTRACT

DECADAL-SCALE TRENDS IN FOREST SUCCESSION AND CLIMATIC SENSITIVITY IN A RED SPRUCE-FRASER FIR FOREST AT ROAN MOUNTAIN, PISGAH AND CHEROKEE NATIONAL FORESTS

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I used dendrochronological techniques to investigate the temporal stability of a climate signal in relation to successional processes and disturbance events in the heavily disturbed red spruce (*Picea rubens* Sarg.) and Fraser fir [*Abies fraseri* (Pursh) Poir.] forest of Roan Mountain, Tennessee and North Carolina. To document precise temporal information on the stand age, disturbance regime, recruitment patterns, and successional trajectory of the forest community, I collected increment cores from all trees within six 0.05 ha plots located in spruce-fir co-dominant stands. I developed a red spruce tree-ring chronology from cores collected in my sampling plots and from trees located elsewhere in the study area. To test the stability of regional climate signals, I performed statistical correlation and response function analyses within moving intervals using DendroClim 2002 software. Red spruce was the oldest dominant canopy species, while Fraser fir exhibited the most prolific recruitment patterns with high amounts of regeneration during the past 50 years. Changes in forest structure and species richness coincided with stand-wide disturbance events such as balsam woolly adelgid (*Adelges piceae* Ratz.) infestation and widespread early twentieth-century logging. I detected shifts in climatic sensitivity

during periods of changing forest composition following disturbances. Most notably, a significant shift in red spruce temperature sensitivity occurred during the 1940s, coinciding with a period of aggressive clearcut logging. Red spruce climatic sensitivity was often sporadic and fluctuating in signal strength, leading to the hypothesis that stand dynamics may play a larger role than climate in limiting spruce-fir tree growth in a frequently disturbed, closed canopy forest. As exogenous disturbances are expected to continue altering the structure of this forest throughout the region, the climatic sensitivity of these species may become increasingly unstable.

DEDICATION

This thesis is dedicated to my mother and father for the learning spirit they instilled in me and to my wife Krista for her enduring love and support.

God has cared for these trees, saved them from drought, disease, avalanches, and a thousand tempests and floods. But he cannot save them from fools.

— John Muir

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CHAPTER 1

INTRODUCTION

1.1 Background

The red spruce (*Abies picea* Sarg.) and Fraser fir [*Abies fraseri* (Pursh) Poir.] forest of the southeastern United States has undergone a major shift in structure and composition during the last several decades, and has been the subject of much scholarly research (Johnson and Siccama 1983, Cook *et al.* 1987, Dull *et al.* 1988, Eagar and Adams 1992, Goelz *et al.* 1999, Busing 2004). Anthropogenic activities have resulted in an alteration of the forest's natural disturbance and successional regimes. Researchers have also hypothesized an alteration of the forest as a result of human-induced climate change (Cook and Johnson 1989). Red spruce and Fraser fir dominate the subalpine forest of the southern Appalachians, and the forest community exists in only a few disjunct, island populations. The spruce-fir forests of the southern Appalachians have greater height and plant diversity than similar northern forests, and sustain several endemic species (Delcourt and Delcourt 2000). The rare southern spruce-fir forest type is highly valued by ecologists, park and land managers, silviculturists, and the public; and currently there is a great deal of concern regarding the resilience and vigor of this ecosystem.

During the mid-20th century, scientists observed widespread growth decline and tree mortality in the red spruce-Fraser fir co-dominant forests in the southern ranges of

the Appalachian Mountains (Hornbeck and Smith 1985, Adams and Eagar 1992). Since the 1950's, an invasive exotic pest that kills mature Fraser fir trees, the balsam woolly adelgid (*Adelges piceae* Ratz.), has cyclically infested the southern spruce-fir forest at differing time scales at different locations. The balsam woolly adelgid rapidly killed approximately 67% of mature Fraser fir trees across its range (Dull *et al.* 1988), drastically altering the natural disturbance regime of the spruce-fir forest. Few mature Fraser fir specimens remain today, and the removal of Fraser firs from the ecosystem has had both favorable and adverse effects on red spruce ecology (Busing *et al.* 1993, Busing 2004).

Previous researchers have asserted red spruce to be in a state of decline since the 1960s (Hornbeck and Smith 1985, Eagar and Adams 1992). Some (Cook and Johnson 1989, Webster *et al.* 2004) have described the 20th century red spruce decline as an abnormal event, leading to the conclusion that the decline may be related to human alterations to the environment. Anthropogenic disturbances such as pollution and acidic deposition have been presented as causes (Mohnen *et al.* 1990, Adams and Eagar 1992, Webster *et al.* 2004). Others have suggested that CO₂- induced global warming could be detrimentally affecting red spruce through temperature stress (McLaughlin *et al.* 1987, Cook and Johnson 1989). Determining a single cause for the decline is difficult because forests are complex systems that are subjected to multiple stresses, and often respond slowly to those stresses (Cook and Johnson 1989, Pitelka and Raynal 1989). Although scientists determined with relative certainty that red spruce was experiencing a reduction in growing vigor in its northern populations (Cook *et al.* 1987, Cook and Johnson 1989), the prevalence of a decline in the species' southern population was uncertain (Hyink and

Zedaker 1987, Cook and Zedaker 1992). Furthermore, recent research has found some southern Appalachian red spruce stands to be in a state of increased growth, bringing the presence of a decline into debate (Goelz *et al.* 1999). However, as little research has been conducted on the subject since the early 1990s (except see Busing 2004), scientists remain uncertain of the 20th century red spruce decline in the southern Appalachians, the causes of decline, and the overall current status of red spruce health.

The science of dendrochronology (tree-ring dating) has developed into a leading method for recording climate trends and monitoring natural ecological processes and human-caused changes in the environment. In temperate or seasonal environments, the annual nature of tree growth permits the tree to serve as a bio-recorder for the duration of its lifetime. By studying these annual growth rings, scientists can determine how forests have changed over time and relate growth with climatic factors such as temperature, precipitation, and drought (Fritts 1976). Because these climatic factors often regulate tree growth, much of our current knowledge of Earth's past climate has been inferred from tree-ring data (Jacoby and D'Arrigo 1989, Meko *et al.* 1995, Esper *et al.* 2002). This ability accentuates the importance of tree-rings as a tool for understanding forest dynamics and climatic variability on a temporal scale.

Growth rates of red spruce and other tree species that exist at high elevations and latitudes are thought to be primarily limited by temperature (Fritts 1976). In other words, tree species inhabit these areas because temperatures there are cool enough to support them, and temperature is the primary regulator of tree growth. In addition, trees that exist near the outer limit of its species' range are believed to be the most climatically sensitive because they inhabit areas that are nearest to their climatologically limiting factors (Fritts

et al. 1965). Therefore, prevailing dendroclimatic thought would dictate that disjunct populations of red spruce along the peaks of the southern Appalachian Mountains would be among the most temperature sensitive of the species. Though dendroclimatologists have found red spruce to be a useful indicator of climate change, little research with the species has taken place in the southern Appalachian Mountains since the 1980's (Cook 1988), and scientists do not fully understand the relationships between tree growth, climate, and stand dynamics in the Southern Appalachian spruce-fir forest (Cook and Zedaker 1992). Research has also shown that shifts in the prevailing climate regime affect how the environment regulates spruce-fir forest productivity (Cook 1988, Cook and Zedaker 1992).

Dendroclimatologists have recently discovered that the relationship between some tree species and climate may be more complex than previously understood, particularly with temperature sensitive tree species (such as those found at high elevations or latitudes) (D'Arrigo *et al.* 2008). Many recent studies have tested the temporal stability of the relationship between temperature and tree growth and found that temperature-sensitive trees may not respond consistently to climate variables over time (Jacoby and D'Arrigo 1995, Briffa 2000, D'Arrigo *et al.* 2004). Hence, a divergence may exist between instrumentally recorded climate data and tree-ring derived climate inferences. This revelation, labeled the "divergence problem," has developed into a major concern for the dendroclimatology field, as it calls into question the validity of standard dendroclimatological principles and data analyses (D'Arrigo *et al.* 2008). As a result, it has become essential that researchers seeking to reconstruct past climate using tree rings carefully inspect the climate-tree growth relationship to avoid erroneous predictions of

past climate. No research has attempted to investigate how small scale forest disturbance may affect the stability of the red spruce climate signal. Moreover, the presence of a divergence between climate and tree growth may be specific to a particular site or species characteristics (D'Arrigo *et al.* 2008), accentuating the importance of a close inspection of disturbance history when studying climate-growth relationships.

Among the highest peaks of the Appalachian Mountains, Roan Mountain hosts one of the region's few red spruce-Fraser fir forest communities. Demarcating the boundary between a portion of Tennessee and North Carolina, the Roan Massif area has endured a century of European land use change and disturbance that have greatly affected the ecology of its high-elevation landscape. The spruce-fir forest above 1,650 m on Roan Mountain has been heavily disturbed in the past century. Intensive logging operations on the mountain in the 1930s (Wilson 1991) and repeated balsam woolly adelgid infestations have drastically altered the natural stand dynamics and successional trajectory of the forest (Dull *et al.* 1988, Potter *et al.* 2005), yet no previous dendrochronological research has sought to quantify the reaction of this forest to these disturbances. As no prior large-scale dendroecological investigations have been conducted on Roan Mountain, a thorough investigation of the forest's stand age, composition, and successional trajectory is needed. Furthermore, the forest provides an opportunity to explore how the interaction between climate and disturbance influences red spruce tree growth over time. Thus, this investigation fills an important gap in our understanding of this rare and threatened plant community.

1.2 Objectives

My master's thesis research seeks to explain the complex interactions between climate, disturbance, and stand dynamics in the boreal disjunct red spruce-Fraser fir forest of Roan Mountain. The specific research objectives of my thesis project include:

1. How has Roan Mountain's red spruce-Fraser fir forest developed following the cessation of logging activities in the late 1930s, and what is its current successional status?
2. What role have forest disturbances such as balsam woolly adelgid infestation played in shaping the current spruce-fir forest structure?
3. Are climatic factors the primary regulators of red spruce tree growth at Roan Mountain, or has excessive disturbance overridden the influence of climate over tree growth?
4. Which climatic factors, if any, regulate red spruce growth at Roan Mountain?
5. Is a red spruce climate signal strong and temporally stable, or does the climate response change over time?

CHAPTER 2

LITERATURE REVIEW

2.1 Biogeography of the Spruce-Fir Ecosystem in the Southern Appalachians

Red spruce is widely distributed across eastern North America, ranging from boreal forests of Canada to high-elevation forest communities of the southeastern United States (Figure 2.1). The northern distribution of the species ranges from central Quebec eastward through Ontario, Newfoundland, and Nova Scotia (USDA 2008a). The northern extent of red spruce is circa 49° N in New Brunswick, Canada (White and Cogbill 1992). The species forms near-continuous stands across low and high elevations in the New England states of Maine, New Hampshire, Vermont, and Massachusetts (White and Cogbill 1992, USDA 2008a). As its range extends southward, red spruce is restricted to the upper slopes of the Adirondack and Appalachian Mountains. At its southern extent in North Carolina and Tennessee (ca 35° N) (White and Cogbill 1992), spruce stands typically occur above 1,350 meters (Delcourt and Delcourt 2000).

Fraser fir is restricted to small, high-elevation island-like populations of the southern Appalachian Mountains (Figure 2.2). This rare species was a major historical component of the high-elevation spruce-fir forest of the southeastern United States and is endemic to the southern Appalachian Mountains. It is found only in mountainous regions of Virginia, Tennessee, and North Carolina, replacing its northern relative, the balsam fir

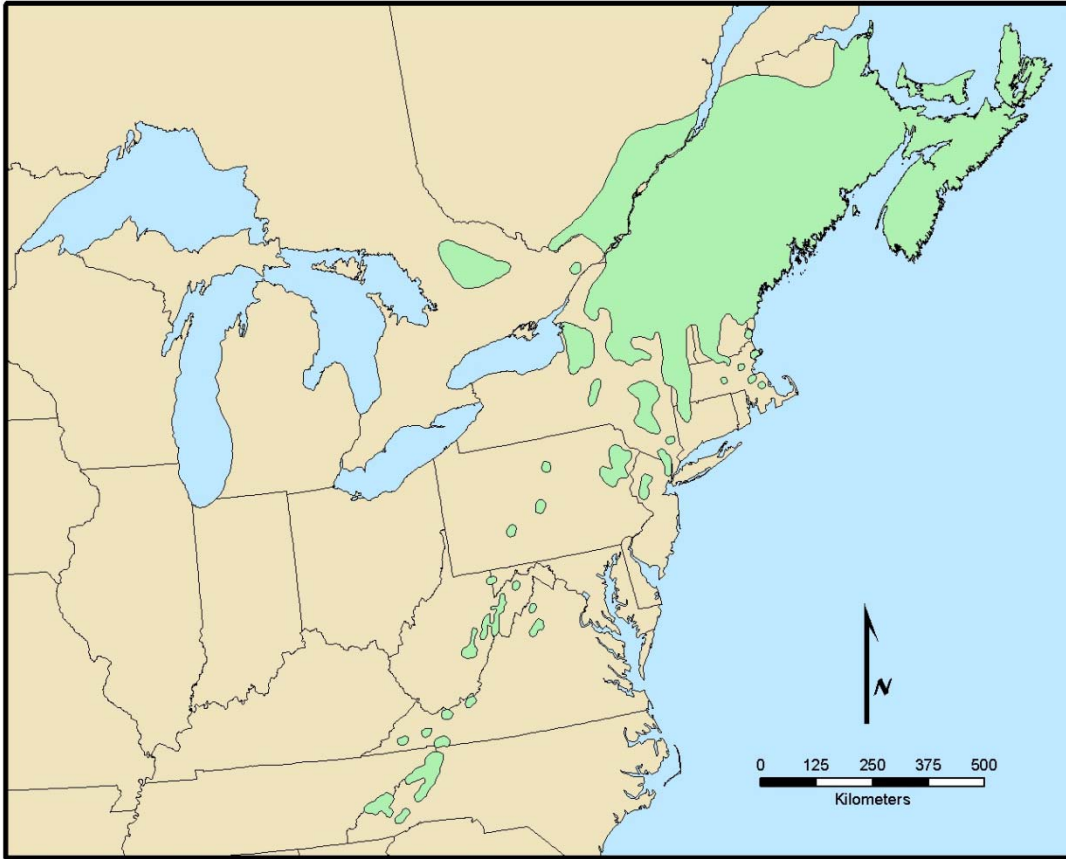


Figure 2.1 Map showing distribution of red spruce in eastern North America. Source: USDA 2010.

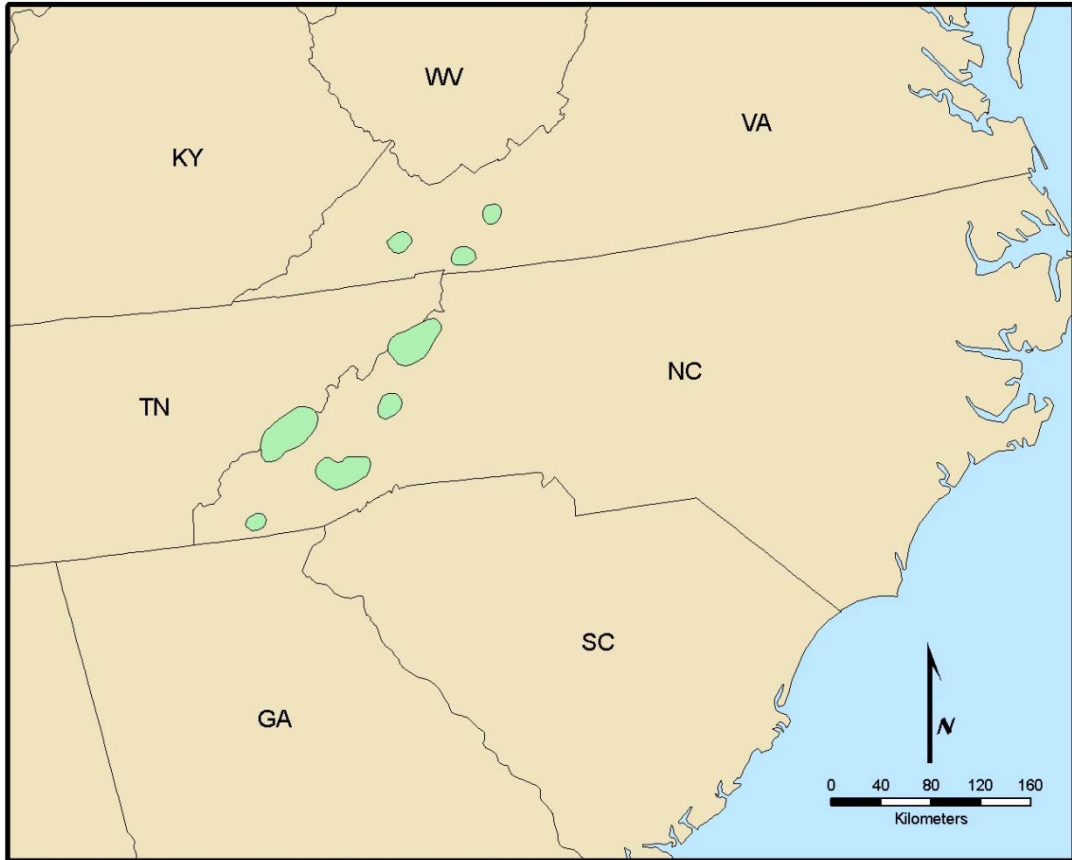


Figure 2.2 Map showing distribution of Fraser fir. Source: USDA 2010.

[*Abies balsamea* (L.) Mill.], in the southern spruce-fir forest (Delcourt and Delcourt 2000). Co-occurring with red spruce, Fraser fir becomes the dominant canopy species of the spruce-fir forest above 1,800 meters (Whittaker 1956, Busing *et al.* 1993). The species is listed as threatened by the federal government due to Balsam Woolly Adelgid infestation (USDA 2008a).

The spruce-fir ecosystem of the southern Appalachian Mountains is an archetypal mountain-island habitat. Webster *et al.* (2004) define island habitats as small disjunct populations, separate from larger contiguous stands. Such spruce-fir forests occur in only six major island populations: Mount Rogers in Virginia; the Great Smoky Mountains National Park (GSMNP) and Roan Mountain on the Tennessee/North Carolina border; and the Black Mountains, the Balsam Mountains, the Plott Balsams, and Grandfather Mountain in North Carolina (Figure 2.3, 2.4). There are also three small, secondary communities at Shining Rock, Cataloochee Balsam, and the Plott Balsams of North Carolina (Potter *et al.* 2005). A small population of red spruce also exists on Whitetop Mountain in Virginia, near Mount Rogers, but no Fraser fir are present (Potter *et al.* 2005). The southern montane spruce-fir forests are thought to be ice-age relicts of a vast boreal forest that dominated the southeastern United States during the Wisconsin Glaciation over 12,000 years ago (Whitehead 1981, Delcourt and Delcourt 1987).

The spruce-fir forest of the southern Appalachian Mountains is highly valued for both aesthetic and ecological reasons. The GSMNP is the most visited National Park in the United States, and the park and surrounding National Forests are a popular recreational destination for millions of tourists, travelers, and hikers each year (NPS 2008, USDA 2008b). Researchers value the forest because of its renowned biodiversity

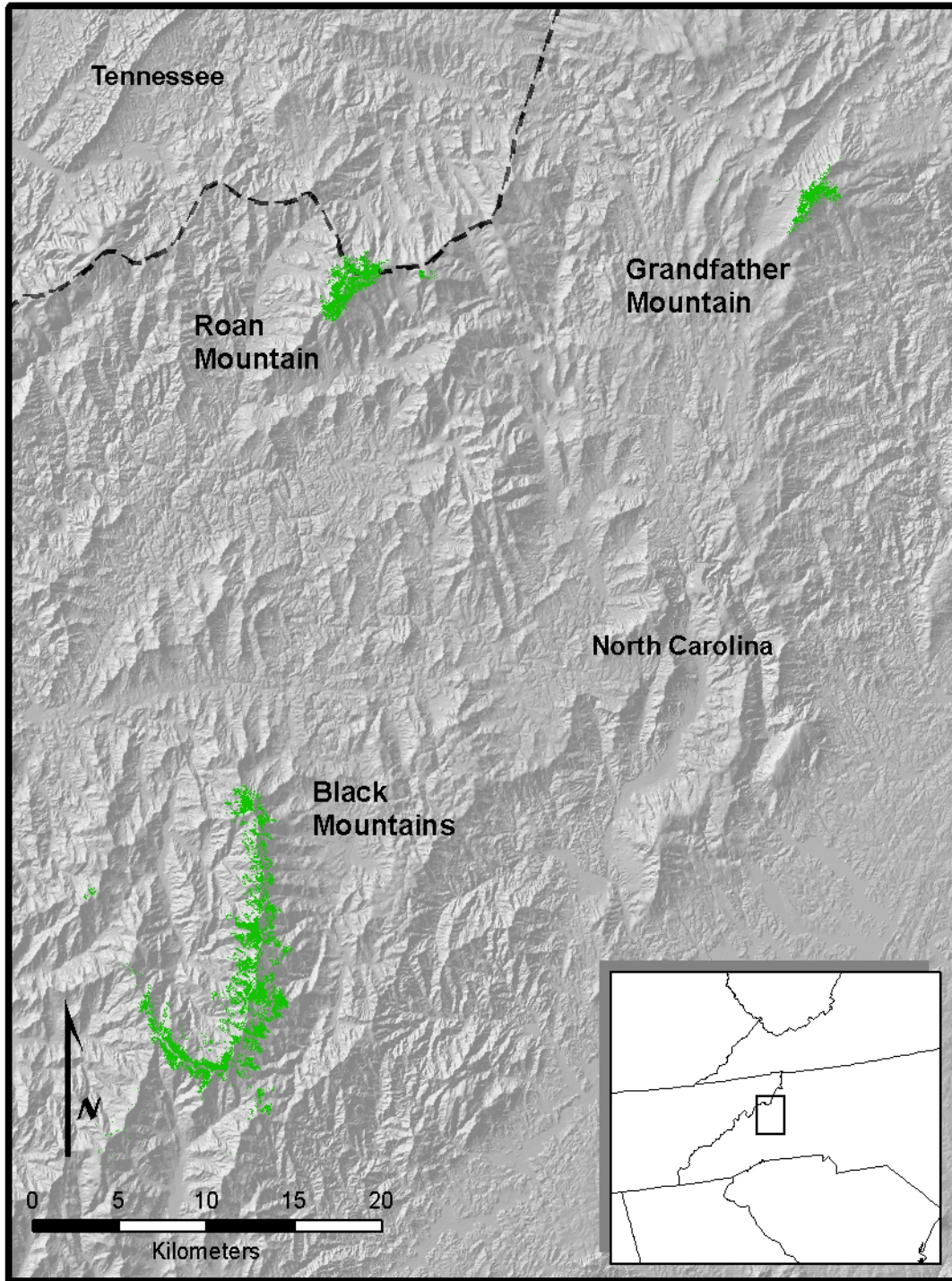


Figure 2.3 Mountain-top island populations of red spruce and Fraser fir (in green) at Roan Mountain, Grandfather Mountain, and the Black Mountains. Source: Southeast Gap Analysis Project (SEGAP 2010).

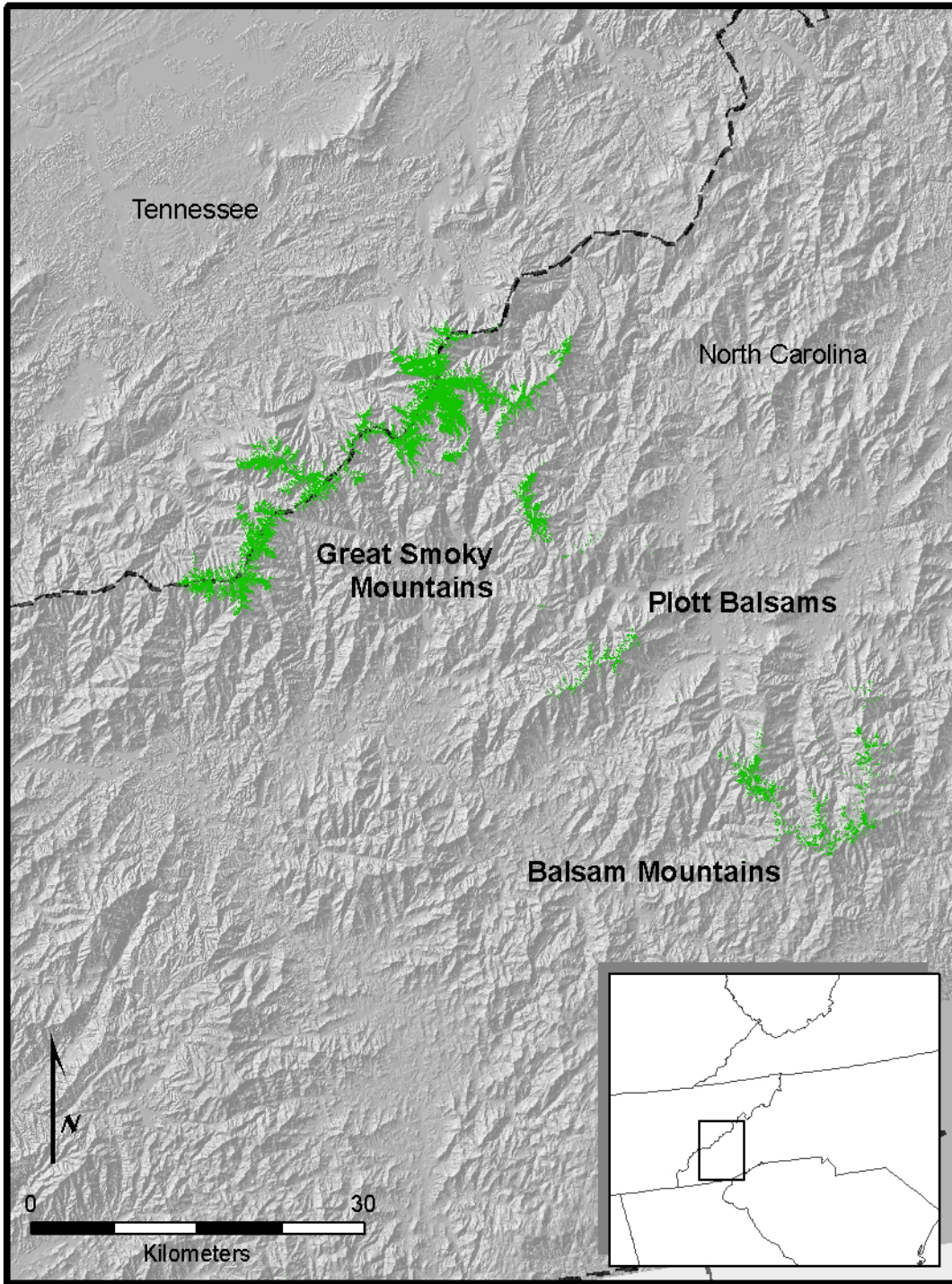


Figure 2.4 Mountain-top island populations of red spruce and Fraser fir (in green) at the Great Smoky Mountains, the Plott Balsams, and the Balsam Mountains. Source: Southeast Gap Analysis Project (SEGAP 2010).

and rare plant populations. The southern spruce-fir ecosystem also has a greater average tree height, greater herb and bryophyte cover, and more diverse understory than the northern spruce-fir forest (Oosting and Billings 1951, Whittaker 1956, White 1984, Delcourt and Delcourt 2000). White (1984) found eight vascular plants endemic to the forest out of 132 total catalogued vascular species. Additionally, the forest is a habitat for two endangered species: the Carolina northern flying squirrel (*Glaucomys sabrinus coloratus* Shaw) and the spruce-fir moss spider (*Microhexura montivaga* Crosby), and ten federally listed species of concern (USFWS 2008).

2.2 Succession in the Spruce-Fir Forest of the Southern Appalachians

Succession is a naturally occurring change in species composition over time within a given landscape (Oliver and Larson 2002). Successional changes that take place within a particular vegetation community often occur as a result of disturbances to the biotic life of that community. A disturbance is an event that damages and kills life in an ecological community, and it is the driving force behind successional changes (Oliver and Larson 2002). Examples of naturally occurring disturbances that result in structural and compositional forest changes include wildfire, insect or pathogen outbreaks, wind damage, mass movement, and flooding. Anthropogenic disturbances such as logging, grazing, and pollution also occur frequently. Forest disturbances are loosely categorized into two groups: minor disturbances that affect a forest on the scale of gap openings; and major disturbances that result in a complete removal of a forest stand (Oliver and Larson 2002). Minor disturbances occur at frequent intervals, but are typically limited to a smaller scale successional response. A major disturbance affects a forest less frequently,

but with a more devastating result. In addition, the longer a forest remains without experiencing a disturbance, the more likely it is to experience a major disturbance. This phenomenon is referred to as *predisposition* (Oliver and Larson 2002). For example, the longer a forest remains without a fire, the more woody debris builds up as fuel, resulting in a larger fire and, hence, a major disturbance. Though major disturbances result in more broad-scale successional changes, minor disturbances play a more significant role in the stand dynamics of a typical forest (Oliver and Larson 2002).

Succession is widely considered to occur in primary and secondary modes, the former resulting after a disturbance has removed all the natural land cover (no soil remaining) and the latter resulting after a disturbance has removed the vegetative canopy (soil and possibly herbaceous layer remaining) (Oliver and Larson 2002). For the purpose of this literature review, I will focus on the properties of secondary succession because it is the more frequently occurring successional process in the spruce-fir forest. Oliver and Larson (2002) describe four stages of successional activity following disturbance. The primary stage is the stand initiation stage. During this stage, shade-intolerant (and short-lived) pioneer species invade the disturbed area and densely establish themselves to begin the process of re-vegetation. The second stage occurs as the densely established shade-intolerants begin a process of self-thinning as the more vigorous individuals out-compete lesser individuals for sunlight. Oliver and Larson (2002) refer to this stage to as the stem exclusion stage. Later, the understory initiation stage occurs when shade-tolerant species begin repopulating the understory of the now heightened canopy of the shade-intolerants. The forest stand during this stage is mostly even aged (single cohort). As this stage progresses, longer lived shade-tolerant species

slowly advance into the canopy, a characteristic of an aging forest. The fourth and final stage is referred to as the old-growth stage. In this phase, the shade-tolerant species dominate the canopy, and the short-lived shade intolerants have been mostly removed. During the old-growth phase, the forest exhibits a greater variety in ages and sizes (multi-cohort) as competition and minor disturbances have created gaps in which advance regeneration has occurred.

In the disjunct boreal forest of the montane southeastern United States, red spruce and Fraser fir are considered shade-tolerant species (USDA 2009). In the spruce-fir forest, deciduous hardwoods such as yellow birch (*Betula allegheniensis* Britton) and pin cherry (*Prunus pensylvanicum* L.) are common shade-intolerant pioneer tree species; these species frequently populate recently clearcut high-elevation stands. As a canopy begins to form following a disturbance in the spruce-fir ecosystem, dense clumps of Fraser fir seedlings and saplings dominate advance regeneration in the understory (Busing *et al.* 1988, Busing 2004). As a result, single cohort stands of Fraser fir are common in post-logging disturbed areas (Smith and Nicholas 1999, 2000). Fraser fir advance regeneration dominates over red spruce because fir produces heavy seed crops every other year, as opposed to red spruce producing large seed crops on three to eight year cycles (USDA 2009). Though Fraser fir has a competitive advantage over red spruce in seed production, red spruce is known to be even more shade tolerant than fir, lasting up to 145 years in a state of suppression (USDA 2009). In addition, red spruce is a much longer-lived species than Fraser fir; the former can live in excess of 400 years while the average lifespan of the latter is around 150 years (USDA 2009). The competitive advantages that both species hold over the other result in a climax forest with

spruce and fir co-dominance. An old growth red spruce-Fraser fir forest therefore consists of 200+ year old spruce and 100–150 year old fir dominating the canopy, with fir being the more common in intermediate and understory positions.

2.3 Disturbance in the Spruce-Fir Forest of the Southern Appalachians

2.3.1 Natural Disturbance

Canopy gaps related to wind blowdown dominate the natural disturbance regime in the spruce-fir forest. White *et al.* (1985) identified two types of wind disturbance events at their site in the GSMNP: large blowdowns covering an area greater than 200 square meters and small, spatially restricted gap opening events. Researchers have found fire to be less important in the southern spruce-fir forest compared to its northern counterpart, likely because the forest is frequently immersed in clouds and remains perpetually humid and moist (Barden and Woods 1973, Fahey and Reiners 1981, Harmon 1982). Disturbance from debris avalanche has also been reported, though instances are extremely rare (Bogucki 1970).

2.3.2 Logging

Human disturbance in the past centuries has affected the forest health and successional trajectory of the spruce-fir forests of the southern Appalachian Mountains. Southern Appalachian forests were severely damaged and altered by the aggressive logging practices and subsequent soil erosion and burning that were common in the region during the late 1800s and early 1900s (Pyle 1984, McLaughlin *et al.* 1991). The great economic value of red spruce lumber during the early 1900s ensured that as many

trees as possible were logged with little regard towards long-term management plans (Korstian 1937, Pyle 1984, Hayes *et al.* 2007). Red spruce-Fraser fir forests were either extensively clearcut or selectively logged at nearly all of their disjunct locations including GSMNP, the Balsam Mountains, the Black Mountains, Grandfather Mountain, the Plott Balsams, Roan Mountain, and Mount Rogers (Pyle and Schafale 1988, Smith and Nicholas 1999, Hayes *et al.* 2007). Pyle (1984) hypothesized that as much as 50% of all southern Appalachian spruce-fir forests may be failing to recover and replace themselves from logging.

Smith and Nicholas (1999) conducted a thorough investigation of post-logging spruce-fir forest recovery at nearly all forest locations in the southern Appalachian region outside of GSMNP. The researchers established seven spruce-fir forest study areas (including Roan Mountain) and installed plots in both logged and un-logged spruce-fir stands at each site. Smith and Nicholas (1999) initially measured basal diameters and surveyed seedlings and saplings in their plots in 1984 and re-sampled them in 1991 to detect post-logging recovery trends in the spruce-fir forest. Predictably, their study determined that logged stands had greater densities of deciduous taxa and fewer spruce than un-logged stands. The logged stands also exhibited greater amounts of growth between sampling periods and higher amounts of regeneration. The authors hypothesized that it may be many decades before logged spruce-fir forests begin to reach the structural characteristics of un-logged forests.

Using remote sensing and Geographic Information Systems (GIS) techniques, Hayes *et al.* (2007) investigated post-logging spruce-fir forest regeneration in GSMNP. They analyzed ecotone positions of logged versus un-logged spruce-fir forests to infer the

consequences of human disturbances on the extensiveness of the spruce-fir forest. The research also explored topographic and elevational differences between the logged and un-logged study areas to determine if pre-logging spruce-fir forests are returning or if they have been converted to deciduous stands. Hayes *et al.* (2007) found that on south-facing slopes, the spruce-fir ecotones of logged sites were significantly further upslope than corresponding ecotones at un-logged sites, indicating that spruce-fir forests were recovering weakly from logging. In addition, the researchers used vegetation classification data combined with elevation, slope, and aspect data to predict the total area of the spruce-fir forest in GSMNP under the hypothetical scenario that it had never been logged. Their model predicted that the park would have over 17,000 more hectares of spruce-fir forest than it currently possesses had the area never been logged. This result supported that great amounts of spruce-fir forest may be permanently lost due to the aggressive logging of the early 1900s.

2.3.3 Acidic Deposition

Researchers have linked the effects of acidic deposition to forest decline in red spruce forests of the United States (Johnson and Siccama 1983, Johnson *et al.* 1988, Mengel *et al.* 1990, Mohnen *et al.* 1990, Eagar and Adams 1992) as well as other Eastern North American forests (Morrison 1984) and areas of Europe (Schütt and Cowling 1985, Krause *et al.* 1986). As fossil fuel-burning automobiles and heavy industry emit pollutants into the atmosphere, chemicals dissolve into airborne water molecules, resulting in water vapor with abnormally low pH levels (acidic). Acidic deposition onto the landscape then occurs via wet deposition (acid rain or snow), dry deposition (direct

deposition of pollutants to a surface), or cloud-water deposition (vegetation intercepts acidic water vapor while immersed in clouds or fog) (Mohnen 1992). Though natural precipitation is somewhat acidic (pH 4–5), its effects are typically neutralized by alkaline material naturally found in air, soil, rocks, and water. However, acid precipitation can have a pH level as low as 1.0 and has the strength to dissolve naturally occurring alkalis (EPA 2008).

Forest damage from acidic deposition comes primarily from soil nutrient deficiencies (Johnson *et al.* 1988) and foliar damage (Jacobson *et al.* 1990). Joslin *et al.* (1988) found an inverse relationship between soil aluminum levels and foliar calcium and magnesium levels, suggesting that high aluminum concentrations in soil may inhibit nutrient uptake. In a study examining calcium:aluminum ratios over elevational gradients, McLaughlin *et al.* (1991) concluded that higher elevations were subjected to higher soil-aluminum levels. Researchers have also concluded that foliar nutrient leaching occurs when spruce needles come into direct contact with acidic precipitation and water vapor (Jacobson *et al.* 1990, Mengel *et al.* 1989). Mengel *et al.* (1990) observed a red-brownish discoloration of needles after treating red spruce seedlings with acidified mist for two weeks.

The effects of acidic deposition are intensified at high elevations (McLaughlin 1985, Adams and Eagar 1992). The geographic location of the southern Appalachian Mountains makes the range particularly vulnerable to pollution because of an intense concentration of fossil fuel-burning power plants west of the range (TVA 2008) and prevailing westerly winds that drive the polluted air towards them. Furthermore, cloudwater has been shown to have a greater effect on high-elevation ecosystems than

precipitation (Mohnen 1992). Cloud climatology studies have determined that peaks above 1400 m in the Appalachians are immersed in orographic clouds during approximately 28–48% of the growing season, and more often during the dormant season (Mohnen *et al.* 1990). Natural cloudwater has higher sulfate and nitrate concentrations and lower average pH (3.5) than natural precipitation (4.2) (Adams and Eagar 1992). Therefore, cloudwater infused with pollutant material is potentially much more harmful than acidic precipitation. Thus, high-elevation montane forests are more often subjected to the effects of acidic deposition than low-elevation forests.

2.3.4 Balsam Woolly Adelgid Infestation

The invasion of the balsam woolly adelgid to the spruce-fir ecosystem has resulted in severe mortality in mature Fraser fir stands. An exotic aphid-like insect from Europe, the balsam woolly adelgid was introduced to the northeastern United States in 1908 (Hain 2005). Fraser fir mortality related to the balsam woolly adelgid is most severe in the southern Appalachian Mountains (Potter *et al.* 2005). The balsam woolly adelgid was first identified in the southern Appalachians in 1957 on Mount Mitchell, in the Black Mountains. Populations quickly spread by wind dispersal to Mount Rogers and Roan Mountain by 1962, GSMNP and Grandfather Mountain by 1963, and the Balsam Mountains by 1968 (Speers 1958, Amman 1966, Dull *et al.* 1988, Eagar 1984). Mature Fraser firs experienced 91 percent mortality in the GSMNP by the early 1980s (Dull *et al.* 1988) and 67 percent mortality elsewhere throughout the species' range (Potter *et al.* 2005). Mount Rogers is the only balsam woolly adelgid infested area that has not

experienced severe fir mortality (White and Cogbill 1992), though the reason is largely unknown (Wentworth *et al.* 1988)

Less than one millimeter in length, the balsam woolly adelgid has a complex life cycle consisting of an egg stage, three larval stages, and an adult stage (Potter *et al.* 2005). The adelgid is mobile only in its first larval stage and is subject to wind dispersal during this time. Following this “crawler” stage, the adelgid spends its entire adult life immobile (Eagar 1984). In North America, balsam woolly adelgid populations consist only of female specimens. This phenomenon is possible because the adelgid reproduces asexually by means of parthenogenesis (Potter *et al.* 2005). The balsam woolly adelgid attacks all fir species, but the mature Fraser fir is particularly susceptible to infestation due to fissures that develop in its bark as the tree ages (Hain 2005). The balsam woolly adelgid inserts its stylet into the bark fissures to feed and releases salivary compounds that cause abnormal xylem production (Smith and Nicholas 2000). Consequently, the abnormal xylem inadequately conducts water, resulting in foliar dieback and death in two to nine years (Potter *et al.* 2005).

Balsam woolly adelgid infestation has widely eliminated old-growth Fraser fir stands in the southern Appalachians, though individual mature trees have survived. Currently, Fraser fir is experiencing increased regeneration in highly impacted stands, resulting in stand composition consisting of a high density of juvenile Fraser firs and relatively few mature specimen (Smith and Nicholas 2000). Smith and Nicholas (2000) hypothesized that Fraser fir stands would undergo a decrease in population with each successive generation. Other studies have documented intense juvenile Fraser fir

advance regeneration as well (Boner 1979, Witter and Ragenovich 1986, Nicholas *et al.* 1992).

Many studies have attributed a decline in red spruce in the southern Appalachians to the stand-altering affects of the balsam woolly adelgid (Busing and Clebsch 1987, Busing *et al.* 1988). The loss of the forest codominant Fraser fir has been observed to have both negative and positive effects on red spruce (Busing 2004). A major concern among scientists is that intense Fraser fir mortality has resulted in a more open canopy and increased wind exposure for red spruce (Peart *et al.* 1992). Busing (2004) found that the loss of Fraser fir trees coincides with increased red spruce mortality by wind blowdowns. Busing (2004) also reported vigorous growth rates among spruce from 1993 to 2003. Both of these results were directly related to Fraser fir mortality. Though the increased exposure has made the red spruce more vulnerable to wind damage, it has also enabled greater growth and establishment rates.

2.4 Dendrochronology in the Spruce-Fir Forest

2.4.1 Climate Response

In light of growing concerns during the 1980s of a decline in red spruce health, much research was conducted regarding how climatic factors limit growth of red spruce across the species range (Cook *et al.* 1987, Eagar and Adams 1992, Webster *et al.* 2004). The balsam woolly adelgid had decimated mature Fraser fir stands prior to widespread use of dendroclimatic techniques in the Eastern United States, and, as a result, very little is known about the climatic sensitivity of Fraser fir. While researchers have submitted 21

red spruce chronologies to the International Tree-Ring Data Bank, there are no Fraser fir chronologies available on the database (ITRDB 2010).

Many dendroclimatic studies involving red spruce have confirmed that the species is temperature sensitive within its typical range of habitats (Cook *et al.* 1987). However, dendroclimatologists have determined that climatic response in red spruce is not temporally stable (Cook *et al.* 1987, Johnson *et al.* 1988, Smith and Nicholas 1999, Webster *et al.* 2004,). In related studies, Cook *et al.* (1987) and Johnson *et al.* (1988) examined temporal variability in growth response of red spruce in the northeastern United States to climatic factors by creating multiple-regression climate response models and testing their validity on a pre- and post-1960 period. For the pre-1960 period, red spruce growth was inversely related to prior-August temperatures and positively related to prior December temperatures. Therefore, above average growing season temperatures and below average winter temperatures caused reduced red spruce growth during the following growing season. This model developed for the pre-1960 period failed to predict growth during the post-1960 period. For the post-1960 period, both studies found that red spruce growth related positively to warm current July temperatures and warm prior-November temperatures (in contrast to the previously mentioned negative winter relationship). Johnson *et al.* (1988) and Cook and Johnson (1989) hypothesized that climatic conditions may have exceeded some critical threshold that triggered a change in red spruce sensitivity. Hence, the shift in sensitivity could be related to global warming.

In a similar study, Webster *et al.* (2004) temporally tested the climate-growth relationships of a high-elevation and low-elevation red spruce chronology developed from trees growing in GSMNP. The researchers examined the high and low-elevation

chronologies' relationships with climate initially during the period 1910 to 1998 and then from 1940 to 1998. With their high-elevation chronology, Webster *et al.* (2004) reported significant positive relationships between precipitation and growth during the current August, and temperature and growth during the current January for the 1910–1998 period. The 1940–1998 period showed a significant direct relationship with growth, and precipitation was again found in the month of August, but a January relationship with temperature was not significant. The researchers' low elevation chronologies exhibited a significant positive relationship between precipitation and growth during three months (previous November, March, and September) and a significant negative relationship between temperature and growth during February. The same relationships were found for the 1940–1998 period with growth and precipitation, but the growth-temperature relationship again broke down as with the high-elevation chronology. The authors credited much of the variance between the high and low elevation chronologies to differences in elevation and topology, while the temporal fluctuation in climatic sensitivity was attributed to pollutant emissions.

A major inference can be deduced from the Webster *et al.* (2004) study: elevation plays a very important role in determining red spruce climatic sensitivity. With decreased elevation, water availability became an increasingly important factor in limiting growth. As the highest elevations of the southern Appalachians receive significant amounts of moisture from cloud and fog cover in addition to precipitation (Mohnen *et al.* 1990, Mohnen 1992), it comes as no surprise that moisture is not as great a limiting factor at high elevation. Furthermore, the Webster *et al.* (2004) study found that red spruce in the southern Appalachians exists very near its temperature threshold, as evidenced by the

conflicting temperature signals observed between high and low red spruce populations. As higher elevation populations benefited from warmer winter temperatures, the same conditions were detrimental to the lower elevation red spruce forest, accentuating the role topographic relief plays in determining temperature regime. Webster *et al.* (2004) also observed the change in temperature sensitivity that Cook *et al.* (1987) and Johnson *et al.* (1988) previously reported, although Webster *et al.* (2004) found a complete loss of temperature signal over time rather than a shift.

The instability of the red spruce climate signal may be related to the ‘divergence problem’ identified in temperature sensitive trees across the world’s northern latitudes (D’Arrigo *et al.* 2008). D’Arrigo *et al.* (2008) defined this phenomenon as a weakening in the climate-tree growth relationship in the form of a loss or change in temperature sensitivity in recent decades. No consensus exists among dendroclimatologists as to the cause of the divergence, but D’Arrigo *et al.* (2008) outlined four primary hypotheses. First, recent global warming may have caused the change in relationship due to temperature-induced drought stress, changes in seasonality, or the passing of a critical threshold in temperature sensitive trees. A second hypothesis attributed divergence to a global dimming phenomenon that may occur at higher latitudes. Global dimming is the occurrence of more frequent cloud cover due to increased global temperatures, an event that may reduce amounts of incoming solar radiation and, thus, net photosynthesis. D’Arrigo *et al.* (2008) also identified methodological issues as a potential cause in the form of end effects in tree-ring chronology development and standardization. The authors also pointed out that anthropogenic influences may be altering how trees respond to climate. Anthropogenic influences upon tree growth could include nitrogen deposition,

increased ultra-violet radiation, ozone exposure, and elevated atmospheric CO₂ levels (Bartholomay *et al.* 1997, Briffa *et al.* 1998, Soulé and Knapp 2006). Researchers have long recognized that such factors influence red spruce growth, and some dendroclimatologists have found that these effects significantly distort red spruce climatic sensitivity in the southern Appalachian Mountains (Webster *et al.* 2004).

2.4.2 Red Spruce Decline

Dendrochronologists and forest ecologists have found declining red spruce forests across the northeastern United States (Cook and Johnson 1989, LeBlanc and Raynal 1990) and in some locations in the southern Appalachian Mountains, including the GSMNP and surrounding areas (McLaughlin 1985, Adams and Stephenson 1989). McLaughlin (1985) classifies a state of decline as a progressive weakening of trees resulting in foliar dieback in segments of the canopy. Reduced radial growth rates and increased susceptibility to biotic and abiotic stresses are common symptoms of a state of decline (Manion 1981). Manion (1981) further stated that a decline was likely a result of an interaction between several causal agents. There are many stress agents currently affecting the southern spruce-fir forest, ranging from climate change to multiple natural and anthropogenic disturbances (Cook and Johnson 1989). Though researchers cannot identify a single disturbance as the causal force of decline, the interrelated disturbances of wind damage, pollution, infestation, and climate change are likely changing the dynamics of the southern spruce-fir forest.

2.4.3 Red Spruce Decline in the Northeast

To understand all possible factors related to red spruce decline, one must be aware of the state of the species in the northeastern United States. Researchers have used dendroecological techniques to determine if the decline event is an anomaly (and thus, abnormal and possibly anthropogenic) or a cyclical, naturally occurring event. Though red spruce decline is not a new phenomena (Pitelka and Raynal 1989), most researchers agree that the post-1960 decline in growth rates and increased mortality rates of red spruce in the northeastern United States are unprecedented (Cook and Johnson 1989).

Some researchers have suggested that northeastern red spruce decline is related to natural stand dynamics (Hornbeck and Smith 1985, Hyink and Zedaker 1987, and Zedaker *et al.* 1987). The stand dynamics hypothesis attributes the decline of red spruce to changing stand dynamics related to past logging effects, insect activity, increased stand density, and age related effects (Van Duesen 1987). Based on study sites consisting of second-growth red spruce stands, Van Duesen (1987) reasoned that observed red spruce growth reductions are a result of second-growth forests converging to old-growth conditions, and he concluded that the decline is not unprecedented. However, several other studies have noted a near synchronous ring-width decline at sites with uneven stand ages and notably different disturbance histories, effectively ruling out the stand dynamics hypothesis in the northeastern United States (Siccama *et al.* 1982, Scott *et al.* 1984, Johnson and McLaughlin 1986, Johnson *et al.* 1988, Cook and Johnson 1989, Cook and Zedaker 1992). Scientists supporting the theory that northeastern red spruce decline is unprecedented believe that decreased spruce growth rates and increased spruce mortality is a result of either acidic deposition and/or climate change. Foliar leaching and increased

soil acidity have also been expressed as possible reasons for the decline (Johnson and Fernandez 1992, Schier and Jensen 1992, DeHayes 1992).

Several dendroecological studies have also concluded that climate change may be directly responsible in part for red spruce decline (Cook and Johnson 1989). Cook *et al.* (1987) and Johnson *et al.* (1988) found a link between temperature stress (i.e. unusually warm prior-August temperatures and colder than average prior-December temperatures) and previous red spruce decline events. The detection of a winter-temperature stress signal is supported by evidence of an increased amount of observed winter injuries beginning in the 1950s and 1960s (DeHayes 1992). Johnson *et al.* (1988) proposed that an increased amount of summer temperature stress events in the 1940s and 1950s may have made red spruce trees more susceptible to winter damage as well. Their results suggested that the mid-1900s decline was not an anomalous event, but rather a result of a relatively short-term climatic trend towards harsh winters (Sheppard *et al.* 1989, DeHayes *et al.* 1990, Wilkinson 1990). Research has also shown that winter injuries to red spruce can cause a growth decline in individuals of up to 50% in following years (Curry and Church 1952). In addition, a global warming-induced extension of the red spruce growing season could result in an increased susceptibility to winter injury because the trees may not be physiologically prepared (i.e. freeze hardened) for sudden early winter freeze events (Cook and Johnson 1989).

2.4.4 Red Spruce Decline in the Southern Appalachians

Spruce-fir decline is most notable in the southern Appalachians at Mt. Mitchell, North Carolina (Bruck *et al.* 1989). Several studies performed during the 1980s

characterized unprecedented red spruce declines in the GSMNP (McLaughlin *et al.* 1987, Van Duesen 1988, Adams and Sepsenon 1989) and the mountains of West Virginia and western Virginia (Adams *et al.* 1985). However, some cast doubt on the anomalous nature of the decline (Cook and Zedaker 1992), and a reversal of declines in the southern Appalachians has been observed (Reams *et al.* 1993, Goelz *et al.* 1999, Busing 2004). Dendroecological researchers have determined that, in the southern Appalachians, declines are greatest at high-elevation (> 1900 m) spruce stands (Cook 1988, Zedaker *et al.* 1988). Furthermore, forest maturation level plays a more significant role here than in the northeast (Goelz *et al.* 1999, Busing 2004). Webster *et al.* (2004) found that topography played a major role in decline at sites in the GSMNP. They found significant differences regarding timing and rate of decline and homogeneity of decline between sites on ridges and sites on draw topography. These studies provide strong evidence that red spruce decline in the southern Appalachians is likely a localized, site-specific phenomena and not as widespread as in the northeastern United States.

The presence and possible causes of red spruce decline are more uncertain in the southern Appalachian Mountains where less research has been conducted. There are likely many complex interactions between multiple factors driving the dynamics of the spruce-fir forest of the southern Appalachians. Webster *et al.* (2004) developed a multivariate-regression model to explain growth variation in declining red spruce stands. They determined that as much as 59.5% of growth of red spruce from ridge-top locations was explained by chemical pollutant emissions (nitric oxides and sulfur dioxide) and as little as 7.6% by climatic conditions, clear evidence that acidic deposition is greatly influencing spruce decline. Acid deposition was found not to greatly influence growth at

sites of draw topography. Others have found that soil-mediated effects may be more important to spruce decline in the southern Appalachians than the northern mountains due to higher observed aluminum concentrations (Raynal *et al.* 1990, Johnson *et al.* 1991, Adams and Eagar 1992).

CHAPTER 3

STUDY AREA

3.1 Geography and Climate

Roan Mountain is a part of the Unaka Mountains, a subset of the southern Appalachians and part of the Blue Ridge physiographic province (Clark 2008). The mountain is located at approximately 36° 6'16.42" North, 82° 7'47.39" West, its ridgeline delineating the state border between Tennessee and North Carolina (Figure 3.1). Roan Mountain proper (including Roan High Bluff and Roan High Knob) is situated in Carter County in Tennessee and Mitchell County in North Carolina, and encompasses approximately 19 square kilometers. The entire Roan Massif, however, is much larger and extends along the North Carolina-Tennessee border for approximately 30 kilometers. Some of the notable topographic features on the massif are from south to north: Roan High Bluff, Roan High Knob, Carvers Gap, Round Bald, Jane Bald, Grassy Ridge, Little Hump Mountain, Bradley Gap, and Hump Mountain. The highest point on the Massif is 1,916 meters above sea level at Roan High Knob, followed by Roan High Bluff at 1,910 meters. All of Roan Mountain and much of the massif are jointly managed by Pisgah National Forest in North Carolina and Cherokee National Forest in Tennessee, though some areas along the massif remain privately owned. Roan Mountain drains to the Doe River to the west and the Toe River to the east, both of which flow within the Tennessee

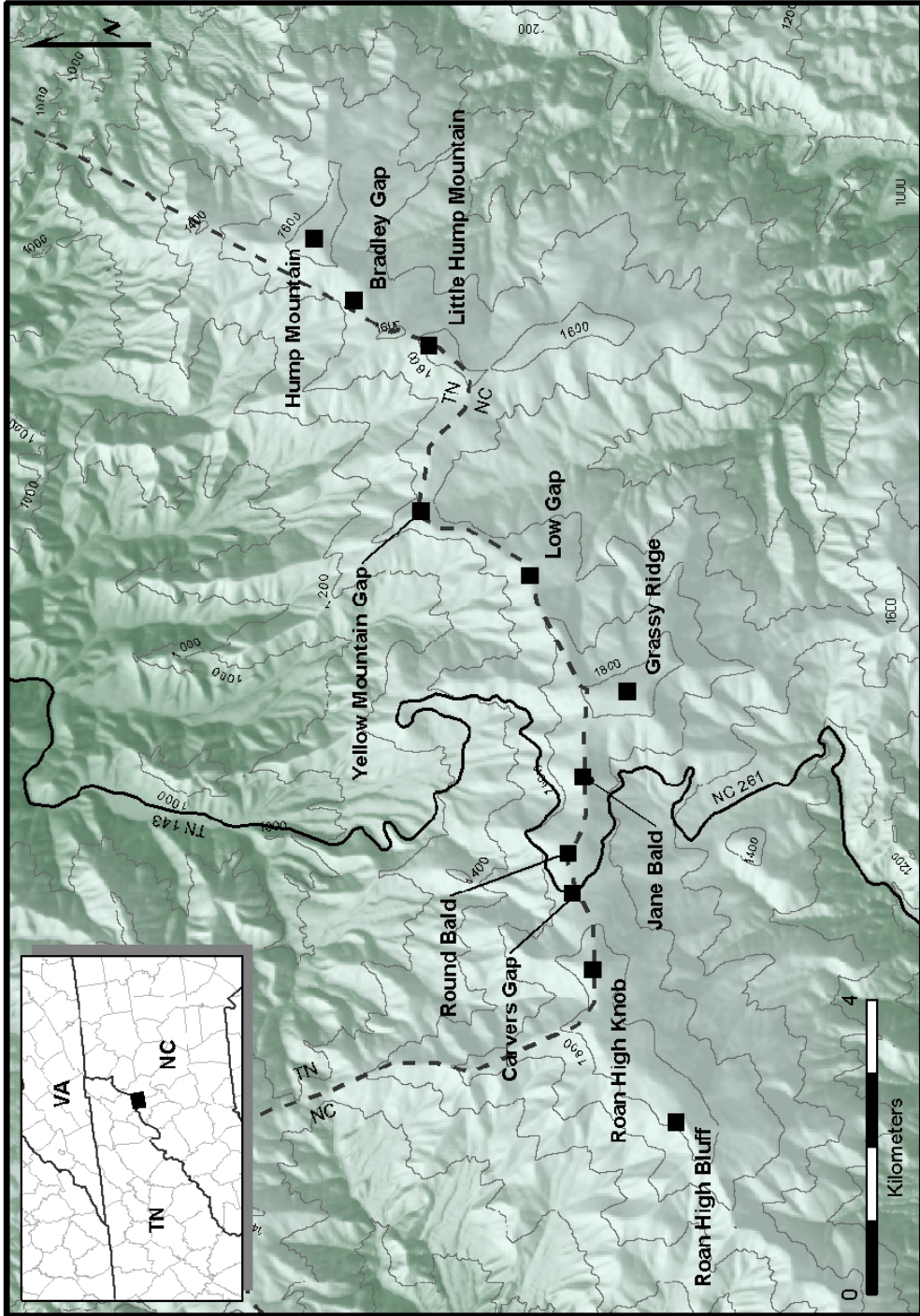


Figure 3.1 Map showing the major topographic features of the Roan Massif.

River Watershed. Most of the Roan Massif's summits are crossed by the Appalachian Trail, the longest marked footpath in the United States at 3,505 kilometers in length. The Appalachian Trail and its scenic vistas make Roan Mountain a popular destination amongst tourists and hikers.

Roan Mountain's high elevations are classified as Cfb under the Köppen climate classification system (Christopherson 2006). This marine west coast classification is based upon the cooler temperatures and increased precipitation associated with high elevation and orographic uplift (Christopherson 2006). Accurate weather and climate data are often difficult to determine for high mountains because they rarely have weather observation stations on location (Daly *et al.* 2001). Data from nearby weather stations therefore often fail to accurately represent high elevation environments because they are typically located at much lower elevations. The nearest National Weather Service (NWS) weather station is the Banner Elk, North Carolina station (elevation: 1,142 m). The station receives an average of 1,259 mm of annual precipitation and averages 19.3° C in July and -1.3° C in January (SCONC 2010). Some researchers have attempted to derive high elevation climate data using Geographic Information System elevation modeling techniques (Daly *et al.* 2001). The highest quality derived spatial climate datasets currently available were developed by the PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate group (PRISM 2010a). The PRISM model incorporates point climate data, digital elevation models, and other topographic parameters to represent climatic data on an elevation-adjusted spatial grid (PRISM 2010b). The PRISM-derived climate data for the area focused on Roan Mountain reports a total of 1,579 mm annual precipitation, with average temperatures reaching 14.7° C in

July and -2.8° C in January (PRISM 2010b). These elevation-adjusted figures are considerably cooler and moister than the Banner Elk weather station data, a reflection of Roan Mountain's high elevation climate.

3.2 Geology and Soils

Roan Mountain is largely a product of the Alleghenian orogeny. The Alleghenian orogeny occurred approximately 300 million years ago during the late Carboniferous geological period (Clark 2001). During this mountain-forming event, the North American and African continental plates collided and uplifted what are now the Appalachian Mountains (Clark 2008). The collision of the North American and African plates formed the central area of the super-continental landmass known as Pangaea (Clark 2008). Much of the bedrock of the southern Appalachian Mountains is Precambrian in origin (Clark 2001), and the dominant bedrock of Roan Mountain is comprised of metamorphic gneiss (Gulley 1985). The oldest metamorphic gneiss found on Roan Mountain dates to the Grenville orogeny, which occurred approximately one billion years ago during the Proterozoic eon (Gulley 1985).

Red spruce and Fraser fir trees grow primarily on soils of the inceptisol order (USDA 2009). Inceptisols are generally considered as young soils that exhibit intermediately developed horizons (Christopherson 2006). Soils belonging to the inceptisol order typically exist in humid regions and often on steep slopes (Christopherson 2006), and the soils that occupy the high elevations of the southern Appalachian Mountains are usually inceptisols (NRCS 2010). Soils in the Roan Mountain spruce-fir forest are primarily loams that form on steep, rocky slopes and ridge tops

(NRCS 2010). The most common soils in the area are Balsam loam and Tanasee-Balsam loam complexes, which the USDA Natural Resource Conservation Service describes as well-drained soils occurring at elevations above 1,280 m on steep, concave slopes (2010). Wayah-Burton loam complexes also occur frequently (NRCS 2010). The Wayah-Burton are well drained complexes that are characterized as occurring on ridges, summits, mountaintops, and on convex slopes (NRCS 2010).

3.3 Vegetation

Brown (1941) conducted extensive vegetation surveying on Roan Mountain prior to the extensive logging that took place in the 1930s. The author established sampling plots to characterize the herb, shrub, and tree layers in Roan Mountain's oak-chestnut, beech-maple, and spruce-fir communities. Brown (1941) determined altitudinal zones for these forest communities as follows: spruce-fir occurring above 1,524 m; beech-maple occurring between 1,067 and 1,524 m; oak-chestnut occurring only at elevations less than 1,067 m. Brown (1941) installed plots over an even distribution throughout both the beech-maple and spruce-fir zones; he omitted the oak-chestnut community from thorough surveying citing the non-existence of mature specimen due to agricultural clearing, logging, and chestnut blight [*Cryphonectria parasitica* (Murrill.) Barr.] (Brown 1941).

In the beech-maple community, Brown (1941) established sixty 10 by 10 m tree-surveying plots located in uneven-aged forest stands, as well as hundreds of smaller plots to survey shrub and herbaceous layers. On average, Brown found that 73% of trees in beech-maple plots were American beech (*Fagus grandifolia* Ehrh.), while sugar maple (*Acer saccharum* Marshall) ranked second at 22%. Nearly three percent of trees in the

beechn-maple zone were mountain maple (*Acer spicatum* Lam.) and 1% were striped maple (*Acer pensylvanicum* L.). Nine other species occupied the remaining 1.3%. Brown (1941) determined that American beech accounted for 66% of total basal area in the beech-maple forest and sugar maple made up 16.67%. Brown (1941) also found that sugar maple was the most common tree species in the understory, though American beech became more frequent at heights greater than 0.3 m.

In the spruce-fir zone, Brown (1941) established 32 10 by 10 m tree-surveying plots located within two previously unlogged stands, in addition to over 200 smaller shrub and herbaceous plots. The author found a codominance in the canopy between red spruce and Fraser fir, the two species together accounting for 89.2% of all trees (62.3 percent belonging to Fraser fir and 26.9% to red spruce). Yellow birch was the third most frequent species at 6.2%. The remaining 4.6% of trees were mountain maple, American beech, mountain ash (*Sorbus Americana* Marsh.), yellow buckeye (*Aesculus octandra* Aiton), and pin cherry. Though Fraser fir was the most frequently occurring tree, red spruce had greater basal area overall. In the spruce-fir plots, red spruce accounted for 57.5% of total basal area, while Fraser fir made up 23.5%. Yellow birch ranked third in basal area at 17.4% (though the species was the largest tree in the community on average). Fraser fir was the most frequently occurring tree in the shrub layer by far, confirming its status as an earlier successional species than red spruce (Brown 1941).

3.4 Land-Use History

The Roan Massif has a long and varied land use history. The earliest known inhabitants of the Roan vicinity were the Catawba Native American tribe, for whom the

area's ubiquitous Catawba rhododendron (*Rhododendron catawbiense* Michx.) is named (Wilson 1991). Many of the early European explorers of the Roan Massif were botanists, often traveling under the sponsorship of foreign governments (Wilson 1991). It was common practice in the late-18th century for European governments to commission botanists to collect North American plant specimens for botanical gardens in Europe (Welch 1998). The great French botanist André Michaux (1746–1802) came to Roan Mountain in 1794 during his explorations of the southern Appalachians on behalf of the French government (Wilson 1991). Scotsman John Fraser (1750–1811) explored Roan Mountain in 1787, 1789, and 1799 in service of the Russian government (Wilson 1991). Fraser is credited with discovering the Fraser fir and the Fraser magnolia (*Magnolia fraseri* Walter), both of which are endemic to the southern Appalachians. During the mid-19th century, botanist Asa Gray (1810–1888) began his work in the southern Appalachians and explored Roan Mountain in 1840 (Gray 1892). The Harvard botanist found a previously *Lilium* species on Roan Mountain which was subsequently named Gray's Lilly (*Lilium grayi* S. Watson) (Wilson 1991).

Around 1870, John Thomas Wilder, a wealthy industrialist from New York, purchased seven thousand acres atop Roan Mountain for \$25.15 per acre (Wilson 1991). Wilder, an officer in the Union Army during the American Civil War, took advantage the economic opportunities of the post-war South, and established many iron and rail operations throughout eastern Tennessee (Wilson 1991). At Roan Mountain, Wilder realized the potential of the area as a tourist attraction and constructed the Cloudland Hotel near the summit of Roan High Knob (Wilson 1991). The Cloudland Hotel was preceded by a smaller 20-room structure built of the mountain's spruce timber

constructed in 1877 (Wilson 1991). Construction of Wilder's Cloudland Hotel began in the early 1880s and, according to Wilson (1991), the hotel was built primarily out of "balsam" wood (presumably spruce and fir). Wilder instigated the first significant logging operations in Roan Mountain's spruce-fir forest in support of the Cloudland Hotel construction. The building of the hotel demanded the installation of a steam-powered sawmill on site so the local spruce and fir timber could be used (Wilson 1991). The hotel was promoted as a summer-time resort for those seeking the perceived health benefits of an alpine environment, and, in its prime, Cloudland successfully attracted many wealthy American and European visitors (Wilson 1991). The building of the hotel was accompanied by the building of the first access road to Carver's Gap, an effort led by Wilder (Wilson 1991). The road granted access to the area from both North Carolina and Tennessee and effectively opened Roan Mountain to tourism. Ownership of the Cloudland Hotel remained with Wilder throughout its duration, but the hotel's management changed hands several times (Wilson 1991). By the turn of the 20th century, the hotel was declining and eventually fell into disrepair and was abandoned, and in 1910, Wilder sold the remaining materials of the hotel for salvage (Wilson 1991). Today, the stone foundation of the Cloudland Hotel remains as evidence of the past resort.

Logging, and its negative environmental effects, has a long association with Roan Mountain. Following the death of John Thomas Wilder, his lands on Roan Mountain were divided among his heirs, who, in turn, sold the area's timber stocks to logging companies (Wilson 1991). Prior to the commercial logging that began in the late 1800s, local settlers cleared areas on the lower slopes of the Roan Massif for agricultural purposes (Brown 1941). Larger logging operations began with construction of the

Cloudland Hotel as well as commercial cutting of hardwoods on the Mountain's lower slopes (Wilson 1991). As the logging industry had effectively depleted the hardwood stocks of the northeast and mid-Atlantic regions by the mid-1800s, companies began exploiting the old-growth forests of the southern Appalachians (Rheder 2004). From 1883 to 1886, relatively conservative, selective logging of cherry, birch, and maple took place on the Roan Massif (Brown 1941). During this period, loggers only removed hardwoods greater than 50 cm thick (Wilson 1991). These logging efforts were supported by several log flumes and a narrow gage railroad on the slopes of Roan to transport lumber (Brown 1941). This period of logging notably reduced slope stability in logged areas resulting in heavy erosion and frequent landslides (Wilson 1991). The increased runoff associated with this era of logging is thought to have significantly contributed to heavy flooding in the area in 1901 and 1902 (Wilson 1991).

The logging of Roan Mountain during the late 1800s serves only as a mild precursor to the aggressive logging of the 1920s and 1930s. The Champion Coated Paper Company began logging the red spruce-Fraser fir forest of Roan Mountain in 1929 (Wilson 1991). The Champion Company, owned by Peter G. Thomson, exploited Roan Mountain's spruce-fir forest to supply pulp for paper manufacturing. The company practiced clearcut-logging techniques, removing every specimen from the spruce-fir forest that was greater than 15 cm in diameter (Wilson 1991). To support their logging activities, the company constructed a road, built out of boards, which fully encircled the spruce-fir forest and ran along the spruce-fir/deciduous ecotone (Wilson 1991). The Champion Company cut all of the old-growth spruce and fir stands on Roan Mountain, and even removed rhododendron from the mountain to sell to landscapers across the

country (Brown 1941). As logging took place, East Tennessee State University botanist D.M. Brown inventoried Roan Mountain's last old-growth spruce-fir stands before they were logged. In his 1941 publication, Brown reported finding two virgin red spruce-Fraser fir stands at Roan Mountain in 1934. Brown stated that cutting began on these stands approximately one hour after he completed his survey (1941). This era of logging lasted until 1937, and effectively denuded the highest elevations of Roan Mountain (Wilson 1991).

The Roan Mountain area received long-awaited Federal protection following the end of the Champion Company's aggressive logging in the late 1930s (Wilson 1991), but the push for establishment of National Park and Forest lands in the southern Appalachians began as early as the 1890s (NPS 2010). The early 20th century saw many conservation groups based in both nearby Knoxville, Tennessee, and Asheville, North Carolina pressure Congress for a public preserve, and President Calvin Coolidge signed a bill in 1926 that sought to establish GSMNP (NPS 2010). Congress fully authorized GSMNP in 1934 following a long land acquisition effort, but this legislature omitted Roan Mountain from the new National Park. Unfortunately, the Champion Company was clearcut logging Roan Mountain as GSMNP was gaining vital protection approximately 95 km to the southwest. The United States Forest Service (USFS) eventually acquired much of the lands of the southern Appalachian Mountains that remained unprotected following the establishment of GSMNP (Wilson 1991). In 1941, the USFS purchased approximately 2,800 ha atop Roan Mountain from logging companies and the Wilder estate (Wilson 1991), granting the much-needed protection of the area's rare spruce-fir forest. Unlike National Park Service lands, the USFS does permit logging in National

Forests, but the USFS allows only limited, selective logging that follows a sustainable method (USFS 2010). No logging has occurred in Roan Mountain's spruce-fir forest since the USFS acquired the lands, and the spruce-fir forest is still slowly recovering and restoring itself following the devastating logging of the 1930s.

CHAPTER 4

METHODS

4.1 Field Methods

4.1.1 Age Structure

I established six circular 0.05 ha fixed-radius ($r = 12.66$ m) plots within red spruce-Fraser fir codominant stands to evaluate age composition and frequency of disturbance events at Roan Mountain (Figure 4.1). I established all plots at approximately 1,800 m or higher in stands that exhibited characteristics of uneven tree ages. I targeted stands of uneven tree ages because an uneven age distribution within a stand is often indicative of episodic disturbance events (Christensen 1989). Many areas within the spruce-fir forest of Roan Mountain have been heavily damaged in the past decade by balsam woolly adelgid infestations. In these areas, abundant Fraser fir advance regeneration has resulted in very dense stands of fir saplings with few mature spruce or fir trees. Therefore, it was necessary to target stands with a variety of age classes in order to develop a historical timeline of disturbance events. I established the age structure plots parallel to and downslope from the generally southwest to northeast trend of the ridgeline, and all plots were separated by at least 100 m. I recorded Global Positioning System (GPS) points, percent slope, and aspect from the center point of each plot.

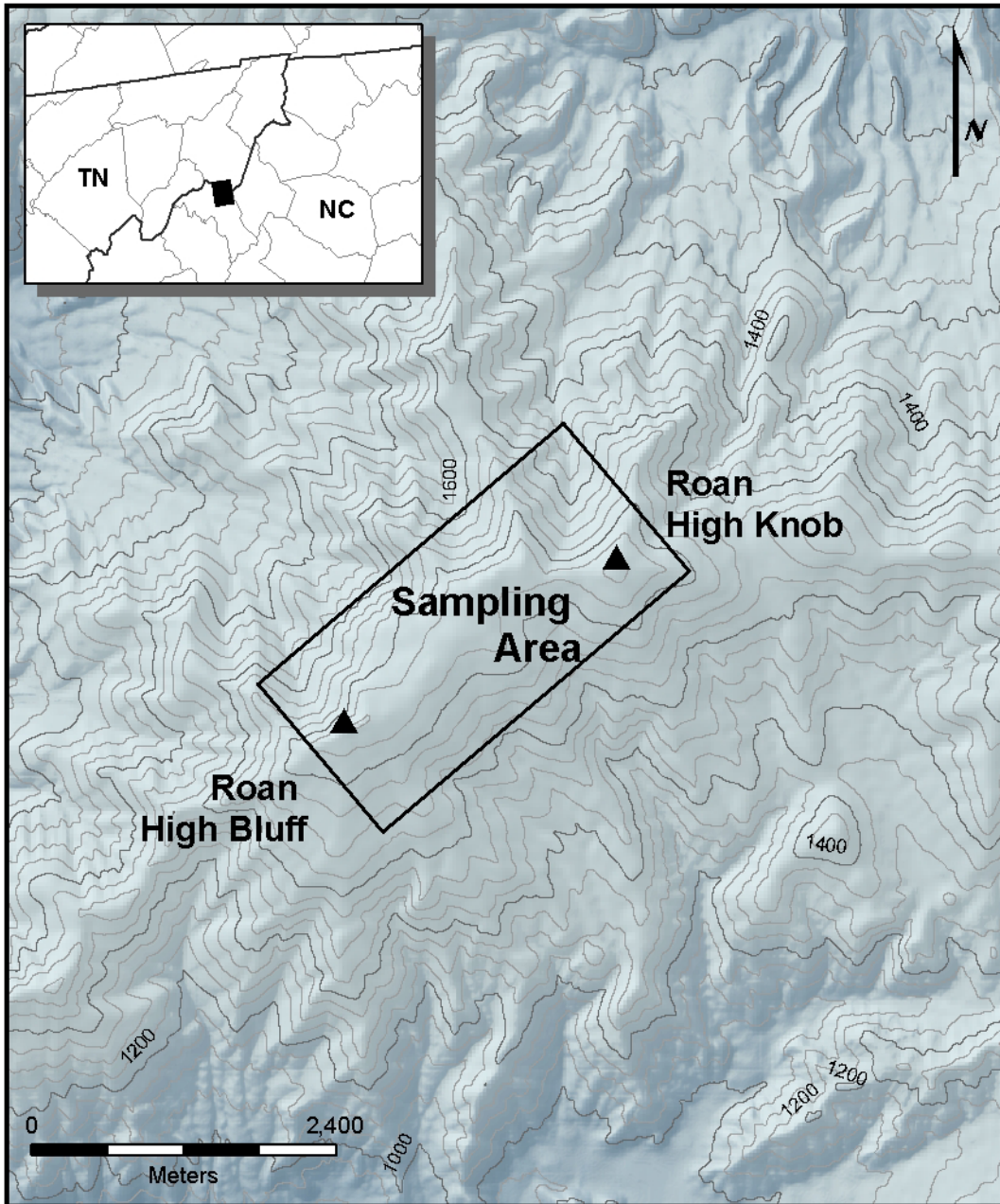


Figure 4.1 Map of the Roan Mountain sampling area.

To determine ages of trees within the sampling plots, I collected increment cores from all trees within each plot ≥ 10 cm diameter at breast height (DBH) (Figure 4.2). I cored each tree using an increment borer parallel to the slope contour to minimize the distorting effects of reaction and tension wood on growth patterns (Fritts 1976). I cored each tree as near to the ground as possible to obtain the maximum amount of growth rings in the core (Fritts 1976). I placed each core in a labeled paper straw for storage and transportation to the lab. Cores with extensive rot and decay were deemed unusable and discarded, but these were relatively few in number.

4.1.2 Stand Composition

I collected stand composition data from the six 0.05 ha study plots by inventorying species, DBH, and canopy class of all trees from which increment cores were removed within each plot. Using a diameter tape, I measured the diameter of each tree at breast height (1.4 m above the ground) and taxonomically classified each tree within the plot ≥ 10 cm DBH. I visually assessed each tree's canopy position based on the amount and direction of intercepted light and designated each tree as occupying either dominant, codominant, intermediate, or suppressed positions (Oliver and Larson 2002). In each sampling plot, I established fixed-radius 0.01 ha nested plots ($r = 5.66$ m) to evaluate advance regeneration of tree species in the understory. Within each sampling plot I tallied all saplings (woody stems < 10 cm DBH, ≥ 1 m height) by species within three size classes (class 1: < 2.5 cm DBH; class 2: between 2.5 and 4.9 cm DBH; class 3: between 5.0 and 9.9 cm DBH).



Figure 4.2 Philip White coring a Fraser fir tree at Roan High Knob (photo taken by Krista White).

4.1.3 Chronology Development

In addition to cores collected within the stand age and composition study plots, I cored select red spruce trees throughout the study area for chronology development. I collected these cores strictly for chronology development and they were not included in the stand age analyses. As an acceptable chronology sample depth of red spruce trees was not available within the stand age plots, I selectively sampled mature trees outside of the study plots that exhibited characteristics of climatically sensitive trees (i.e. lack of evident nearby disturbance or recent damage). I removed two core radii from these supplementary trees and processed them following standard techniques (Stokes and Smiley 1996). To develop a red spruce chronology, which shows the average standardized rate of radial tree growth across the study area, I used selected core samples obtained from both the study plots and the additional trees sampled.

4.2 Laboratory Methods

4.2.1 Sample Preparation

All increment cores remained in the paper straws until they were air-dried completely. After the samples were thoroughly dried, I mounted each core using wood glue to a wooden mounting strip with cells aligned vertically to ensure the transverse plane of each core was visible (Stokes and Smiley 1996). I then sanded each core using a belt sander with progressively finer grit sand paper beginning with ANSI 80-grit (177–210 μm) and finishing with ANSI 400-grit (20.6–23.6 μm) (Stokes and Smiley 1996, Orvis and Grissino-Mayer 2002). This sanding technique produces a flat wood surface that permits clear visibility of the core's cellular structure under 10x

magnification and allows for identification of ring boundaries. I then initially dated each core by placing dots on every decadal ring (i.e. 2000, 1990, 1980, etc.). I placed one dot on each decadal ring, two dots on every 50th ring of a century, three dots on the century ring, and four dots on the millennial ring (Figure 4.4) (Stokes and Smiley 1996).

4.2.2 Age Structure and Stand Composition

I dated and visually crossdated every core sample taken from the age structure and composition sampling plots. Most core samples intersected the tree's pith or very nearly intersected pith (as indicated by the presence of curvature in the formation of inner rings). I assigned calendar year dates to every complete ring present within each core sample. To obtain the nearest possible date of establishment for each tree, I recorded the date of the innermost complete ring present in each core. I calculated the standard descriptors of density, basal area (dominance), and importance values of each tree species sampled with the six study plots per hectare following standard forest mensuration techniques (Cottam and Curtis 1956, Ludwig and Reynolds 1988, Matthews and Mackie 2007). I calculated relative density per hectare by first multiplying the total amount of each species from all plots by a blow up factor of 3.33 (blow up factor = total area surveyed in square meters divided by total square meters in one hectare) which reflects the amount of each species per hectare. Then, I divided the amount of each tree species per hectare by the total amount of trees per hectare to determine relative densities of each species. To determine basal area, I multiplied the squared DBH of each individual tree by a constant of 0.00007854, which produces basal area of a single tree in square meters (Matthews and Mackie 2007). To calculate basal area of each species per hectare, I

multiplied the sum of all individual trees of a species by the blowup factor 3.33. I then calculated relative dominance, the percentage of total basal area per hectare occupied by a single species, for each species. I also calculated relative importance values per ha of each species by averaging relative density and relative dominance values. The importance value represents a useful measure in characterizing the current forest's composition based upon volume and density (Cottam and Curtis 1956). I used sapling tallies from all six 0.01 ha nested sub-plots and a blow up factor of 16.66 as a representation of understory sapling species per hectare. Canopy class data were also calculated per hectare.

4.2.3 Crossdating and Chronology Development

I used a combination of visual and statistical techniques to crossdate red spruce cores deemed suitable for chronology development. I considered some red spruce cores collected from age structure plots unsuitable for use in the reference chronology because they were too young (i.e. less than 30 years old). Crossdating is a process that involves matching ring-width variation and growth patterns among all trees growing nearby or within the study area (Fritts 1976). The crossdating procedure ensures that correct dates are assigned to the exact calendar year in which each growth ring was formed (Fritts 1976). I initially crossdated red spruce cores following the list method developed by Yamaguchi (1991). Following this method, I visually identified frequently occurring large and narrow “marker” rings that were common among the samples (Yamaguchi 1991). I then measured the width of each growth ring of every sample to the nearest 0.001 mm using a Velmex measuring system coupled with MEASURE J2X software.

I statistically verified crossdating accuracy of the red spruce core samples using the computer program COFECHA (Holmes 1983, Grissino-Mayer 2001). COFECHA confirms the temporal placement of each tree ring using segmented time-series correlation analysis (Grissino-Mayer 2001). COFECHA uses spline-fitting algorithms and autoregressive modeling to remove low-frequency trends that often distort the climate signal needed for accurate crossdating (Grissino-Mayer 2001). Such low-frequency trends are typically caused by natural or human-related disturbances and must be removed to detect year-to-year, high-frequency trends related to climate (Grissino-Mayer 2001). I tested the statistical agreement between each sample and all other samples based on consecutive 40-year segments (each segment overlapping by 20 years). If correlation coefficients for any series fell below a correlation level of 0.3665 (representing a 99% confidence level), the segment was flagged by COFECHA and a higher correlated temporal placement, if present, was suggested (typically +/- one year) (Grissino-Mayer 2001). When necessary, I reexamined the tree-ring samples and adjusted the dating to ensure proper dates were assigned to every ring.

I evaluated overall crossdating quality by assessing the interseries correlation of the entire chronology. Interseries correlation is the average of all correlation coefficients based on each individual series' relationship to all other series in the chronology (Grissino-Mayer 2001). Interseries correlation measures crossdating strength and is the most important indicator of the validity of a tree ring chronology. Dendrochronologists generally desire interseries correlation values greater than 0.50 (Grissino-Mayer 2001). Mean sensitivity, standard deviation, and autocorrelation are also useful descriptive statistics in characterizing a tree-ring chronology (Dewitt and Ames 1978). High mean

sensitivity and standard deviation measures coupled with low autocorrelation values are common traits among chronologies that are highly sensitive to climate (Fritts 1976).

I standardized the red spruce tree-ring chronology using the computer program ARSTAN (Cook 1985). Standardization removes age-related growth trends from the series that may distort the chronology's climate signal (Fritts 1976). ARSTAN first removes age-related trends by dividing each ring width measurements from every sample by the value obtained from a negative exponential curve or straight line fit to each series (Cook 1985). ARSTAN then creates an index for each series that has no positive or negative linear trend and a mean value of one. This process makes rapid juvenile tree growth more comparable to slower, mature growth (Fritts 1976). Standardization also minimizes the effects of non-climatic influences such as stand disturbances, density, and competition. ARSTAN averages together each yearly value from all standardized series to form a single index representing average red spruce tree growth at the Roan Mountain study area (Cook 1985).

4.3 Climate Analysis

4.3.1 Instrumental Climate Data

I analyzed the red spruce growth-climate relationship using National Climatic Data Center (NCDC) divisional data for the North Carolina Northern Mountains climate division (NCDC 2010). I obtained monthly average temperatures, monthly rainfall totals, and monthly Palmer Drought Severity Index (PDSI) values. As temperature and water availability often form the primary link between climate and trees' biological systems, dendrochronologists often use these variables when assessing the growth-climate

relationship (Fritts 1976). The temperature, precipitation, and PDSI datasets represented the period 1895 to 2008. PDSI is a meteorological index that quantifies the intensities of dry and wet periods (Palmer 1965). Negative PDSI values are indicative of dry periods and positive values indicate wet periods (Palmer 1965). Values greater than 3.0 and less than -3.0 are considered severe conditions (Palmer 1965). Dendrochronologists often use PDSI in dendroclimatic studies, and the index has been found to significantly correlate with tree-ring chronologies in both the western (Hughes and Brown 1992, MacDonald and Tingstad 2007) and eastern United States (D'Arrigo *et al.* 2001, Hart *et al.* 2008).

4.3.2 DENDROCLIM2002

I performed all climate analyses using the computer program DENDROCLIM2002 (Biondi and Waikul 2004). DENDROCLIM2002 calibrates tree growth to climatic variables using both Pearson product-moment correlation analysis as well as response function analysis. A benefit to using the program is that it tests the significance of response function and correlation coefficients using bootstrapped confidence intervals, allowing for more rigorous evaluation of significance levels (Biondi and Waikul 2004). Another advantage of performing climate analyses with the DENDROCLIM2002 program is that it allows for the testing of temporal changes in the growth-climate relationship (Biondi and Waikul 2004). Many researchers have observed changes in climate-growth relationships over time, and testing for this phenomenon has become essential for those wishing to reconstruct past climate using tree-ring chronologies (D'Arrigo *et al.* 2008). DENDROCLIM2002 tests temporal climate sensitivity by computing relationships for multiple segments, or intervals, throughout the

time series. The interval testing is achieved using either moving, forward evolutionary, or backward evolutionary intervals. Using the moving intervals option, a user-defined constant interval advances progressively by one year (Figure 4.5). With the forward and backward evolutionary options, the testing interval progressively enlarges one year at a time from either the least recent year (forward) or most recent year (backward) (Biondi and Waikul 2004). The program saves analysis results in ASCII format and produces a color-coded output chart (Biondi and Waikul 2004).

4.3.3 Correlation and Response Function Analysis

I used the complementary techniques of correlation analysis and response function analysis to initially determine which climate variables significantly related to red spruce tree growth. The primary difference between correlation and response function is that correlation coefficients are univariate while response function coefficients are multivariate (determined by principal components analysis) (Biondi and Waikul 2004). While the response function technique has been criticized in the past for overstating significance levels, DENDROCLIM2002 uses bootstrapped confidence intervals to more accurately test significance. I tested the relationship between red spruce tree growth and the climate variables of temperature, precipitation, and PDSI for the period 1930 to 2008 (78 years). As climate conditions during the previous growing season often have a “preconditioning” effect on tree growth (Fritts 1976), I tested the climate-growth relationship between the red spruce ring-width chronology and monthly climate variables for the 18-month period beginning with April of the previous year and ending with October of the current growing season. For example, the tree-ring chronology value

representing the year 2000 was tested against a period beginning with October 2000 and extending to April 1999.

4.3.4 Moving Correlation Analysis

To detect possible changes in the climate-growth relationship over time, I also used DENDROCLIM2002 to perform correlation analyses in moving intervals. Using a 36-year moving interval, I tested monthly temperature, precipitation, and PDSI values. I tested monthly climate variables for a span of months beginning with April of the previous year and ending with October of the current year. I used a 38-year interval because DENDROCLIM2002 requires an interval length that is at least twice the amount of predictor months (19 months). I elected to calculate correlation coefficients for the period 1896 to 2008. Dendroclimatologists often elect to omit dates prior to 1930 from their analysis citing poor data quality. However, as the purpose of the moving correlation analysis was to determine shifts in climatic sensitivity over time, I elected to use the longest testing period possible. I omitted the earliest year (1895) of the instrumental climate datasets from this analysis because no data exists of the previous season's climatic variables for this initial year. The resulting analysis therefore examined a span of 112 years. In conducting moving correlation analysis, I aimed to detect both shifts in climatic sensitivity (i.e. gradual or abrupt changes) and fluctuations in the strength of a climate signal (i.e. a weakening and strengthening of the climate-growth relationship).

4.4 Disturbance History

The detection of release events in tree-ring series is a fundamental and often used approach for inferring the disturbance history of a forest community (Lorimer and Frelich 1989, Rubino and McCarthy 2004, Hart *et al.* 2008). A release event is defined as a period in which radial tree growth abruptly increases (Rubino and McCarthy 2004). Release events occur because following a canopy level disturbance trees located in subcanopy positions receive an increased amount of sunlight and are released from the suppression of canopy trees felled by the disturbance (Fraver and White 2005). I elected to use one sample from every tree included in the red spruce chronology plus several other measured and crossdated series that were not included in the final chronology. These additional samples were omitted from the chronology because their correlation values were low enough that they may have affected the detection of a clear climate signal. Though these samples were confidently crossdated, they often contained segments with visible release events that likely negatively influenced their correlations with the master tree-ring chronology. However, these traits were desirable for characterizing the forest's disturbance history, and I elected to include them in this stage of analysis. I used only one core per tree for this stage of analysis to avoid artificial inflation of release episodes.

I used the computer program JOLTS to identify release events in each tree-ring series (Holmes 1999). The JOLTS program analyzes raw ring-width measurement values to identify release events based upon user-defined parameters. I analyzed changes in ring-width as compared to a 10-year running average of the previous and subsequent 10 years. Within the JOLTS program, I specified release detection parameters of 100% for a major

release, 50% for a moderate release, and 25% for a minor release, with a minimum of five years between each event. For example, a ring exhibiting a major release event was identified as 2.0 times greater than the average of the preceding and following 10 years. To determine if release events represented localized or stand-wide disturbances, I analyzed the proportion of trees that exhibited a release in a given year. An event was defined as a stand-wide disturbance if 25% or more of all trees experienced a release in a given year (Nowacki and Abrams 1997, Rubino and McCarthy 2004). These synchronous release events are indicative of a large-scale exogenous disturbance, while asynchronous events (fewer than 25%) were considered localized and related to single tree deaths (Orwig and Abrams 1994).

CHAPTER 5

RESULTS

5.1 Stand Composition and Age Structure

I surveyed a sum of 292 trees among the six 0.05 ha plots established in the Roan Mountain red spruce-Fraser fir forest. The dominant species above 1,800 m at Roan Mountain was Fraser fir; accounting for 83.21% of all trees surveyed (Table 5.1). Fraser fir was the most significant species found, with relative dominance and relative importance scores both > 80 , far exceeding all other species surveyed in the forest. The only other common species was red spruce. Combined, 98.62 percent of the forest was Fraser fir and red spruce, while combined relative dominance and importance values for spruce and fir were 99.58 and 99.1, respectively. Other species present included mountain ash, pin cherry, and yellow birch, but these species only accounted collectively for 1.37% of the forest. Fraser fir was also the dominant species in every canopy class (Figure 5.1). The codominant canopy position was the most frequently occurring, with 576 trees in codominant positions per ha (of which 83.8% were Fraser fir and 15.6% were red spruce). The overall high frequency of Fraser fir to red spruce remained consistent among all other canopy classes as well. In the understory, Fraser fir accounted for 85.92% of all saplings, dominating all size classes (Table 5.2). I calculated 4734.28 saplings from all size classes per hectare. Mountain ash was the second most frequent species I found in the sapling survey, while the only other species present was red spruce.

Table 5.1 Density, basal area, dominance, and importance values of trees located in the spruce-fir forest study plots at Roan Mountain.

SPECIES	TREES/HA	REL DENSITY	REL BA/HA	REL DOMINANCE	REL IMPORTANCE
<i>Abies fraseri</i>	810	83.22	38.22	80.06	81.63
<i>Picea rubens</i>	150	15.41	9.32	19.52	17.47
<i>Sorbus americana</i>	6.67	0.69	0.10	0.21	0.45
<i>Prunus pensylvanicum</i>	3.33	0.34	0.07	0.14	0.24
<i>Betula allegheniensis</i>	3.33	0.34	0.03	0.07	0.20
TOTAL	973.33	100	47.74	100	100

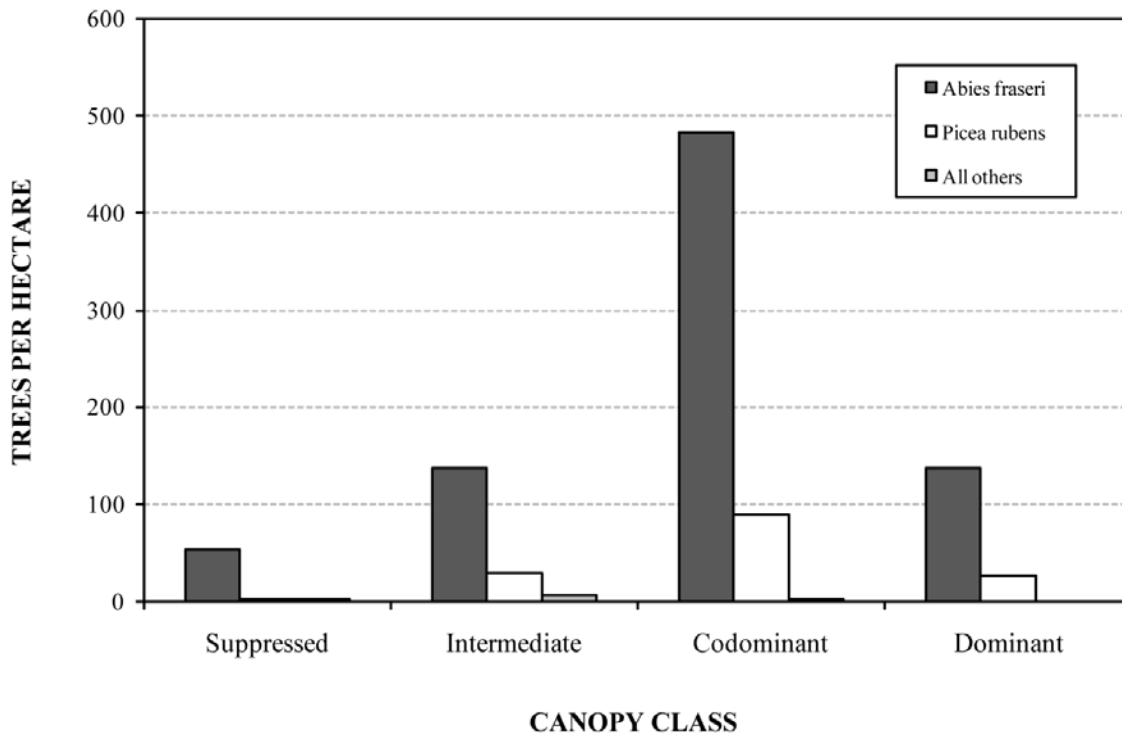


Figure 5.1 Canopy positions of tree species surveyed in spruce-fir forest study plots at Roan Mountain calculated per hectare.

Table 5.2 Raw sapling totals per class (class 1 = < 2.5 cm DBH; class 2 = between 2.5 and 4.9 cm DBH; class 3 = between 5.0 and 9.9 cm DBH), total saplings, saplings per hectare, and relative density of saplings per hectare, sorted by species.

SPECIES	CLASS 1	CLASS 2	CLASS 3	TOTAL	SAPLINGS/ HA	REL/ DENSITY
<i>Abies fraseri</i>	127	99	18	244	4067.48	85.92
<i>Picea rubens</i>	7	8	1	16	266.72	5.63
<i>Sorbus americana</i>	23	1	0	24	400.8	8.45
TOTAL	157	108	19	284	4734.28	100

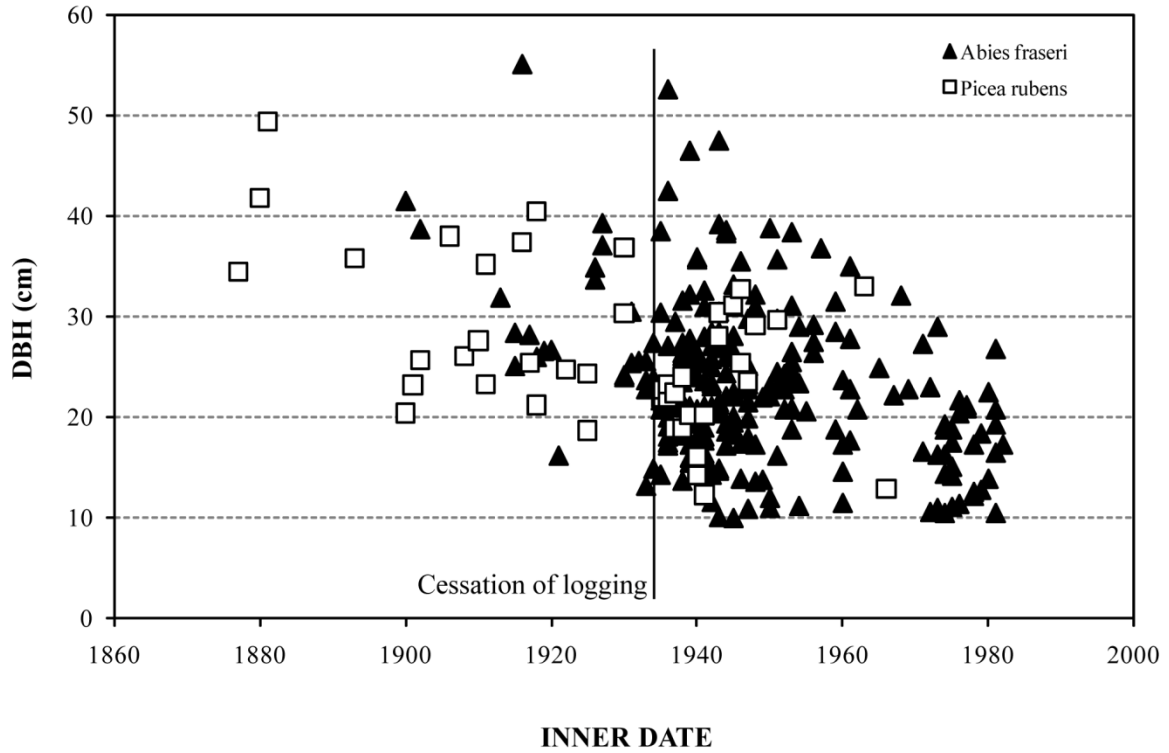


Figure 5.2 Age-diameter relationships for red spruce and Fraser fir trees cored within study plots at Roan Mountain. The black vertical line indicates the cessation of logging and subsequent pulse in tree establishment.

Age structure analysis revealed a distinct shift in forest composition in the late 1930s and early 1940s, coinciding with the cessation of logging activities (Figure 5.2). This period marked a change from a red spruce dominated forest to a densely populated Fraser fir community with fewer red spruce specimens. The oldest tree found within the sampling plots was a red spruce that was at least 136 years old. The oldest Fraser fir found was a minimum of 109 years old. Nearly 56% of all red spruce specimens had interior dates before 1937, the final year of the Champion Company logging operations, while 82.77% of all Fraser fir trees sampled had interior dates of 1937 or later. Although the post-logging pulse in tree establishment sustained both new Fraser fir and red spruce trees, Fraser firs establishing during the period far outnumbered red spruce. Among all trees sampled, 91.17% had inner dates after the cessation of logging, of which 90.78% were Fraser fir. Following the post-logging establishment period, tree establishment gradually decreased until a second, smaller establishment pulse occurred in the 1970s and 1980s. This episode was restricted to Fraser fir only. Tree DBH measures generally increased with tree age, though some post-logging Fraser firs grew to a relatively large size with respect to age, a likely result of abundant light conditions.

5.2 Roan Mountain Red Spruce Chronology

The Roan Mountain red spruce chronology (RMS) was 136 years in length, spanning from 1874 to 2009 (Figure 5.3). The chronology consisted of 28 dated tree-ring series with 2,762 rings in total. I detected common narrow marker rings that assisted in the crossdating process in the years 1883, 1896, 1904, 1907, 1927, 1958, 1931, 1977, and

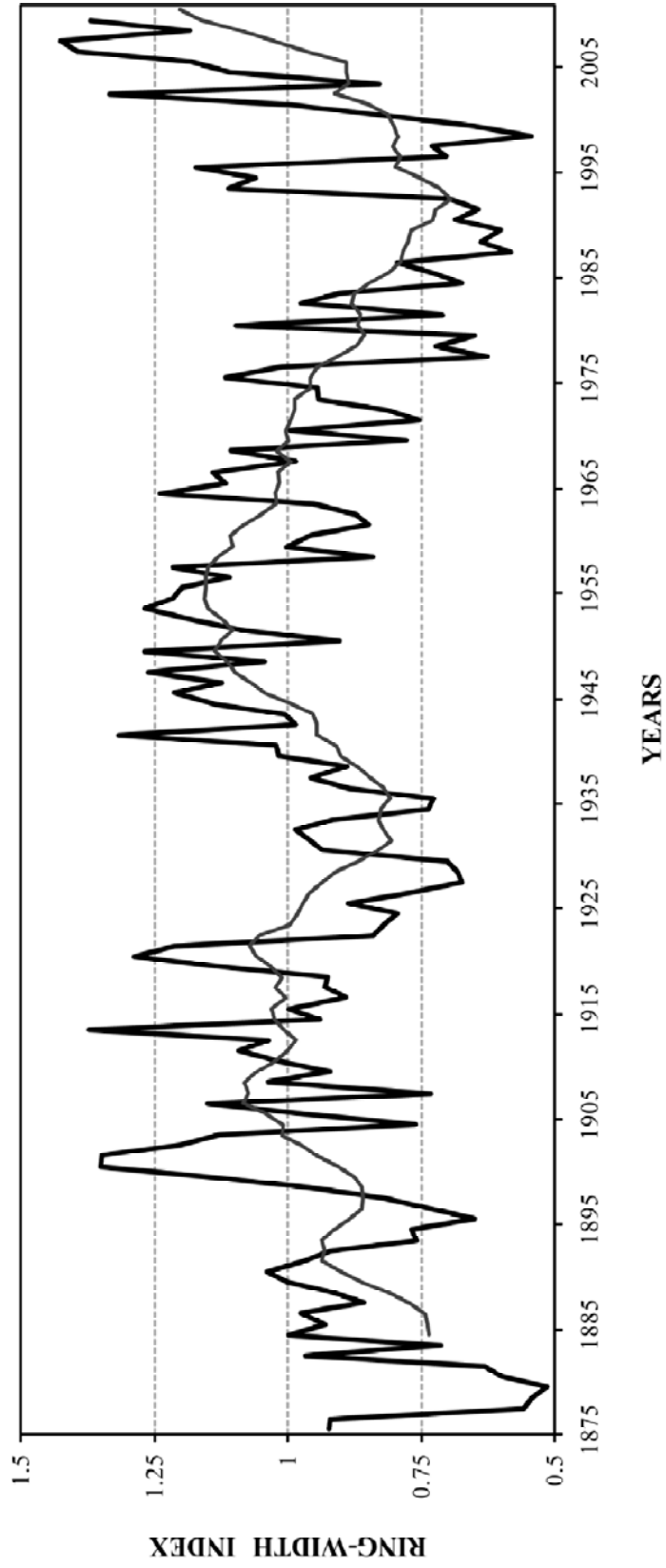


Figure 5.3 The master Roan Mountain red spruce chronology ring-width index. The gray line represents a 10-year moving average of the chronology.

1998. The mean length of all series in the chronology was 98.6 years, and the oldest dated sample was 135 years old. The interseries correlation of the RMS chronology was 0.551 ($p = 0.01$), while the mean sensitivity was 0.252. These measures compared favorably to other red spruce chronologies developed from the southern Appalachian Mountains (ITRDB 2010) and are considered reasonably strong for tree-ring chronologies from the eastern United States (Grissino-Mayer 2001). The relatively high interseries correlation and mean sensitivity coupled with the low autocorrelation (-0.046) of the chronology was indicative of a climatically sensitive data set.

5.3 Climate Response

5.3.1 Correlation and Response Function Analysis, 1930–2008

Correlation and response function analysis primarily detected inverse significant relationships between red spruce tree growth and the monthly climatic variables. The strongest and most frequently occurring monthly climate relationships were between growth and temperature during the current and previous growing seasons (Figure 5.4, 5.5). Significant ($p \leq 0.05$) inverse relationships occurred between growth and temperature during July and September of the previous growing season and during July of the current year. The only significant positive relationship I found among all analyses was between temperature and growth during the current year's month of January. The strongest temperature-growth relationship occurred during the previous summer, with July and August correlation coefficients reaching -0.37 and -0.32, respectively, which suggested a previous summer temperature preconditioning signal. The significant relationships between temperature and growth were weaker during the current year, with

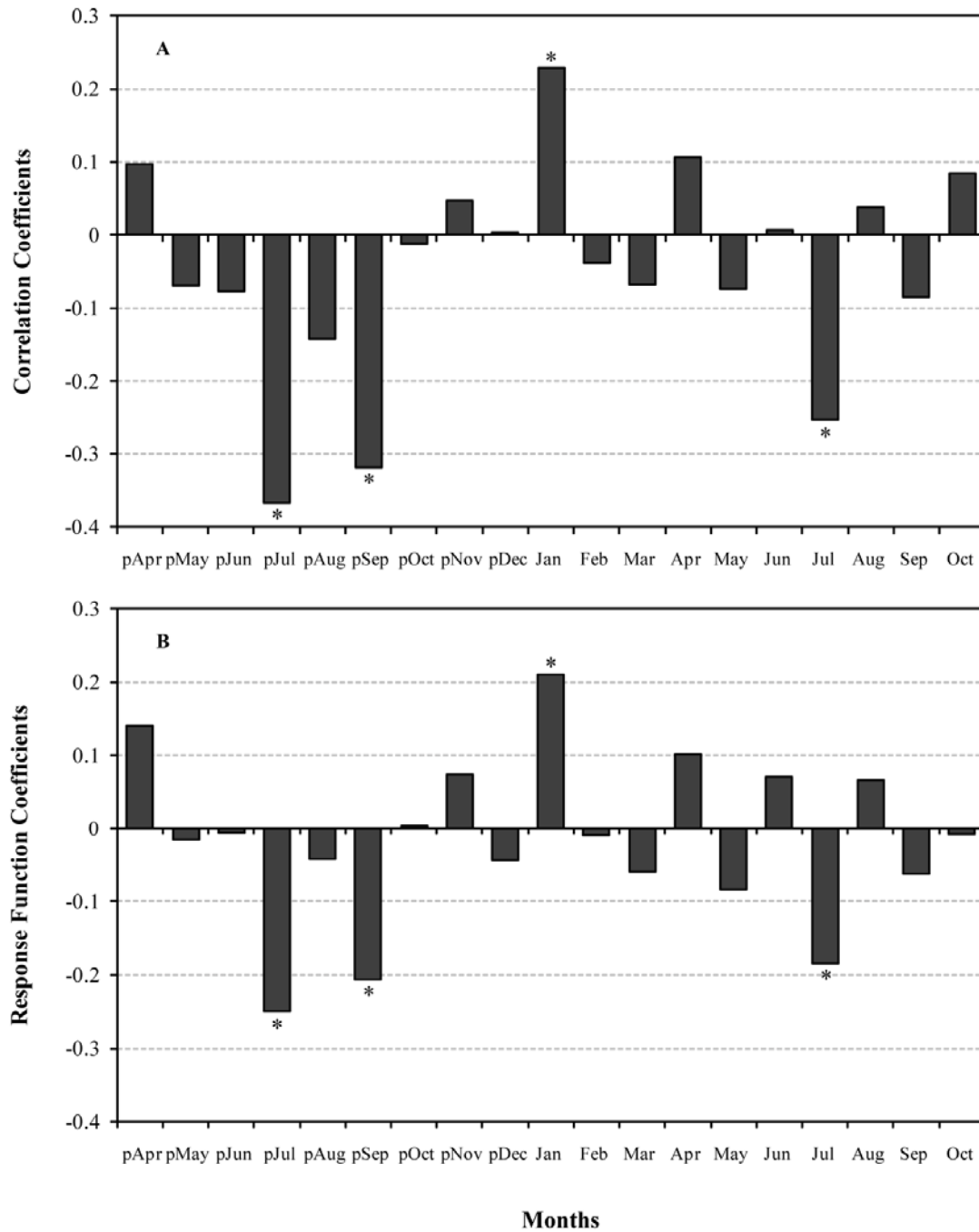


Figure 5.4 1930–2008 monthly correlation coefficients (A) and response function coefficients (B) between red spruce growth and mean monthly temperature at Roan Mountain. Months representing the previous growing season are preceded by “p”. Significant values ($p = 0.05$) are denoted by *.

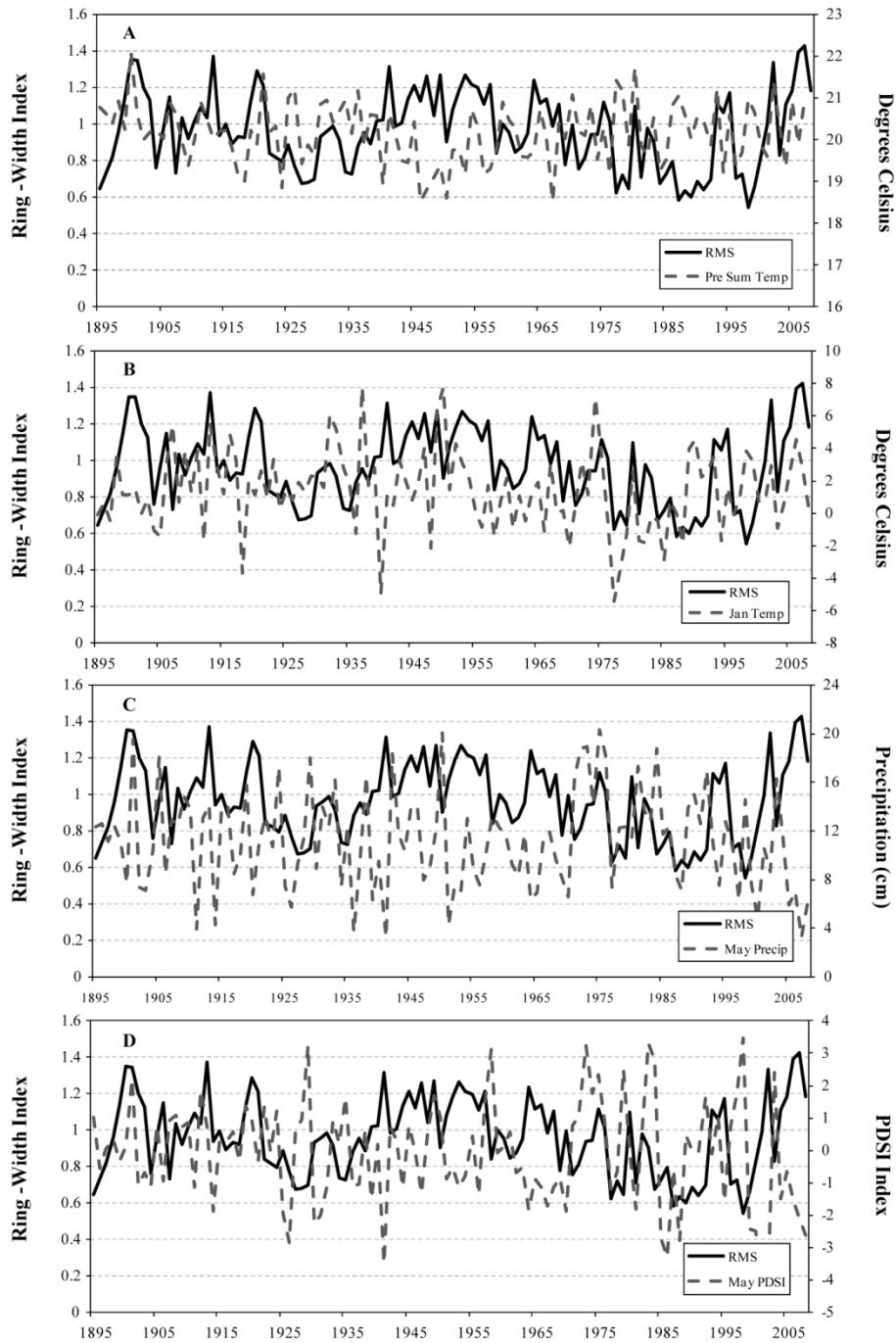


Figure 5.5 Comparisons between the Roan Mountain red spruce chronology and (A) mean previous summer temperature (July–September average), (B) mean January temperature, (C) total May precipitation, and (D) May Palmer Drought Severity Index (PDSI) values.

values of 0.23 in January and -0.25 in July. Correlation and response function analysis yielded similar and complementary results. Both procedures detected relationships in the same months, though correlation analysis produced slightly higher coefficients. Analyses of the relationship between tree growth and both precipitation and PDSI produced similar results. I found significant inverse relationships with both of these variables during the month of May of the current growing season (Figures 5.6 and 5.7). Again, correlation and response function produced nearly identical results with slightly stronger coefficients yielded by correlation analysis.

5.3.2 Moving Correlation Analysis, 1895–2008

Moving correlation analysis detected several shifts and fluctuations of strength in the climate-growth relationship of the RMS chronology. As detected in the correlation and response function analyses, temperature prevailed as the most influential factor on red spruce tree growth (Figure 5.8). The inverse previous-summer temperature-growth relationship was the most temporally stable temperature signal, though it was not prevalent throughout the entire 1895–2008 period and exhibited fluctuations in strength. Notably, the previous-summer temperature signal was absent prior to 1948. In concurrence with the correlation analysis, prior-summer's July and September months exhibited relatively consistent (though fluctuating in strength) relationships during the post-1948 period. Moving correlation analysis detected significant inverse temperature-growth relationships during the previous season's August and June in conjunction with the July and September signals that the static analyses failed to detect. A significant prior

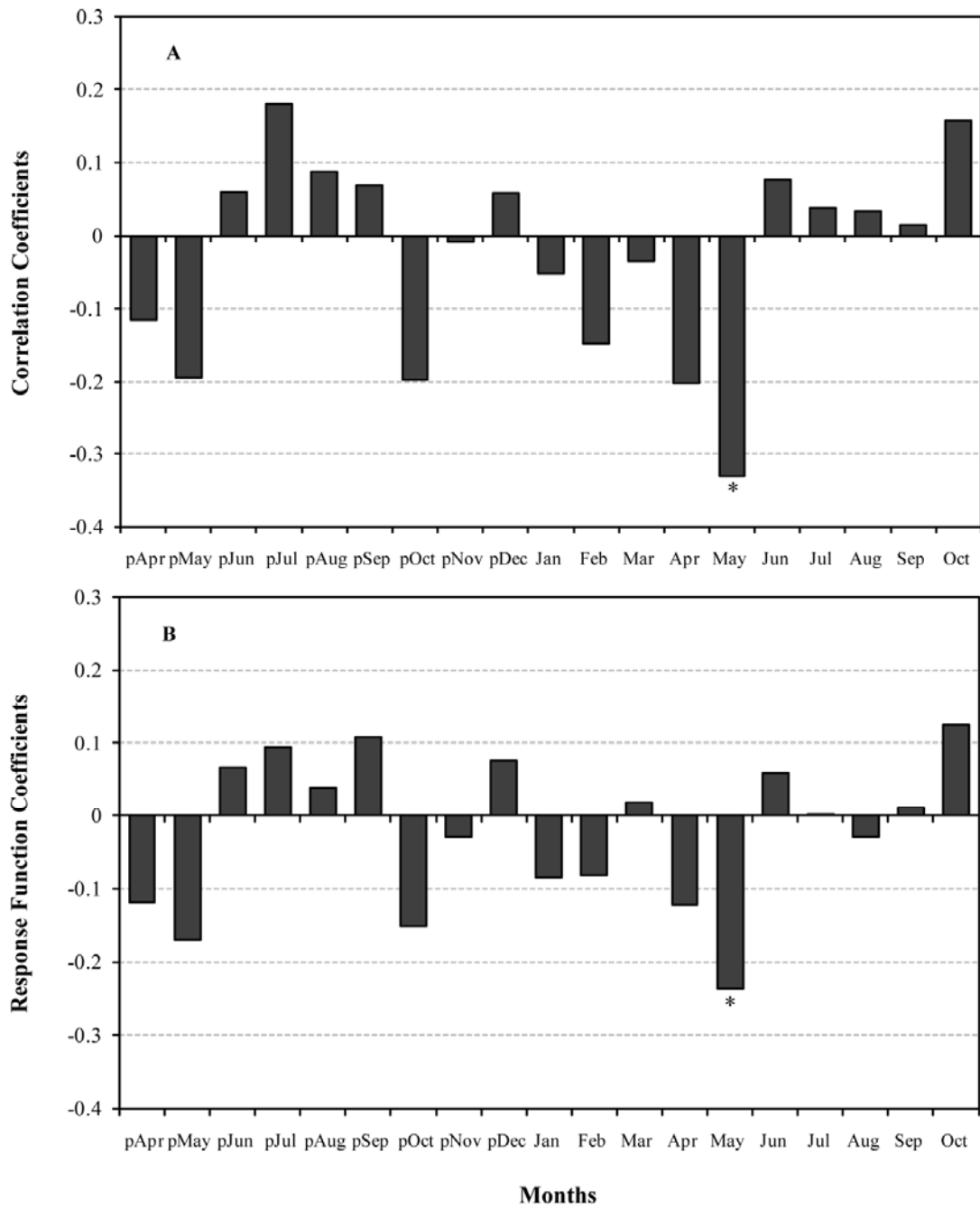


Figure 5.6 1930–2008 monthly correlation coefficients (A) and response function coefficients (B) between red spruce growth and monthly precipitation at Roan Mountain. Months representing the previous growing season are preceded by “p”. Significant values ($p = 0.05$) are denoted by *.

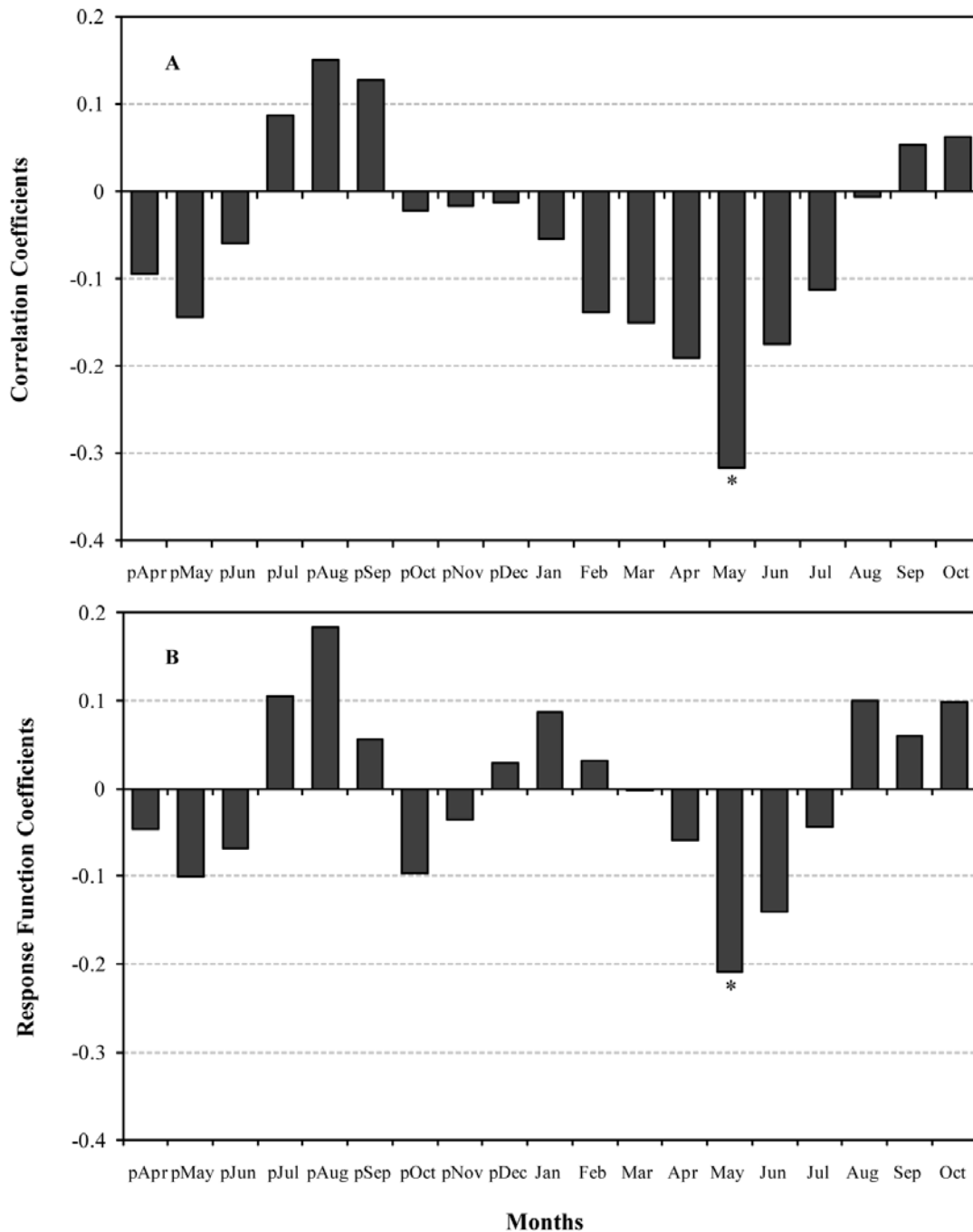


Figure 5.7 1930–2008 monthly correlation coefficients (A) and response function coefficients (B) between red spruce growth and the monthly Palmer Drought Severity Index (PDSI) values at Roan Mountain. Months representing the previous growing season are preceded by “p”. Significant values ($p = 0.05$) are denoted by *.

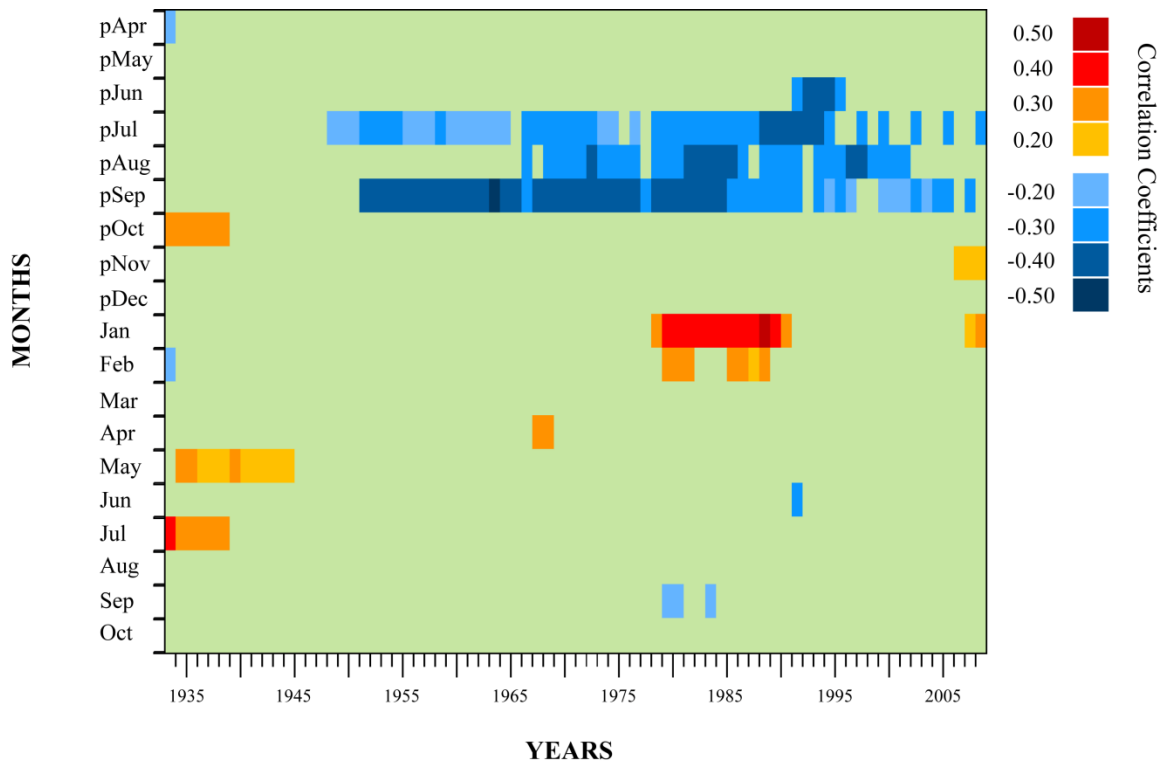


Figure 5.8 Results of 38-year moving interval correlation analysis between temperature and red spruce tree growth. Monthly variables are listed on the y-axis, with variables preceded by “p” representing months from the previous growing season. The final years of each progressing 38-year interval are represented on the x-axis. Red shades indicate direct significant relationships while blue shades represent inverse significant relationships. Strengths of correlations increase with darker hues. Insignificant values are shaded green.

growing season August temperature-growth relationship was present from 1966 to 2001, although the strength varied and the relationship was absent during a few years. A significant prior June temperature signal was only present from 1991 to 1995. Although the summer signal was the most apparent temperature-growth relationship, a weakening of the signal was evident in the later part of the time series. Beginning in the mid-1990s, the inverse prior-summer temperature-growth relationship weakened and became more sporadic. Moving correlation analysis also detected the positive current January temperature relationship that was found using the static correlation and response function techniques. However, this signal was not temporally stable and was only present during the period 1978–1990 and again during 2007 and 2008. During the same period, a significant direct temperature-growth relationship was present during the current February in conjunction with the January relationship. The inverse current July temperature-growth relationship detected using static correlation and response function was absent from the results of moving correlation analysis. In fact, moving analysis detected a direct relationship between temperature and growth during the current July from 1933 to 1938, a result that is in direct opposition to the results of the static techniques. I found direct relationships to current and previous growing season temperatures more commonly occurring during the period of analysis prior to the emergence of the inverse previous-summer temperature signal. In addition to the 1933–1938 current July relationship, significant direct relationships with temperature and tree growth occurred in May of the current year and October of the previous year during the periods 1934–1944 and 1933–1938, respectively.

Moving correlation analysis revealed unstable relationships between red spruce growth and both precipitation and PDSI variables. An inverse May precipitation relationship, the only significant precipitation-growth relationship detected with the correlation and response function techniques, was only significant during 17 of the 112 years tested (Figure 5.9). This relationship was discontinuous and only occurred between 1964 and 1986. Moving correlation analysis also detected a relatively strong but irregular significant inverse relationship between growth and previous October precipitation, occurring mostly from 1964 to 1987. The analysis also detected significant inverse relationships with previous April growth from 1959 to 1971. I found a few other significant precipitation-growth relationships, but they were limited in strength and duration. Moving correlation also detected significant inverse PDSI-growth relationships during the current May (primarily from 1959 to 1976) and prior October (1965 to 1979) (Figure 5.10). These relationships fluctuated in strength and continuity. I also detected an emerging trend of significant direct relationships between growth and PDSI during late-summer months. Beginning in 1993 and lasting through 2007 (with a brief gap in the early 2000s), I found relationships between PDSI and growth during the previous August, September, and, to a lesser extent, July. My analysis found a limited amount of other significant relationships that were typically weak and short-lived.

5.4 Disturbance

I analyzed 26 crossdated red spruce tree-ring series from Roan Mountain for release events using the running-mean method. Of these 26 samples, 23 trees

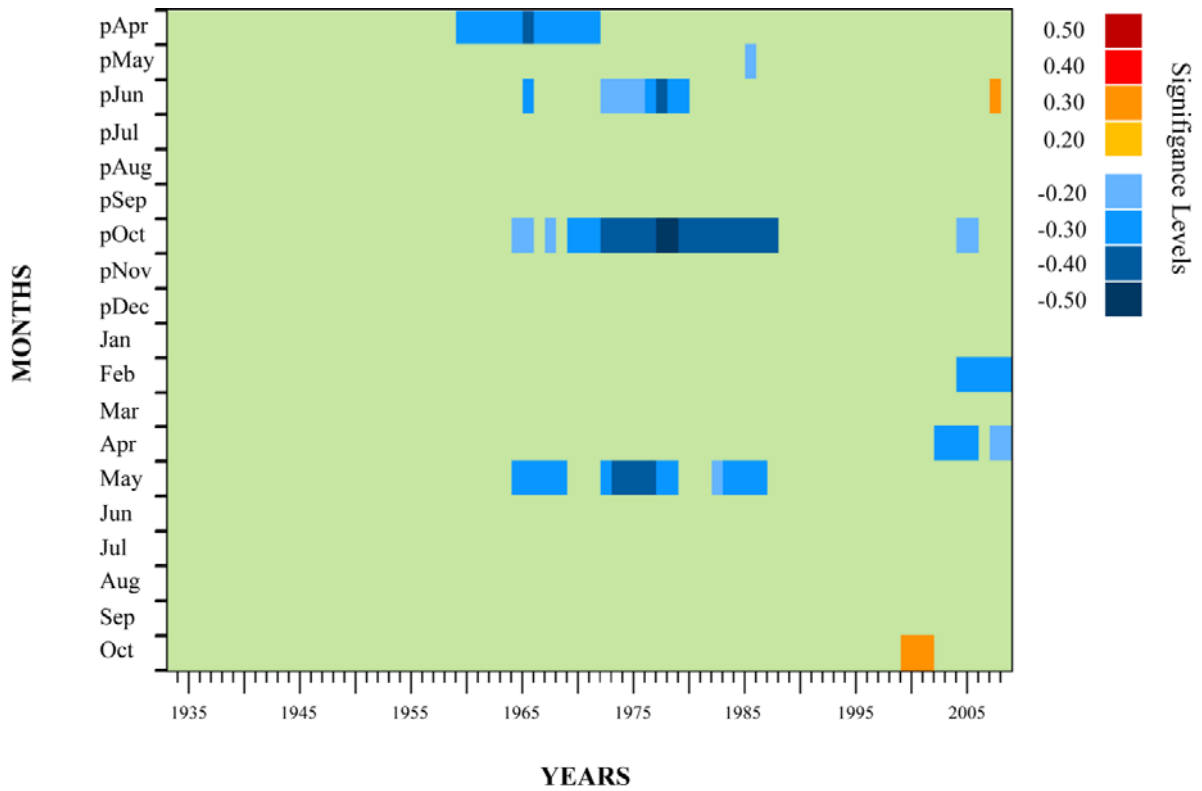


Figure 5.9 Results of 38-year moving interval correlation analysis between precipitation and red spruce tree growth. Monthly variables are listed on the y-axis, with variables preceded by “p” representing months from the previous growing season. The final years of each progressing 38-year interval are represented on the x-axis. Red shades indicate direct significant relationships while blue shades represent inverse significant relationships. Strengths of correlations increase with darker hues. Insignificant values are shaded green.

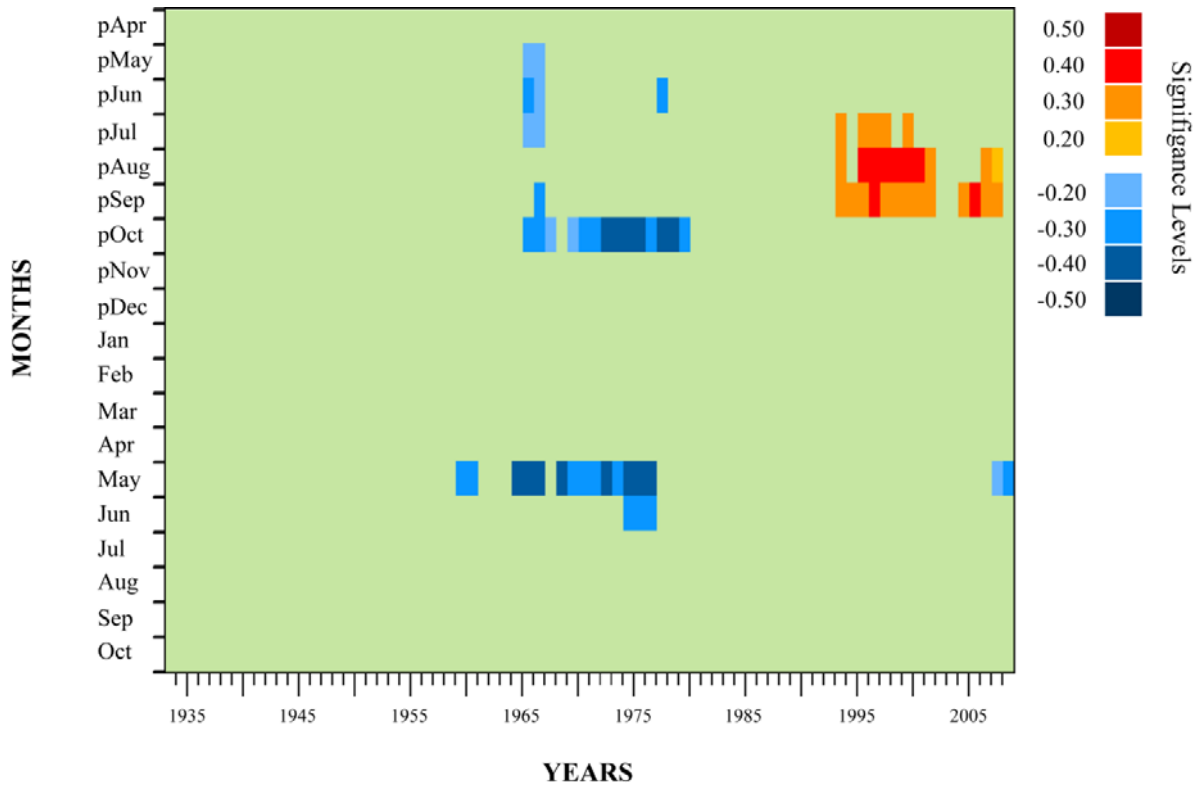


Figure 5.10 Results of 38-year moving interval correlation analysis between the Palmer Drought Severity Index (PDSI) and red spruce tree growth. Monthly variables are listed on the y-axis, with variables preceded by “p” representing months from the previous growing season. The final years of each progressing 38-year interval are represented on the x-axis. Red shades indicate direct significant relationships while blue shades represent inverse significant relationships. Strengths of correlations increase with darker hues. Insignificant values are shaded green.

(88%) experienced 91 release events that were at least minor (25% increase) (Table 5.3). Most trees experienced multiple events; of the 23 trees that exhibited releases, each tree experienced a mean of 3.96 release events. Fewer trees experienced moderate or major events. I found 62 moderate release events in 21 trees while 29 major release events were present in 13 trees. Stand-wide release events occurred periodically and only on minor and moderate release levels (Figure 5.11). Although I detected one major stand-wide release event in 1897, sample depth at this point in the chronology was insufficient to warrant a truly stand-wide event. I found minor and moderate stand-wide events in 1935, 1940, and 2000. The greatest stand-wide event occurred in 2000, when 25% of trees experienced moderate releases and 50% of trees experienced minor releases. I found many distinct periods where clusters of localized events occurred in close temporal proximity to one another. The most evident episode of release events occurred in the 1930s and 1940s during the logging activities of the Champion Company. This group of releases lasted for over two decades and gradually diminished in the 1950s. Other clusters of release events occurred during the 1990s and 2000s, and, to a lesser extent, the 1960s and 1980s.

Table 5.3 Series exhibiting minor, moderate, and major releases, total releases found in all trees, and mean amount of releases among all trees with at least one release.

RELEASE INTENSITY	SERIES WITH RELEASES	RELEASES IN ALL TREES	MEAN RELEASES PER TREES
Minor	23	91	3.96
Moderate	21	62	2.95
Major	13	29	2.23

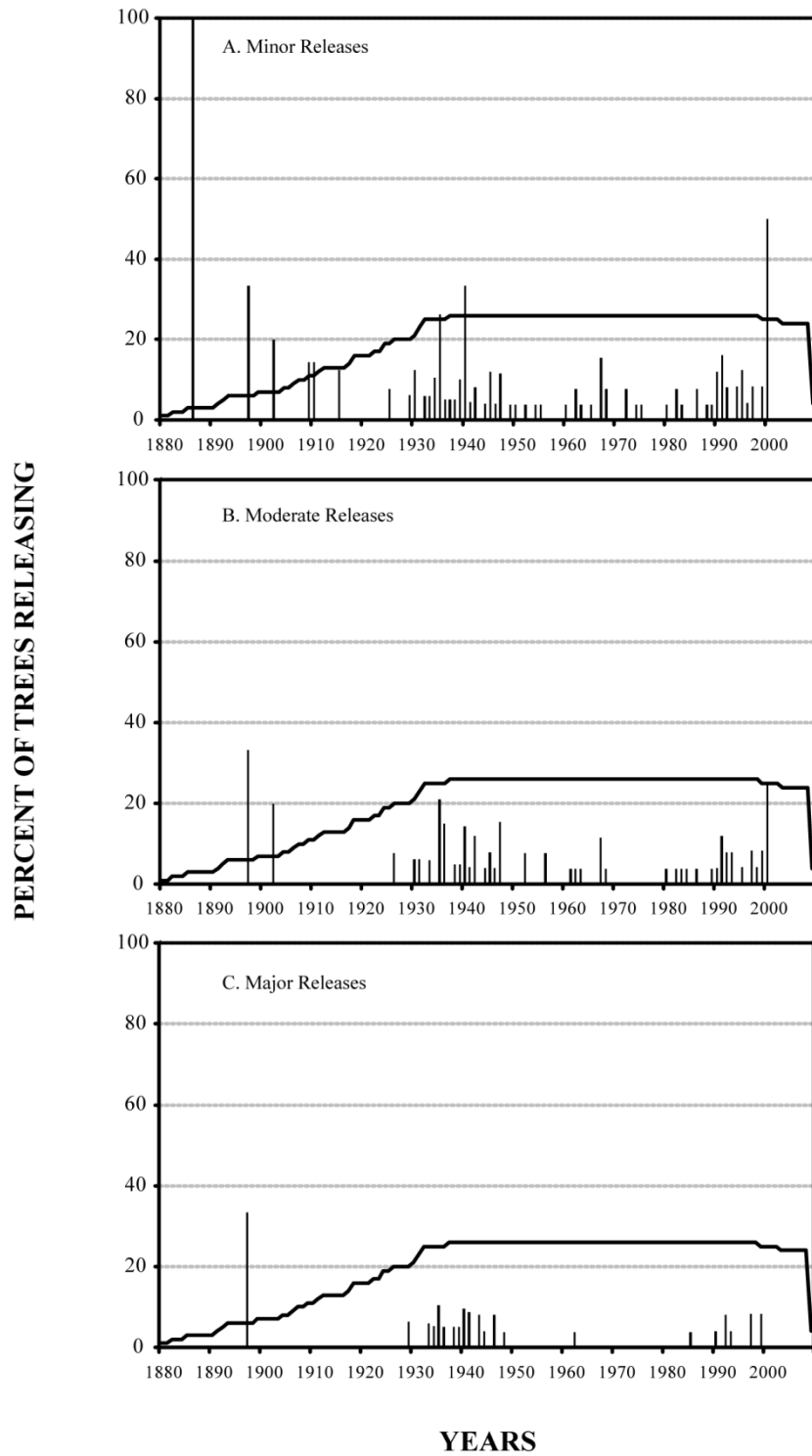


Figure 5.11 Minor (A), Moderate (B), and Major (C) release events found in red spruce at Roan Mountain using a 10-year running mean. Vertical black bars represent percentage of trees experiencing a release in that year. Horizontal black lines represent sample depth.

CHAPTER 6

DISCUSSION

6.1 Red Spruce-Fraser Fir Stand Dynamics

6.1.1 Stand Age and Composition

The red spruce-Fraser fir forest at Roan Mountain endured significant changes during the 20th century, and the forest was much different historically from the heavily disturbed modern forest. Fraser fir was the beneficiary of the clearcut logging of the 1920s and 30s, with establishment of new Fraser firs dramatically outnumbering red spruce in the post-logging period. Red spruce and Fraser fir appeared to share dominance in the pre-logging forest, but the more rapidly regenerating Fraser fir was the dominant tree in the post-logging forest. Although I detected a spruce-fir establishment cohort following the cessation of logging, Fraser fir overwhelmingly dominated this establishment pulse, and red spruce was mostly absent from subsequent pulses in recruitment as well. Fraser fir dominance over red spruce following disturbance is common due to red spruce's higher shade tolerance and less frequent seed crop cycle (USDA 2009), an occurrence that has been documented elsewhere (Busing *et al.* 1988, Smith and Nicholas 2000, Busing 2004). The modern Fraser fir dominated forest was largely an even-aged stand of trees that established during the late 1930s and 1940s. Older individuals likely exhibited irregular growth forms or were small, making them undesirable to loggers. The contrast between the pre-logging and post-logging forest

compositions suggests that clear-cutting at Roan Mountain's high elevations dramatically altered its spruce-fir forest.

The relative dominance, importance values, and understory survey showed that the modern high-elevation forest at Roan Mountain currently occupied an early to mid-successional stage. The high Fraser fir to red spruce ratios I found in the relative dominance and importance values indicated that the forest was still in a relatively early stage of development, a reflection of Fraser fir's earlier successional characteristics compared to red spruce. Fraser fir dominated all seedling classes as well, indicating that an insufficient amount of time had passed for red spruce's shade tolerant attributes to begin overriding Fraser fir's regeneration advantage.

I found little variety in canopy classes in Roan Mountain's spruce-fir forest, with the codominant position far exceeding all other categories. The codominant canopy position suggested that the trees in this stand have formed a single, horizontal crown stratum typical of single-cohort stands. Trees growing within forests of this type, with few dominant trees emerging from the canopy, are spatially limited horizontally, as crowns are crowded from all sides by other trees. This forest condition is characteristic of a stand experiencing the stem exclusion and understory initiation stages of development (Oliver and Larson 2002). As the Roan Mountain spruce-fir forest ages, Fraser fir dominance will likely decrease somewhat as more shade-tolerant red spruce stems slowly reach maturity. Fraser fir's dominant status will likely continue as the stand approaches old growth stage, albeit to a lesser extent, because fir typically occurs more frequently than red spruce above 1,800 m in the southern Appalachians (Delcourt and Delcourt 2000). Therefore, in the absence of future major disturbances, Fraser fir will likely

continue its dominance, though minor canopy disturbances will stratify the canopy and allow red spruce to increase in importance. As the stand matures and aging Fraser fir trees become more susceptible to balsam woolly adelgid infestation, large, stand-wide adelgid disturbances could slowly remove reproducing firs from the forest. Severe future infestations would likely result in increasingly fewer Fraser firs surviving to reproducing age. In addition, this hypothetical development would probably co-occur with the onset of red spruce's natural competitive advantages. Following this scenario, red spruce could eventually reach a level of true codominance, or even dominance in an extreme case.

6.1.2 Disturbance History

The disturbance history of the Roan Mountain's spruce-fir forest is inexorably tied to its logging history, and all disturbances that have occurred during the short existence of the current forest should be considered in its light. The stand-age and release event results proved complementary and demonstrated the large effects the logging period had on the forest. Of the three minor and moderate stand-wide release events I detected, two (1935 minor and moderate, 1940 minor) occurred during or directly after the cessation of logging. Localized disturbances occurred often during the post-logging era on both minor and moderate scales, while major releases occurred less frequently. Much of these disturbances were probably attributable to the balsam woolly adelgid, which first appeared on Roan Mountain in 1962. My analysis did detect a major release event that year as well as a slight increase in minor and moderate release events during the 1960s and 70s. None of these events, however, were stand-wide in nature, indicating that the effects of this initial infestation were perhaps not as severe at Roan Mountain as

those documented in other areas of the southern Appalachians (Dull *et al.* 1988). I hypothesize that the relatively young age of this forest during the initial infestation limited the effects of the adelgid because juvenile Fraser firs are more resistant to infestation than mature trees (Potter *et al.* 2005).

A pattern of localized minor, moderate, and major release events during the mid 1980s, early 1990s, and in the year 2000 was indicative of a broadly decadal cycle of disturbance episodes. These events were likely the result of major adelgid infestation events. No documentation was found regarding Fraser fir dieback events related to the balsam woolly adelgid aside from the 1962 event, and these results did not indicate a clear balsam woolly adelgid infestation signal. It is difficult to assign these localized events solely to pulses in adelgid infestation because a thunderstorm, severe wind, or an ice storm could just as likely be the cause. The exception to this uncertainty was a stand-wide disturbance event in 2000, when 50% of trees experienced a minor release and 25% experienced a moderate release. The 2000 disturbance may have been related to a weather event, but I hypothesize that it was related to balsam woolly adelgid infestation or another insect infestation. An observed southern pine beetle (*Dendroctonus frontalis* Zimmermann) infestation occurred circa 2000 that affected red spruce on Roan Mountain (Jamie Donaldson, personal communication). Although the southern pine beetle does not commonly affect red spruce, there have been some observed incidents in the southeast when warm and dry conditions were prevalent (Thatcher *et al.* 1980). However, this 2000 event co-occurred with the maturation (and resulting adelgid susceptibility) of the post-logging Fraser fir trees, adding to the likelihood of a severe adelgid infestation. Regardless, these results point toward the conclusion that disturbance has greatly affected

this forest and the effects of logging likely hold great long-term influence over the forest's disturbance regime. The devastating logging of the 1930s seemingly mitigated the initial effects of the balsam woolly adelgid on the stand dynamics of Roan Mountain's spruce-fir forest for up to a half-century.

6.2 Roan Mountain Red Spruce Chronology

The red spruce trees used in the RMS chronology produced a chronology of higher than expected quality considering the closed canopy from which they were sampled and the stand's highly disturbed history. The mean series length of 98.6 years predated the most damaging era of logging, indicating that many of these trees were likely small and suppressed during the 1920s and 30s. However, the RMS samples were still relatively young, and it is likely that all of these samples established after initial logging activities began in the late 1800s. The crossdating strength of the RMS chronology was also better than expected given that many of the samples used were taken from plots with the purpose of studying successional dynamics and disturbance. In addition, the targeted red spruce samples were located in the same closed canopy stands in close proximity to the study plots. Consequently, natural forces other than climate, such as competition, stand effects, and natural and anthropogenic disturbances likely exerted significant influence over each of the RMS samples. The chronology was highly correlated (0.551) and the index's 0.252 mean sensitivity fell within a range of sensitivity acceptable for climatic analyses (Fritts 1976).

6.3 Climate Response

6.3.1 Correlation and Response Function Analysis

The most apparent climate signal I found was the inverse relationship between red spruce growth and temperature during the previous summer. Correlation and response function analyses indicated that red spruce growth was restricted by above average temperatures during July and September of the previous growing season (August was notably insignificant, though moving correlation analysis did detect fluctuating periods of August significance). Inversely, cooler summer temperatures promoted growth during the following growing season. For example, a cooling trend in September temperatures occurred in the late 1960s. This period coincided with a period of above average growth in the RMS chronology. Then, in the early 1970s, an abrupt shift to warmer September temperatures resulted in below average red spruce growth. The presence of a previous-summer inverse temperature signal confirmed previous findings of red spruce dendroclimatology research conducted by others (Cook *et al.* 1987, Johnson *et al.* 1988), and was in accord with the theory that trees existing near the ecological limits of their species are climatically sensitive. The Roan Mountain red spruce population exists very near its southern limits, and the more northern, contiguous range of the species inhabits a significantly cooler climate. Therefore, this disjunct population only subsists due to the cooler temperature provided by the mountain's high elevation. Researchers often attribute inverse summer temperature-growth relationships to water stressing caused by the increased evapotranspiration rates related to high temperatures. However, in the case of the high-elevation study area, ample orographic fog and precipitation during summer months ensure that sufficient amounts of moisture are readily available. It is more likely

that warmer than average previous-late summer temperatures prolonged the growing season, which can affect the following growing season in multiple ways. First, trees may have consumed nutrient reserves that are usually stored for the following season late in the prolonged growing season. Such an occurrence leaves little stored growth-inducing carbohydrates for early portions of the next growing season (Fritts 1976). Second, a prolonged growing season may also cause a delay of frost hardening, resulting in a greater susceptibility to tissue damage during early winter storms (Fritts 1976, Eagar and Adams 1992, Schaberg 2000). A combination of these factors likely produced the inverse previous-summer relationship.

In addition to the previous-summer signal, I also found relationships between growth and January temperature (direct) and current July temperature (inverse). At Roan Mountain, warmer temperatures during January likely result in lower amounts of winter snowpack. Warmer winter temperatures also increase soil temperatures and allow moisture to infiltrate the soil (Fritts 1976, Schwarz *et al.* 1997). The combination of these factors would allow a net increase in photosynthesis during the early growing season. An inverse relationship July temperature during the current growing season at Roan Mountain also significantly influenced red spruce growth. The presence of an inverse temperature-growth relationship during the current growing season has somewhat different effects than it does during the previous season. The direct effects of high July temperatures were likely responsible for this signal. During this month, air temperatures may exceed the optimum range for red spruce biological processes, bringing about a reduction in growth rates. Also, excessively high temperatures speed plant respiration,

which may cause consumption of available food at a rate that exceeds replenishment of food stores (Fritts 1976, Schaberg *et al.* 2000).

Both May precipitation and PDSI values correlated inversely with red spruce growth, indicating that excessive spring moisture negatively affected red spruce growth at Roan Mountain. Inverse relationships with precipitation and drought occur less frequently than direct relationships, but they are not unusual in sites where soil drainage is poor and moisture supply is great. Excessive soil moisture conditions can prohibit growth because a reduction in the soil's oxygen level occurs, inhibiting root development (Fritts 1976). At Roan Mountain, melting winter snowpack provides ample moisture in the early growing season and orographic precipitation supplies plentiful moisture during summer months. The overlap of these two variables in early spring likely caused the inverse precipitation and PDSI relationships with growth in May. The combination of a late melting of winter snowpack and a very moist spring would result in a very difficult growing season for red spruce trees. A high amount of rainy spring days could result in reduced early season sunlight which, in turn, would reduce net photosynthesis and plant production. Therefore, average or below average moisture conditions during the month of May were beneficial to red spruce growth at the Roan Mountain study area.

6.3.2 Moving Correlation Analysis

Moving correlation analysis of temperature and red spruce tree growth allowed for a greater depth of insight into the actual nature of the relationship, which was more fluctuating than previous analyses depicted. Once again, the most apparent relationship was an inverse previous-summer temperature signal. In addition to previous July and

September, August of the prior growing season exhibited a relatively stable relationship. This relationship was strongest and most stable during September, reinforcing the hypothesis that a prolongation of the growing season was detrimental to the following season's growth. The July to September previous-summer signal fluctuated in strength perhaps in response to years when temperature conditions varied on the extremes. Interestingly, the late previous-summer inverse relationship did not occur prior to 1948. Prior to this, the following calendar month, the previous October, had a significant direct relationship that ended in 1938. I also detected direct temperature-growth relationships during the 1930s and 40s in the months of May and July of the current year. This evidence suggests that a shift in climatic sensitivity occurred in the 1940s, where positive growth responses to warm temperatures shifted to negative responses. Similar mid-20th century shifts in red spruce sensitivity have been observed elsewhere (Cook *et al.* 1987, Johnson *et al.* 1988). Cook and Johnson (1989) hypothesized climate change may be the causal factor of such a shift. The 37-year moving interval technique did not allow for examination prior to 1933 because the total number of years available during this period was less than 37. It was difficult to determine the longevity of the pre-1940s direct temperature-growth relationship using this technique. While these earlier relationships may have been short-lived, temporary responses to significantly cooler than average temperatures, following the assumption that these responses were long-term and stable, the 1940s change in sensitivity represents a noteworthy finding and a possible signal of climate change. This signal seemed to weaken during the 1990s and 2000s, indicating that another shift in sensitivity may be actively progressing.

Other periods of temperature-growth relationships were present, but were typically sporadic and varying in strengths. The direct January temperature-growth relationship was also detected using moving correlation analysis, but this relationship, though strong, was relatively short-lived, occurring only in the 1980s and early 1990s. Notably, the moving correlation technique did not detect the current July inverse temperature-growth relationship found with the 1930–2008 static correlation and response function techniques. This occurrence may have been methodological in nature. Perhaps the current July relationship was of a temporal frequency beyond the capacity of the 37-year moving analysis window. The discrepancy may also be attributable to the different time scales of the two analysis techniques (a moving analysis scale of 112 years compared to 78 years for the static techniques). Furthermore, the inverse current July signal detected by correlation and response function was not particularly strong (0.254), and this level of correlation fell short of significance under the moving correlation parameters. The instability of the current July inverse relationship as well as the January direct relationship leads to the deduction that the previous-summer inverse relationship is by far the predominant long-term temperature signal, and all other significant temperature relationships only occasionally influenced red spruce growth at Roan Mountain.

Moving analysis of the link between red spruce growth and precipitation and PDSI further demonstrated that moisture availability (or overabundance) is less important than temperature conditions. Significant inverse relationships between growth and precipitation and PDSI during May of the current season were relatively brief and discontinuous, primarily occurring during periods of the 1960s, 1970s, and early 1980s. Several other brief inverse moisture-growth relationships occurred; the most prominent

took place in the previous October during the 1970s and 1980s. This relationship suggests that during this time, red spruce growth benefitted from dryer previous fall conditions. Perhaps the most interesting moisture-growth correlation found was a direct relationship during the 1990s and 2000s. This finding may represent an ongoing trend of red spruce shifting its sensitivity to water availability. During these decades, the dryer conditions that were once favorable to growth seemed to become detrimental to growth. The co-occurrence of this trend with the weakening previous summer temperature signal during the 1990s and 2000s suggested that recent climate changes may have altered the relationship between red spruce growth and climate. However, the recent nature of this trend made it very difficult to determine if it indeed represents a long-term shift or simply another short-lived occurrence.

Given that this population exists on the very edge of the species' limitations, it was not surprising to find that red spruce at Roan Mountain did not exhibit temporal stability in its climatic sensitivity. Even the inverse previous summer temperature signal, the strongest and most stable climate-growth relationship, fluctuated and was discontinuous at times. I hypothesize that disjunct red spruce populations, such as this, are highly susceptible to changes in climate, and, hence, may be a useful indicator of climate change. The instability of the climate-growth relationship casts doubt on the usefulness of the species as a proxy for climatic reconstructions. At the same time, a thorough understanding of red spruce climatic sensitivity may help researchers detect emerging climatic trends. Therefore, researchers should frequently update red spruce chronologies from other disjunct populations in the southern Appalachians and examine closely how the species climatic sensitivity may be changing. However, other factors,

such as disturbance and stand dynamics, are known to influence climatic sensitivity (Fritts 1976), and site history must be fully considered when examining the red spruce climate-growth relationship.

6.4 Climate versus Disturbance

The Roan Mountain site's broad disturbance history could have been a factor in the RMS chronology's unstable climatic sensitivity. The observed shift in temperature sensitivity that occurred during the 1940s coincided with a period of dramatically altered stand dynamics resulting from logging. Disturbance is known to affect tree species' climatic response (Fritts 1976), and it is quite plausible that these events were related. In the aftermath of the clearcut logging of the 1930s, I found a distinct period of insensitivity to climate during the 1940s, followed by the onset of the previous-summer inverse temperature-growth relationship circa 1950. During the late 1930s and 1940s, the unlogged red spruce trees experienced stand-wide release events that seemingly mitigated the influence of climate. As post-logging release events tapered off and the forest canopy began to recover in the 1950s, the influence of climate appeared to reassert itself. However, Roan Mountain's red spruce now responded differently to climate.

There are several possible explanations to this mid-20th century shift in sensitivity. One possible explanation is the dramatic influx of solar radiation following cutting. Under this scenario, the sparse canopy conditions may have resulted in significantly warmer air temperatures, creating the negative previous-summer temperature signal. The prior-summer signal endures far beyond repopulation and canopy reformation, contesting this hypothesis. Alternatively, the dense regeneration and rapid

influx of Fraser fir into the canopy may have also caused a shift in red spruce sensitivity. The unlogged red spruce likely experienced above average air temperature directly following logging, a consequence that would negatively affect growth. By the 1950s, these remaining red spruce trees would have been less competitive for sunlight compared to rapidly advancing Fraser firs. This occurrence would result in a heavily shaded understory. The quick cool-down provided by the rapidly advancing Fraser firs may have been beneficial to red spruce. Such an effect would produce an inverse temperature-growth relationship because the cooler air temperatures would have provided a return to more favorable red spruce growing conditions. A third explanation was that disturbance did not cause such long lasting effects, and, rather, changes in climate caused the shift. Ultimately, identifying one direct cause for the mid-20th century sensitivity shift is unlikely, though the close temporal proximity of the shift to the logging disturbance implied a relationship between these two events at least to some extent. Red spruce sensitivity responded to a combination of disturbance and climatic fluctuations.

Acid rain may have also influenced red spruce growth at Roan Mountain. I observed a general decline in red spruce growth beginning around 1960 and lasting until approximately 1990. This decline may be related to acidic deposition, a hypothesis that much research of red spruce decline is in support of (Johnson and Siccama 1983, Mohnen *et al.* 1990, Eagar and Adams 1992). I also found a weakening trend in the previous-summer inverse temperature growth relationship beginning in the mid 1990s. The weakening of the temperature signal in the 1990s may be related to reduced acid deposition levels resulting from the pollution controls enacted by the Clean Air Act. An improvement in soil acidity may have caused an increase in growth rates unrelated to

climate. More research should be done at Roan Mountain to quantify the effects of acidic deposition on red spruce growth and determine its influence on climatic sensitivity.

Aside from the 1940s and 50s sensitivity shift, the only other period when disturbance and changes in climate response co-occurred was around the year 2000. I observed a weakening of the inverse previous summer temperature relationship, an emergence of a direct previous summer drought relationship, and a relative increase in localized disturbance in the 1990s culminating with a stand-wide event in the year 2000. The root cause of this disturbance is unclear, but the balsam woolly adelgid or possibly the southern pine beetle may have been responsible. A severe adelgid infestation during the 1990s would have caused many tree deaths over a period of a decade, resulting in stand-wide openings in the canopy. The resulting influx of solar radiation to the understory combined with a warming trend and less precipitation could have resulted in unusually dry soil conditions and an increased sensitivity to drought. On the other hand, if this event was related to the southern pine beetle, then evidence exists that climate change may have actually induced a disturbance. Normally, the beetle inhabits warm, xeric stands of yellow southern pines (Thatcher *et al.* 1980), but above average warm temperatures and dry conditions may have brought upon such an occurrence. Such an occurrence would be an example of a positive feedback loop, where hot and dry conditions initiate a disturbance, and then the more open canopy further warms and dries the understory and soil. Further research is necessary to determine if such a link exists. The temporal proximity of climatic shifts and disturbance events suggested that these forces might have been interrelated.

CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH

I investigated the disturbance history, stand dynamics, and climatic sensitivity in the red spruce-Fraser fir forest located at Roan Mountain in Tennessee and North Carolina. I found notably different stand composition and climatic sensitivity between the pre- and post-logging periods. The pre-logging forest reported by Brown (1941) consisted of 62.3% Fraser fir and 26.9% red spruce, compared to the density values 83.2 Fraser fir and 15.4 red spruce found in this study. Although Fraser dominated the pre-logging forest surveyed by Brown (1941) fir, red spruce and other species were much more common during that period than in the modern forest. Prior to the intense logging of the 1930s, red spruce exhibited greater importance in Roan Mountain's spruce-fir forest, and the tree-ring data of this study indicated that the pre-logging forest showed signs of a late-successional development stage. In contrast, a Fraser fir cohort that established during the post-logging 1940s dominated the modern forest. I observed a similar shift in red spruce climatic sensitivity coinciding with the altered stand composition of the 1940s. Although red spruce was consistently sensitive to temperature during the 20th century, the species temperature sensitivity shifted from direct to inverse before and after logging. The results of this study lead to the hypothesis that major disturbances may cause short-term distortions to the climate signal, and may result in long-term alterations to climatic sensitivity. The spruce-fir successional status information gained from this study should

be used by the USFS in managing this rare forest community. As this forest will likely increase in susceptibility to balsam woolly adelgid infestation as it matures, it is important that land managers are aware of how the community responds to disturbance. Knowledge of how Roan Mountain's red spruce population responds to climate and disturbances can help the USFS develop management strategies under future climate change scenarios and disturbance events.

7.1 Major Conclusions

1. Tree-ring evidence from Roan Mountain's red spruce-Fraser fir forest indicated great differences between the historic and modern forests.

Using stand age and composition analyses, I determined that red spruce was formerly of greater importance in the red spruce-Fraser fir community at Roan Mountain. The red spruce specimens that survived the aggressive logging of the 1930s indicated that the species were of greater size and occupied more significant canopy positions in the pre-logging period. The pre-logging forest also exhibited greater variation in age classes, indicating that it occupied a more advanced successional stage than the current forest. A cohort of Fraser fir trees that established directly following logging dominated the spruce-fir forest in the modern, post-logging era. The earlier successional advantages of Fraser fir over red spruce has resulted in an even-aged Fraser fir dominant modern forest that occupies a relatively early stage of successional development. It was evident that the stand-wide logging disturbance of the 1930s dramatically altered the composition and structure of the area's red spruce-Fraser fir forest.

2. Periodic localized minor and moderate disturbances with few stand-wide disturbances characterized the post-logging disturbance regime of Roan Mountain's spruce-fir forest.

I detected only a few stand-wide disturbances in the spruce-fir community during the post-logging period, although I found many localized disturbances that caused minor and moderate canopy release events. Trees recorded release events most frequently during the decade directly following the cessation of logging. This period was characterized by stand-wide release events as the forest recovered from the heavy logging of the 1930s. The only stand-wide disturbance (characterized by the detection of release events in $\geq 20\%$ of all trees) that was not apparently related to logging occurred in the year 2000. Although the first balsam woolly adelgid infestation at Roan Mountain occurred in 1962, the effects of the adelgid seemed to have been mitigated by the relatively young age of the fir dominated post-logging forest. The stand-wide disturbance of the year 2000 was most likely caused by an adelgid infestation because the post-logging Fraser fir cohort had reached higher levels of infestation susceptibility as it matured. In the future, balsam woolly adelgid infestations will likely exhibit greater influence over the forest's disturbance regime, resulting in a slow resurgence in red spruce importance over time.

3. *Red spruce at Roan Mountain climatically responded most sensitively to temperature while precipitation and drought exhibited less importance in regulating growth.*

The strongest climate-growth correlation I detected was an inverse relationship between red spruce growth and previous summer temperature, indicating that red spruce at Roan Mountain benefited from cool temperatures during the previous summer. Correlation and response function techniques detected this relationship during the previous July and September while moving correlation analysis also found a significant inverse relationship in the previous August. These results were in agreement with previous research on red spruce (Johnson *et al.* 1988, Cook and Johnson 1989, Smith *et al.* 1999). Inverse relationships with spring precipitation and drought during the current growing season indicated that above average spring moisture negatively affects red spruce growth.

4. *Red spruce exhibited shifts in climatic sensitivity and fluctuations in signal strength throughout the 20th century.*

Moving correlation analysis allowed for greater insight upon the relationship between red spruce growth and climate. I detected a distinct shift in red spruce temperature sensitivity circa 1950. In the post-1950 period, the previous summer inverse temperature-growth relationship was by far the strongest and most temporally stable relationship, remaining significant until the present. The temperature-growth connection was less clear prior to the emergence of the previous-summer inverse relationship circa 1950. During this time, significant direct temperature-growth relationships were

common, but the strengths of these relationships fluctuated and their longevity was brief and uncertain because I was unable to perform moving correlation analyses prior to 1933 due to sample depth restrictions. This apparent 1950s shift in temperature sensitivity was accompanied by several other short-lived direct and inverse temperature-growth relationships. Moving correlation analysis also revealed that the inverse spring moisture-growth signal was only present during relatively brief periods, suggesting that the moisture-growth relationship was less frequently of importance to red spruce growth. The overall shifting nature of the red spruce climate-growth relationship was likely a result of changes in both the area's climate and disturbance regime. Disturbance effects related to balsam woolly adelgid infestations or acidic deposition may have also distorted the climate-growth relationship.

5. The major logging disturbance of the 1930s may have resulted in a shift in red spruce climatic sensitivity.

The notable shift in red spruce temperature-sensitivity coincided with the major stand composition and canopy structure changes that resulted from the 1930s logging activities. I detected direct temperature-growth relationships during the previous summer and current season during the 1930s, then an absence of relationship during the mid to late-1940s, followed by a distinct inverse relationship after 1950. A relationship between this sensitivity shift and the post-logging change in forest structure seems highly plausible. Spruce trees that survived the logging era experienced an open canopy directly after logging followed by a rapidly closing canopy as Fraser fir regeneration advanced upward. This series of abrupt changes may have resulted in a change in how red spruce

responded to climate. I could not attribute such a shift in sensitivity solely to disturbance, as past researchers have attributed shifts in red spruce sensitivity in forests with less disturbed histories to climate change (Johnson *et al.* 1988, Cook and Johnson 1989, Smith *et al.* 1999). An interaction of climatic influences and forest disturbance likely influenced red spruce climate sensitivity shifts and fluctuations in signal strengths. Thorough statistical models focusing on the temporal trends of summer temperature and tree growth should be developed to further characterize this phenomenon. Regardless of the root cause of climate sensitivity changes, my research indicated that red spruce's climate-growth relationship should be heavily scrutinized when attempting to use the species' tree-ring record as proxy climatic data.

7.2 Future Research and Improvements

Several areas of future work could build upon this research. Continued monitoring of Roan Mountain's red spruce-Fraser fir forest should take place in order to keep track of the forest's successional status and trajectory and to characterize its overall health. The forest remains far from old-growth status, and further monitoring of its disturbance regime would assist in future management initiatives. Greater time and resources would have allowed a higher sample depth that could have greatly improved this study. A greater sample depth may have detected disturbance events that were not captured by this research. Future sampling plots could therefore further characterize the site's disturbance regime.

Additional analyses could improve this research and respond to some of the uncertainties this study brought to light. A major question raised by this research was

whether the shifts in red spruce climatic sensitivity were attributable to climate change or disturbance. In-depth statistical modeling of the climate-growth relationship could assist in answering this question. Advanced modeling techniques would more precisely determine the proportion of red spruce growth that can be directly attributed to climate and how the relationship changes over time. Statistical modeling on varying time-scales (similar to Cook *et al.* 1987, Johnson *et al.* 1988, Webster *et al.* 2004) would complement the moving correlation analysis technique and assist in isolating climate response trends. Statistical analyses of trends in the instrumental climate data would also help to determine if long-term climate change may be responsible for the observed shifts in red spruce sensitivity. In addition, other climatic variables such as winter snow and ice accumulation and long-term climatic oscillations (such as the Atlantic Multidecadal Oscillation or the North Atlantic Decadal Oscillation) should be tested to determine if they influence red spruce growth in the southern Appalachian Mountains. Red spruce chronologies at other disjunct southern Appalachian sites should be analyzed to determine if similar shifts have occurred elsewhere, or if this phenomenon is isolated to Roan Mountain. If similar trends were observed among disjunct red spruce populations with less disturbed stand histories, then evidence would stand that climate change is responsible for changes in sensitivity. Research of this scale could be conducted with relative ease given the availability of regional red spruce chronologies on the International Tree-Ring Data Bank.

The findings of this research suggest that further investigations of the temporal stability of the climate tree-growth relationship should be conducted. Other species in the eastern United States and elsewhere should be examined for temporal shifts in climatic

sensitivity. In the eastern United States, yellow pines are the only other species in which a mid-20th century shift in sensitivity has been observed (Biermann 2009). As many other species are relied upon in the region as proxy climate recorders, more research should be conducted to determine if other species exhibit shifts in climate sensitivity as well. Future research should also investigate red spruce climate response in old growth forests to detect how age of red spruce trees may affect climate response. Age-related shifts in climate response in western conifers have been investigated (Knapp and Soulé 2010) but this phenomenon has yet to be explored among tree species in the eastern United States. More research should be conducted on the subject of temporal stability of tree species' climatic sensitivities. Red spruce populations in the southern Appalachian Mountains are exceptionally suited for such research because of the disjunct nature of their habitats. Future studies should target red spruce populations of wide-ranging ages and disturbance regimes to more accurately gauge the species' response to interactions between climate and disturbance under differing stand-histories.

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ATTACHMENT I: APPENDIX A

APPENDIX A. Roan Mountain red spruce chronology COFECHA output summary statistics.

PART 5: CORRELATION OF SERIES BY SEGMENTS:
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 Correlations of 40-year dated segments, lagged 20 years
 Flags: A = correlation under .3665 but highest as dated; B = correlation higher at
 other than dated position

Seq	Series	Time_span	1880 1919	1900 1939	1920 1959	1940 1979	1960 1999	1980 2019
1	RM3006A	1912 2008		.40	.42	.57	.68	.48
2	RM3007A	1924 2008			.45B	.50	.45	.45
3	RM3009A	1918 2008		.30A	.28A	.61	.57	.53
4	RM3011A	1906 2008		.55	.32A	.68	.83	.81
5	RM3014A	1909 2008		.47	.42	.51	.70	.76
6	RM3015A	1892 2008	.67	.74	.31B	.46	.71	.74
7	RM3017A	1874 2008	.47	.67	.31B	.40	.68	.68
8	RM3025A	1899 2008	.38	.37	.44	.62	.73	.78
9	RM3031A	1891 2008	.38	.41	.50	.54	.54	.54
10	RM4026A	1931 2008			.54	.57	.51	.52
11	RM4032A	1922 2008			.51	.70	.75	.68
12	RM4039A	1926 2008			.61	.56	.54	.56
13	RM5022A	1911 2008		.35A	.45	.53	.45	.38
14	RM5048A	1882 2008	.77	.72	.59	.53	.62	.62
15	RM5048B	1882 2008	.66	.70	.57	.58	.65	.72
16	RMX012A	1907 2009		.55	.28B	.38	.53	.51
17	RMX012B	1936 2009			.29A	.20A	.36A	.39
18	RMX017A	1885 2008	.51	.50	.52	.74	.73	.70
19	RMX017B	1905 2009		.53	.49	.71	.73	.78
20	RMX019B	1924 2009			.52	.75	.82	.78
21	RMX021A	1917 2009		.55	.59	.66	.71	.75
22	RMX021B	1917 2009		.46	.48	.61	.69	.71
23	RMX023A	1932 2008			.33A	.40	.60	.72
24	RMX024A	1904 2009		.66	.63	.47	.31A	.42
25	RMX024B	1904 2009		.67	.52B	.49	.53	.54
26	RMX025A	1930 2008			.73	.80	.73	.61
27	RMX027A	1937 2008			.37	.39	.63	.77
28	RMX027B	1922 2009			.25B	.51	.55	.61
Av segment correlation			.55	.53	.45	.55	.62	.63

APPENDIX A. Continued

PART 7: DESCRIPTIVE STATISTICS:
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Filtered -----\\				Corr //----- Unfiltered -----\\ //----												
Auto	AR	No.	No.	No.	with	Mean	Max	Std	Auto	Mean	Max	Std				
Seq	Series	Years	Segmt	Flags	Master	msmt	msmt	dev	corr	sens	value	dev				
corr	()															
.007	1	1	RM3006A	1912	2008	97	5	0	.437	1.47	5.03	.932	.814	.270	2.54	.354
-.028	1	2	RM3007A	1924	2008	85	4	1	.420	.96	3.05	.834	.933	.332	2.77	.428
.067	1	3	RM3009A	1918	2008	91	5	2	.476	1.02	2.36	.528	.883	.207	2.48	.367
-.128	1	4	RM3011A	1906	2008	103	5	1	.599	1.11	6.08	1.068	.814	.326	2.58	.391
-.016	1	5	RM3014A	1909	2008	100	5	0	.619	.93	2.25	.527	.898	.230	2.64	.527
-.073	1	6	RM3015A	1892	2008	117	6	1	.597	.90	2.82	.575	.786	.284	2.61	.445
-.002	3	7	RM3017A	1874	2008	135	6	1	.487	1.23	3.89	.811	.901	.336	2.73	.475
-.104	1	8	RM3025A	1899	2008	110	6	0	.543	.92	2.12	.535	.849	.353	2.53	.406
-.012	1	9	RM3031A	1891	2008	118	6	0	.466	.90	4.12	.647	.898	.223	2.66	.424
-.070	3	10	RM4026A	1931	2008	78	4	0	.519	1.79	4.78	.951	.822	.234	2.73	.559
-.005	1	11	RM4032A	1922	2008	87	4	0	.624	1.65	3.86	.802	.881	.202	2.68	.413
-.022	1	12	RM4039A	1926	2008	83	4	0	.578	1.36	5.99	1.460	.971	.275	2.67	.463
.012	1	13	RM5022A	1911	2008	98	5	1	.395	1.59	5.10	1.144	.904	.262	2.61	.422
-.061	1	14	RM5048A	1882	2008	127	6	0	.658	1.48	4.58	1.005	.912	.216	2.62	.434
-.090	2	15	RM5048B	1882	2008	127	6	0	.651	1.40	5.02	1.107	.927	.217	2.57	.393
-.096	1	16	RMX012A	1907	2009	103	5	1	.497	1.78	5.54	1.536	.944	.256	2.59	.392
-.077	1	17	RMX012B	1936	2009	74	4	3	.347	2.15	4.79	1.272	.920	.235	2.66	.555
-.037	1	18	RMX017A	1885	2008	124	6	0	.615	1.32	4.22	.900	.905	.229	2.69	.427
-.101	1	19	RMX017B	1905	2009	105	5	0	.683	1.23	3.84	.740	.902	.206	2.61	.454
-.005	1	20	RMX019B	1924	2009	86	4	0	.659	1.72	4.20	1.135	.929	.223	2.77	.440
-.102	1	21	RMX021A	1917	2009	93	5	0	.675	1.67	3.40	.627	.771	.217	2.71	.466
-.027	1	22	RMX021B	1917	2009	93	5	0	.585	1.34	3.78	.732	.716	.252	3.27	.531
-.034	1	23	RMX023A	1932	2008	77	4	1	.457	3.06	6.53	1.480	.838	.226	2.54	.517
-.064	1	24	RMX024A	1904	2009	106	5	1	.516	1.47	5.57	1.077	.816	.215	2.75	.506
-.060	1	25	RMX024B	1904	2009	106	5	1	.565	1.84	5.04	1.137	.838	.248	2.62	.449
-.045	1	26	RMX025A	1930	2008	79	4	0	.631	2.11	4.29	.619	.671	.186	2.60	.501
-.073	1	27	RMX027A	1937	2008	72	4	0	.612	2.39	7.97	1.339	.743	.281	3.05	.537
-.016	1	28	RMX027B	1922	2009	88	4	1	.408	2.79	7.19	1.360	.720	.271	2.91	.439
Total or mean:		2762	137	15	.551	1.50	7.97	.945	.858	.252	3.27	.450				

- = [COFECHA RMS COF] = -

BIOGRAPHICAL SKETCH

Philip White was born on 15 April 1985 in Knoxville, Tennessee. His mother and father are Brad and Susan White, and he is married to Krista White. In 2007, Philip earned a Bachelor of Arts degree with a major in Geography from the University of Tennessee, Knoxville. Philip graduated with *Magna cum Laude* honors from the University of Tennessee, and he was awarded *Outstanding Undergraduate in Geography*. While working towards his bachelor's degree, Philip became academically interested in forest ecology and dendrochronology. Philip elected to continue pursuing his academic interest in these fields as a master's degree student at Appalachian State University in Boone, North Carolina. Philip was awarded an out-of-state tuition waiver, the *Stephen Vacendak Graduate Fellowship in Geography*, and a National Science Foundation funded research assistantship by Appalachian State University's Department of Geography and Planning to support his graduate education and research interests. The North Carolina Native Plant Society funded his thesis research topic, which Philip completed in August 2010. Philip earned the degree of Master of Arts in Geography from Appalachian State in August 2010, graduating with *Summa cum Laude* honors.