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I am submitting herewith a dissertation written by Georgina DeWeese entitled "Past Fire Regimes of Table Mountain Pine (*Pinus pungens* Lamb.) Stands in the Central Appalachian Mountains, Virginia, U.S.A." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

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PAST FIRE REGIMES OF TABLE MOUNTAIN PINE (*PINUS PUNGENS* LAMB.)
STANDS IN THE CENTRAL APPALACHIAN MOUNTAINS, VIRGINIA, U.S.A.

A Dissertation
Presented for the
Doctor of Philosophy
Degree
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Georgina DeWeese
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DEDICATION

This dissertation is dedicated to my cockatiel, Cha. She was always there for me and understood when I did not have time to scratch her neck. Most of this dissertation was written with her sitting on my left shoulder.

I also dedicate this work to Michelle D. Pfeffer (1981–2006), who was a valuable friend and undergraduate assistant to me for many years.

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Abstract

Table Mountain pine is an Appalachian endemic that occurs in a patchy distribution from Georgia to Pennsylvania and is prolific at sites with a history of fire disturbance. The purpose of this dissertation was to reconstruct the fire regimes of Table Mountain pine stands in the Jefferson National Forest, Virginia. Sections from fire-scarred Table Mountain pines were collected at four sites to analyze fire history, while increment cores and stand composition information were collected from macroplots within each fire history site to investigate the possible influence of fires that were more ecologically severe. Results show that fire was frequent before the fire suppression era, with a Weibull median fire return interval between 2–3 years. The majority of fires occurred during the dormant season and beginning of the early growing season. Two of the four sites had a more even distribution of fire seasons, and these sites also had significant Table Mountain pine regeneration. Cohorts of tree establishment were visible in the fire charts of three of these sites, indicating fires that were likely moderate in severity. The canopy at three of the four sites is currently dominated by Table Mountain pine, but the understory at all sites has large numbers of fire-intolerant hardwoods and shrubs. These Table Mountain pine stands will likely succeed to xeric oak and fire-intolerant hardwoods, such as red maple and black gum, in the future. Fire statistics indicate that all four sites currently exist outside their range of historical variation in fire occurrence.

Table Mountain pine was found to be sensitive to climate (monthly precipitation and temperature, PDSI and PHDI, North Atlantic sea surface temperatures, and NAO). Climate analyses revealed that Table Mountain pine growth is reduced when the previous year's September is drier than normal, the current year's February is wetter than average, and the winter is colder than average. Results of these climate analyses illustrate a regional climate signal in Table Mountain pine stands. The best overall relationship between Table Mountain pine growth and climate was captured using the Palmer Drought Severity Index, which was used to reconstruct climate at the four sites for superposed epoch analysis (SEA). The SEA found no indication that antecedent weather patterns in previous years pre-condition these stands for fire occurrence. Rather, the SEA showed that fire is significantly associated with drought during the year of fire.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

EVOLUTION, BIOGEOGRAPHY, AND HISTORY OF APPALACHIAN YELLOW PINE: WITH EMPHASIS ON TABLE MOUNTAIN PINE (*PINUS PUNGENS*)

1.1 Purpose

The purpose of this dissertation is to document the successional status, historical fire regime, dendrochronological potential, and relationship between climate and fire in the Table Mountain pine (*Pinus pungens* Lamb.)-dominated forest types of the central Appalachian Mountains. Although several studies have been conducted during the past two decades that have established the importance of fire in Table Mountain pine-dominated forests, no study has determined the historic and current fire regimes (including fire frequency, seasonality, and spatial characteristics) of these forests over large spatial and multicentury temporal scales. This study built the longest record of fire yet developed for the central Appalachians to determine the fire regimes under which these stands developed and the fire regime that existed before and during the fire suppression era that effectively began ca. 1930. The current age structure of the stands was determined to assess the possible historic role of fires in initiating establishment of Table Mountain pine cohorts and the health of Table Mountain pine stands. The relationship between fire and climate and the effect of climate variables on Table Mountain pine growth in the central Appalachians were also evaluated.

A primary objective of the USDA Forest Service is to restore and maintain yellow pine (especially Table Mountain pine) stands that have declined during the era of fire suppression. This can only be accomplished through an extensive prescribed fire program that uses baseline information on fire regimes. By reconstructing the fire regimes of yellow pine stands and determining the historical range of variability in fire occurrence (Morgan *et al*. 1994), I hope to provide land managers with a better understanding of the role fire once played in maintaining yellow pine stands. Such ecological reference conditions can be used to guide management (Allen 1994) and are often obtained through dendroecological reconstructions of historic fire regimes. With minimal human intervention, natural disturbances (such as wildfires) would be occurring today as they operated and functioned in the past. In the 20th century, however the frequency, intensity, and locality of these disturbances may have changed with pervasive human disturbance and climate change.

1.2 Justification

The changes that have occurred in the composition of post-settlement forests in many areas of the southeast were produced by changes in the dominant disturbance regime, especially changes in wildfire activity (Cowell 1998). The popular presumption that these forests could revert to their original composition over time is challenged by recent studies that focused on the consequences of altered disturbances regimes, in particular fire suppression (Cowell 1998). Without disturbance, Appalachian yellow pines are replaced in natural succession by hardwoods that are more shade tolerant (Spurr and Barnes 1990; Sanders 1992). An increased consciousness of the role of disturbances on vegetation has initiated more research in disturbance ecology. Disturbances, which are discrete events that disrupt ecosystem composition, structure, and function (Barnes *et al*.

1998), promote the coexistence of species in communities at various successional stages that would otherwise be occupied solely by the best competitors (Lafon 2000).

Fire has been established as a necessary and natural disturbance in most Appalachian forests, but the disruption of this disturbance is resulting in species composition changes in these ecosystems. During the Native American period, fire was an intermediate-scale disturbance that promoted a heterogeneous mosaic of fire-adapted and fire-intolerant species (Delcourt and Delcourt 1997). However, 20th century fire suppression policies in the southern and central Appalachian Mountains are widely considered responsible for the decrease in regeneration of fire-adapted species of pine and oak (*Quercus* spp.) (Barden and Woods 1976; Harmon 1982; Abrams 1992; Delcourt and Delcourt 1997).

Fire suppression also has affected Table Mountain pine physiologically and is threatening the genetic diversity of the species (Gibson *et al*. 1990). Suppressed pines have physiological differences from open-grown pines, such as thin bark (Cain 1990, 1993) and thin crowns with small needles, buds, and branch endings. These characteristics make them more susceptible to lethal damage by fire than open-grown pines of the same size that have larger crowns and thicker bark (Byram 1948; Hare 1965; Cain 1993). Fire suppression creates stagnation in pine stands through the cessation of pine recruitment (Hartnett and Krofta 1989), causes increased outbreaks of southern pine beetle and the Table Mountain pine cone worm (*Dioryctria yatesi* Mutuura and Munroe), and increases the number of trees suffering from butt and root rot (*Phaeolus schweinitzii* (Fr.) Pat.) and heart rot (*Phellinus pini* (Thore:Fr.) Ames) (USDA Forest Service 1990; Gray 2001).

Changes in species composition and deterioration of fire-tolerant pines, particularly in the urban-wildland interface (i.e., where elevated human populations live in natural settings adjacent to population centers (Prestemon *et al*. 2002:686)), make accidental, large-scale, catastrophic fires more likely with little chance for healthy regeneration after the fire. Since the 1930s, accumulated forest fuels have increased the risk to human life, forest resources, and property. Increases in fuel loadings are only part of a problem compounded by an unprecedented number of people now living in the urban-wildland interface, which complicates fire management (McLeod 1999; Hesseln 2001).

Prescribed fire is increasingly important as a management tool for controlling fuels and revitalizing the landscape (Carlson and Burgan 2003). The reintroduction of fire into wildland areas and predicting the behavior of those fires require information on past fire regimes, including fire frequency, fire seasonality, fire severity, spatial characteristics of the fires, and climate-fire relationships (Swetnam *et al*. 1999; Grissino-Mayer *et al*. 2004). To gain a more precise understanding of historic fire regimes in pine stands, dendrochronological dating of fire scars on fire-scarred trees, snags (standing dead trees), stumps, and logs can be used. Fire histories provide information on the frequency and seasonality of fires, but not how fires affect vegetation (i.e., fire severity). Age-structure analysis, however, can be used to clarify the effects of fire on the species composition/cohort establishment in an area (*e.g*., Sutherland *et al*. 1995; Kulakowski and Veblen 2002; Abrams 2003). Previous dendrochronological studies have demonstrated a clear association between fire occurrence and cohort establishment within a stand, *e.g*. the establishment of many trees that coincide with a known fire year. Fire history information, combined with age-structure analysis, can therefore provide a detailed summary of the current composition of yellow pine populations, their relationships with past fire, and their prognosis for survival under the current fire regime.

Deterioration of xerophytic Table Mountain pine and mixed pine-oak stands has prompted concern about their continued survival in the central Appalachian Mountains. Not only do xeric oak-Table Mountain pine stands prevent erosion and promote forest regeneration after major fire events, but Table Mountain pine is an Appalachian endemic that contributes to landscape diversity and provides a food source for many Appalachian wildlife species. Fire ecologists and forest researchers predict that fire-intolerant species will eventually dominate and choke traditional southern pine sites unless fire is restored to these ecosystems (*e.g.*, Farrar 1998, Brose 2001). This would decrease the aesthetic value of these forests, put a strain on plant and animal species dependent on xeric oak-pine communities, and increase the likelihood of catastrophic fires, mudslides, property loss, and potentially the loss of human life.

The fragmented landscape created by Euro-American settlement, introduced aggressive invaders, and increased pathogen outbreaks suggest that pre-modern conditions can never be reproduced (Franklin and Agee 2003). However, this dissertation research will offer useful data necessary for forest managers to reintroduce fire to yellow pine stands for the purpose of maintaining them in a healthy state. Fire/climate and fire seasonality analyses will indicate which months prescribed burns could be implemented to be most beneficial for Table Mountain pine growth. Previous studies have established that fire plays an important role in yellow pine forests, but no study has been extensive enough spatially or temporally to determine more precisely what the exact nature of that role is.

1.3 Evolution of the Appalachian Pines

The ancestors of modern gymnosperms first appeared on Earth 365 million years ago during the Devonian Period (Richardson and Rundel 1998). Ancestors of the *Pinaceae* Family had evolved by the mid-Jurassic Period (159–180 mya) and *Pinus* by the lower Cretaceous Period (144–99 mya) (Stewart 1983; Richardson and Rundel 1998). By the end of the Mesozoic Era (248–65 mya), pines had diversified into two major groups, or subgenera: *Strobus* (Haploxylon, or soft pines, with one fibrovascular bundle in the needle) and *Pinus* (Diploxylon, or hard pine, with two fibrovascular bundles in the needle) (Millar and Kinloch 1991; Richardson and Rundel 1998). Environmental changes during the lower Cretaceous (144–99 mya) led to the diversification and rapid spread of angiosperms throughout the mid-latitudes (Crane *et al*. 1995; Richardson and Rundel 1998). The advancing angiosperms displaced gymnosperms, which where deposed to small, cold, or dry refugia in the polar latitudes, or to scattered high-elevation refugia in the mid-latitudes. These habitats have remained the principal realm of the gymnosperms (Richardson and Rundel 1998).

The Eocene/Oligocene Epoch boundary (34 mya) brought drastic climate change, including the shift from warm to cool periods, rapid cooling of the oceans, a decrease in rainfall, and an increase in seasonality. During this period, complex continental climate patterns developed and continental ice sheets formed (Singh 1988; McGowran 1990; Millar 1998). Extensive volcanism and mountain-building in North America created newly disturbed sites, elevational differences, and fragmentation of pine populations, which led to speciation and divergence in pines (Millar 1998). By the end of the Palaeogene Epoch (24 mya), all major subsections of *Pinus*, except *Cembrae*, had evolved (Axelrod 1986; Millar and Kinloch 1991; Millar 1998). During the Eocene Epoch (55–34 mya), *Australes* (subsection of genus *Pinus*) sought refuge in the Gulf Coast Region of the southeastern US, Central America, and the Caribbean (Millar 1998). The glaciation of the Pleistocene Epoch (began 2.5 mya) did not reorganize *Pinus* the way the Eocene did and there were no *Pinus* extinctions (Millar 1998).

During the last glaciation, Appalachian yellow pines retreated south of 33°N along the Gulf Coastal Plain (Delcourt and Delcourt 1987; Turrill 1998). At that time, the polar front extended south from the glacial front to the upper Atlantic and Gulf Coastal Plains (Turrill 1998). This would have increased storm activity (Hidore and Oliver 1994; Turrill 1998) and also increased lightning strikes in these areas. The increase in lightning-ignited fires would have reinforced fire-adaptive traits in the pines (Turrill 1998). Between 18000 and 12000 yrs BP, *Pinus* populations were centered on the Gulf Coast. Between 12000 and 10000 yrs BP, Appalachian yellow pines were completing migration into the southern Appalachian Mountains. Over the last 8000 years, a period referred to as the "southern pine rise," the area occupied by southern pines increased by 14%. Pine populations increased dramatically, with larger fires becoming more common due to extremely dry conditions, especially at higher elevations and on xeric ridgetops (Delcourt and Delcourt 1987; Turrill 1998). Watts (1979) corroborated these findings and added that a rise in pine pollen occurred in the Appalachian Mountains from Virginia southward during this time (Turrill 1998). It was not until the mid-Holocene, 6000 yrs BP, that southern Diploxylon (hard, yellow) pines increased in dominance in the southern and central Appalachian Mountains.

Over the next 2000 years, the southeastern pines expanded (Webb 1988; MacDonald *et al*. 1998), perhaps facilitated by larger fires that were more common due to prevailing drought conditions. These conditions resulted in a fire mosaic in the Southern Appalachian region of patchy, small burns interspersed irregularly over the landscape (Komarek 1974; Turrill 1998) with occasional larger fires in xeric habitats (Turrill 1998). Lightning-ignited fires reinforced the fire-adapted traits that the southern Diploxylon pines had developed (Turrill 1998). Xeric oak species also increased in numbers in the eastern U.S. during the Holocene epoch after glacial retreat when a warmer drier climate with increased fire occurrence prevailed (Abrams 2003). Modern humans migrated into the southern Appalachians over 12000 years ago (Chapman 1985; Turrill 1998) and began applying cultural burning to the landscape. Native Americans entered Virginia around 9500 BC (Barber 1999; Brown 2000). Approximately 4000 years ago plant associations in the Appalachian Mountains stabilized (Brose *et al*. 2001; Schuler and McClain 2003).

1.4 Biogeography of Appalachian Pines

Appalachian yellow pines include Table Mountain, shortleaf (*Pinus echinata* P. Mill.), Virginia (*Pinus virginiana* P. Mill.), and pitch (*Pinus rigida* P. Mill.) pines (authority Fralish and Franklin 2002). These are not to be confused with the other southern yellow pines (also subsection *Australes*), which include loblolly (*Pinus taeda* L.), slash (*Pinus elliottii* Engelm.), longleaf (*Pinus palustris* P. Mill.), pond (*Pinus* *serotina* Michx.), and spruce (*Pinus glabra* Walt.) pine. Virginia pine is included in the subsection *Contortae*, along with jack (*Pinus banksiana* Lamb.), sand (*Pinus clausa* Chapm.), and lodgepole (*Pinus contorta* Dougl.) pine (Fralish and Franklin 2002). Table Mountain pine, shortleaf, Virginia, and pitch pine are all Diploxylon pines, the yellow or hard pines (Mirov 1967; Sanders 1992). Unlike the Haploxylon, or soft pines, Diploxylon pines have a distinct and abrupt transition from the latewood of one year and the earlywood of the next (Fralish and Franklin 2002), which makes their ring boundaries more visible. Virginia, Table Mountain, and pitch pines have overlapping elevational and latitudinal distributions, with the range of Table Mountain pine being almost entirely contained within the ranges of the other two pines (Critchfield and Little 1966; Zobel 1969).

Despite having low leaf-area index, pines are more effective colonizers because they are able to attain a full canopy of foliage more quickly than other species (Richardson and Rundel 1998). Appalachian yellow pines are pioneer species that have adaptations that allowed them to colonize disturbed areas quickly. Newly disturbed areas are generally devoid of vegetation cover and the environment is harsh (hot/cold, dry/wet, windy); therefore, germination and growth are rapid, so that seedlings can withstand harsh conditions (Barnes *et al*. 1998). Compared to other Appalachian yellow pines, Table Mountain pine has heavier seeds than those of pitch and Virginia pine (U.S. Department of Agriculture 1948; Zobel 1969) which produce heavier seedlings with longer root systems, more lateral roots, and more branch development than pitch or Virginia pine (Zobel 1969) which increases survival rates on drought-prone sites (Sanders 1992). Table Mountain, pitch, and Virginia pines are fire-resilient species with a high degree of cone serotiny, small seeds, and precocious reproduction. They are short-lived and generally of low successional persistence (McCune 1988). Populations are considered fire resilient because of their abundant seed production and the ability of the populations to survive as seeds through infrequent catastrophic fires (McCune 1988).

Natural regeneration of Virginia and pitch pines is propagated by disturbances, such as logging activity, farming, grazing, and fire, but only fire perpetuates Table Mountain pine (Sanders 1992). The ultimate role of disturbance, such as fire, is to remove existing vegetation and create an environment of high sunlight and reduced competition, and thereby create conditions conducive to the germination, establishment, and growth of pioneer species such as pines (Bonan 2002). Disturbance is an important phenomenon in Appalachian communities because it resets the successional sequence to an earlier stage and maintains pioneer pine species that would otherwise vanish from the landscape during succession (Fralish and Franklin 2002). In humid climates, pines are poor competitors against hardwoods in seedling establishment, height growth, and reproduction, and therefore depend upon areas that have been disturbed by fire, areas with extreme climates, or areas that have nutrient shortages where hardwoods cannot compete (Bond 1989; Millar 1998). Fire acts as a filter for an ecosystem, excluding and admitting species based on the existence of traits that correspond to the current fire regime (Bond and Midgely 1995). Fire is a standard influence in the life cycle of pines through nutrient and water cycling, fuel accumulation, succession, and the maintenance of diversity (Barnes *et al*. 1998).

Fire is responsible for the specialized adaptations by pines and for much of the wide distribution of pines across their native range in the northern hemisphere (Agee

1998). According to Barnes *et al*. (1998), four characteristics allow species to persist in fire-prone environments. These characteristics include avoidance of fire damage (thick bark), the ability to recover after a fire event (resprouting), ability to colonize sites after fire events (heat-induced germination), and ability to promote or facilitate fire (release of flammable resin).

Thick bark helps insulate the cambium against low-intensity fires (McCune 1988; Agee 1998), which allows pines to persist in environments that experience repeat fire events. Fire-adapted angiosperms, such as chestnut oak, and some conifers, such as pitch and Virginia pine, can reproduce asexually through sprouting (Barnes *et al*. 1998). Epicormic sprouting is absent in Table Mountain pine and Table Mountain pine has few basal buds to allow recovery of saplings after injury from fire or predators (Gray 2001), although Zobel (1969) reported the ability of Table Mountain pine saplings to reproduce vegetatively after fire events from basal bud sprouts. Keeley and Zedler (1998) also reported Table Mountain pine as being able to reproduce after fire from basal sprouts. Dormant buds are absent in Table Mountain pine and Virginia pine, but present in pitch pine where they occur along the bole and branches and allow for recovery from defoliation (Stone and Stone 1943; Zobel 1969).

Cone serotiny refers to cones that remain closed after the seeds have matured but open rapidly when high temperatures melt the resin that seals the cone (Critchfield 1966; Gray 2001). Serotiny occurs exclusively in conifers growing in the northern hemisphere and is a common trait in species growing in ecosystems that experience fire at intervals of a decade or more (Bond and van Wilgen 1996; Gray 2001). Serotiny varies depending on aspect, stand density, and shading of cones, with variation between stands and within stands being genetic (McIntyre 1929; Zobel 1969). Serotiny is also significantly correlated with elevation (positive) and latitude (negative) (Zobel 1969).

Table Mountain pine cones are serotinous, while pitch pine cones are not serotinous in the southern Appalachians (Williams 1998). Virginia pine cones are not serotinous anywhere within their range (McCune 1988). The evolution of serotinous cones in Table Mountain pine can be attributed to the locations where Table Mountain pines grow. In the Appalachian Mountains, fires are most intense on the upper portions of south-southwest facing slopes (Barden and Woods 1976; Sanders 1992), where Table Mountain pine is commonly found. These sites are dry because of higher insolation and wind, so they tend to burn more frequently and at greater intensities. Flammability is further enhanced by pine litter, which is generally deeper and more flammable than that of hardwoods (Spurr and Barnes 1990; Sanders 1992). Table Mountain pine has an advantage over the other Appalachian yellow pines because of its serotiny. Seeds can be released immediately after fires, regardless of season, while other pines, by releasing their seeds in the fall, are at risk of having their seeds consumed by dormant season fires (Sanders 1992).

Communities that are fire-tolerant or fire-dependent burn more readily than fire-intolerant communities of plants because of natural selection, which favored the development of characteristics that make these fire-tolerant plants more flammable (Mutch 1970). This hypothesis provides the evolutionary rationale for the differences between fire-tolerant and fire-intolerant plant communities (Bond and Midgley 1995). For example, pine litter is more flammable than oak litter and, without fire, pines are replaced by oaks (Williamson and Black 1981; Rebertus *et al*. 1989; Bond and Midgley

1995); therefore, pines evolved flammability to avoid replacement by oaks. However, xeric oaks frequently occur in fire-tolerant Table Mountain pine stands, they are themselves fire-tolerant, and in some cases they have existed in these stands longer than the fire-tolerant pines. Xeric oaks, such as chestnut oaks, are ranked as one of the most fire-resistant eastern species (Starker 1934; Abrams 2003) because they have thick bark (Lorimer 1985; Abrams 2003), produce tyloses which compartmentalize wounds caused by fire scars, and are drought tolerant (Abrams 2003). Table Mountain pine is pitch-producing, which compartmentalizes fire scars (Sutherland *et al*. 1995; Keeley and Zedler 1998), but also increases the tree's flammability and the chances for further scarring.

1.5 History of Fire Regimes in Appalachian Yellow Pine Stands

Since plant associations stabilized 4000 years ago, four different chronological fire regimes have been identified in the mixed oak-pine forests of this region (Brose *et al*. 2001; Schuler and McClain 2003). The first fire regime existed prior to Euro-American settlement and was characterized by periodic, low-intensity fires set by lightning and by Native Americans, who augmented the natural fire regime (Van Lear and Waldrop 1989; Whitney 1994; Delcourt and Delcourt 1997; Schuler and McClain 2003). Wildfire acted as an intermediate-scale disturbance agent that promoted a mosaic of different vegetation types (Delcourt and Delcourt 1997). The abundant distribution of fire-tolerant species during the pre-settlement era indicates that fire was an important force in North American forests before Euro-American settlement (Cowell 1998).

The second type of fire regime began when Euro-American settlers arrived and adopted Native American burning techniques to manage vegetation. Like their Native American predecessors, Euro-Americans continued the equivalent of prescribed burning and considered occasional wildfires part of the natural world (Williams 2000; Pyne 2001; Wise and Freitag 2002). Burning during this period increased as a result of the increase in Euro-American population density (Turrill 1998).

The third type of fire regime began with the Industrial Revolution when widespread timber harvesting used steam-driven locomotives that also provided the ignition source for an era of high-severity fires (Schuler and McClain 2003). Intensive logging created vast areas of dried slash that were easily ignited by stray sparks from the steam power used in lumber transportation and processing (Brose *et al*. 2001). Fires that burned during this period were generally of much greater severity than during the pre-settlement and early-settlement periods and were deleterious to soils, waterways, and adjacent uncut forests (Brose *et al*. 2001), although the fires did allow for the expansion of Table Mountain pine to lower elevations away from xeric ridgetops (Williams 1998). A nationwide conservation movement identifying wildfire as a destructive force was initiated after the massive wildfires of the late 1800s and early 1900s (Brose *et al*. 2001).

Finally, the fourth type of fire regime is marked by fire suppression during the 20th century, which allowed forests to recover, but also allowed fire-intolerant species to increase in dominance and hinder regeneration of yellow pines and xeric oaks (Brose *et al*. 2001). Changes in land use and fire policy eventually slowed and reversed pine expansion with stands on more mesic sites becoming reproductively stagnant and eventually succeeding to hardwood dominance (Williams 1998:81). Fire was viewed as a threat to the nation's timber supply during this time (Pyne 2001; Schuler and McClain 2003) with paper companies in the southeast leading the call against fire (Stanturf *et al*. 2002). Even though early Forest Service leaders understood the dangers of fire suppression, particularly in pine stands (Pinchot 1899; Graves 1910; Eldredge 1911; Stanturf *et al*. 2002) the Forest Service still opposed the use of prescribed fire (Demmon 1929; Schiff 1962; Stanturf *et al*. 2002). Forest Service promotional campaigns (such as Smokey Bear) taught Americans to be careful with fire, but also that fire had no place in maintaining American forests (Brose *et al*. 2001). This last change in fire regimes is considered responsible for the decrease in regeneration of fire-adapted species such as Table Mountain pine (Barden and Woods 1976; Harmon 1982; Abrams 1992). Elimination of low-intensity surface fires has increased the density of stands with mid-stories and understories now consisting of fire-intolerant, shade-tolerant shrubs and trees (Brose *et al*. 2001).

The current period in fire history is also one of fire management, where the historic role of fire is increasingly studied and integrated into forest management (Stanturf *et al*. 2002), mainly through the use of prescribed burns. A prescribed burn is fire that is applied in a knowledgeable manner to forest fuels in a specific area under specific weather conditions to accomplish predetermined, well-defined management objectives (USDA Forest Service 1989; Turrill 1998:12). The first approved prescribed burn took place in 1943 in Osceola National Forest, Florida, but the use of prescribed fire did not become common in the Southeast until after World War II (Stanturf *et al.* 2002). The fires of the 1930s and 1950s during drought periods were disastrous and fueled the call for more prescribed burning to decrease hazards (Stanturf *et al.* 2002). Surveys conducted during the late 1960s and early 1970s found that the public generally believed that all fires were bad and strongly supported aggressive fire suppression (Hendee *et al*. 1968; Cortner *et al*. 1990). By the 1970s, however, people were beginning to accept that some wildfires should be allowed to burn, but that fire suppression was still necessary (Stankey 1976; Cortner *et al*. 1990). By the late 1970s, 70% of respondents understood the beneficial effects of fire and could define prescribed burning, but were still not agreeable to the idea of letting wildfires burn in national parks or forests (Rauw 1980; Cortner *et al*. 1990). Nonetheless, public land management agencies began redirecting emphasis from suppression to management during the 1970s (Cortner *et al*. 1990).

By the early 1980s, surveys found that 80% of respondents approved of prescribed burning and letting some wildfires burn (*e.g*., Zwolinski *et al*. 1983; McCool and Stankey 1986; Cortner *et al*. 1990). It was also during this decade that land managers became increasingly concerned about the shrinking distance between urban and wildland areas (Cortner *et al*. 1990). The National Fire Policy, written in 1995 and updated in 2001, and the National Fire Plan passed by Congress in 2000 acknowledged the importance of naturally-occurring fire and replaced suppression policies with directions for the use of wildland fire as a tool in forest management to maintain and restore ecosystem health (Wise and Freitag 2002). Today, prescribed fire is used to reduce fuel loads and help prevent catastrophic wildfires, most of which are accidentally caused by campfires, debris burning, or sparks from machinery (Stanturf *et al*. 2002).

1.6 Biogeography of Table Mountain Pine

Table Mountain pine was first collected and named in the late 1700s by André Michaux near Tablerock Mountain in Burke County, North Carolina (Michaux 1789, 1810; Sanders 1992). Michaux named the species “Table Mountain pine” because of its considerable presence on Tablerock Mountain (Mollenhauer 1939). Soon after, Lambert (1803, 1805) diagrammed, named, and described the species from a sample collected in the Blue Ridge Mountains of Virginia (Sanders 1992). Table Mountain pine has also been referred to as mountain pine, poverty pine, hickory pine, prickly pine, black pine, southern mountain pine, ridge pine (McIntyre 1929; Sanders 1992), and squirrel pine (Mollenhauer 1939).

Between Georgia and Pennsylvania, Table Mountain pine is found on exposed ridgetops, exposed outcrops, granitic domes, knobs, peaks, and steep slopes of southerly aspect (Whittaker 1956; Racine 1966; Zobel 1969). The species also thrives in cold, windy environments (Walker and Oswald 2000). Table Mountain pine generally occupies the convex areas (i.e., the noses and ridges) of the mountains, areas that receive minimal runoff and seepage from the higher slopes (Zobel 1969). Table Mountain pine is most populous in Virginia, where it accounts for 3.4% of all tree species in the Jefferson National Forest (Della-Bianca 2002). In Virginia, Table Mountain pine has an uneven distribution, appearing mostly along the crest and eastern escarpment of the Blue Ridge Mountains and in the shale regions and high ridges of the Ridge and Valley Province. Table Mountain pine is also found on sandstone ridge caps and higher elevations or lower non-shale outcrops, as well as the western slopes of the Great Smoky Mountains and some Tennessee ridges (Zobel 1969). Scattered stands of Table Mountain pine and Table

Mountain pine-pitch pine occur on the eastern fringe of the Appalachian Plateau Province and on monadnocks and river bluffs of the western Piedmont (Zobel 1969).

Table Mountain pine occurs at the higher elevations, usually between 500 m (1640 ft) and 1350 m (4429 ft) (Fralish and Franklin 2002), although the species occurs as low as 46 m (151 ft) near Newark, Delaware and as high as 1430 m (4692 ft) in Unicoi County, Tennessee (Zobel 1969), and 1767 m (5797 ft) in the Great Smoky Mountains (Stupka 1964; Zobel 1969). Table Mountain pine distribution is restricted to higher elevations because higher temperatures at lower elevations, such as those on the Piedmont, would prevent cone serotiny (Zobel 1969). Table Mountain pine is not limited to growing only on xeric ridgetops, but is found where it competes successfully, including sites at lower elevations that have a history of burning (*e.g.,* Illick 1928, Zobel 1969). Without disturbance, in particular fire, Table Mountain pine would survive only on extremely dry, sterile rock outcrops and steep shale slopes where the canopy would be open with minimal litter cover (Zobel 1969).

Slope aspect is directly correlated with Table Mountain pine presence in the Great Smoky Mountains (Cain 1931; Stupka 1964; Whittaker 1956), the Blue Ridge Mountains (Racine 1966), and in western Virginia (Hack and Goodlett 1960; Zobel 1969). The southern aspect receives 13 times the radiation the north slope does on the shortest day of the year and 1.9 times as much at the equinox, with little difference at midsummer. Direct beam irradiation is largely determined by aspect on slopes (Zobel 1969). Annual insolation, air and soil temperatures, vapor pressure deficit, and evaporation increase from lower to upper slopes and from north to south-facing slopes in Table Mountain pine stands (Mowbray and Oosting 1968; Zobel 1969).

Table Mountain pine prefers soils that are shallow, acidic, and oligotrophic (i.e., low in nutrients) (Turrill 1998) as well as soils that are stony, shallow, and sometimes without profile development. The species can also grow on soils that are strongly acidic, infertile, of low productivity, and well- to excessively-drained (U.S. Department of Agriculture, Soil Conservation Service 1938; Zobel 1969). Topsoils and subsoils under Table Mountain pine stands have a lower nutrient level and pH than those soils under adjoining stands where Table Mountain pine is less abundant (Zobel 1969).

Table Mountain pine can grow to 13 m in height and generally has two leaves per fascicle, which are 3–6 cm in length, twisted, and rigid. Cones are 5–9 cm in length, ovoid, serotinous, and armed with sharp spines or claws (Fralish and Franklin 2002). Table Mountain pine has 2–5+ cones per whorl, with one flush of cones per year on the new growth of the branch (Zobel 1969; Barden 1979; Gray 2001). Smith (1965) suggested that Table Mountain pine cone characteristics are a result of pressure from red squirrels (*Tamiasciurus hudsonicus* Erxleben) because the scales are hard, the basal scales are sterile, and branches have whorled cones that protect the point of attachment. These characteristics reduce the energy yield of eating the pine seeds by squirrels who reportedly cut the limbs containing cones so that cones can be more easily harvested on the ground (Zobel 1969).

Table Mountain pine was not favored by the lumber industry due to its poor form, and short trunk with copious limbs (Walker and Oswald 2000). The quantity of live branches and branch stubs causes knotty wood and problems in harvesting, reducing the commercial value of the wood (Grimm 1950; Zobel 1969). Its unpopularity has translated to numerous Table Mountain pine stands across the landscape, many of which contain fire scars, making it a valuable research species.

Characteristics that allow survival on xeric sites prevent tolerance of shade (Smith and Huston 1989; Lafon 2000). Such characteristics give Table Mountain pine an advantage in rapid establishment, which is necessary in dry, open sites where it occurs (Zobel 1969). Table Mountain pine has a deep root system which anchors it firmly into the bedrock which allows the species to absorb water and nutrients (Della-Bianca 1990; Armbrister 2002) and prevent erosion, especially after fire events, and thereby protect watersheds (Walker and Oswald 2000). Deep, wide-spreading root systems also prevent injury caused by desiccation (Kozlowski and Pallardy 1997). Branches are long to prevent loss of soil moisture and are self-pruning (Sutherland *et al*. 1995; Armbrister 2002), which decreases the risk of crown fires (Barnes *et al*. 1998).

Seeds are winged and triangular and have a heavy weight, which gives them an advantage in establishing quickly in dry environments (Zobel 1969; Gray 2001). These heavy seeds are not meant to be dispersed by wind, but are adapted to regenerate where they fall (Sutherland *et al*. 1995). Mature seeds have a firm, light-colored endosperm and yellow or white embryo which fills the majority of the endosperm cavity (Seeds of Woody Plants of North America 1992; Gray 2001). With decreasing elevation, the length, width, length-width ratio, and seed weight of Table Mountain pine cones decrease (Zobel 1969).

Pollen release occurs the last week in March at low elevations and the second week of April at higher elevations (USDA Forest Service Silvics Factsheet 2003). At low elevations, Table Mountain pines flower in mid-March and at higher elevations in early

April (USDA Forest Service Silvics Factsheet 2003). Table Mountain pine is monoecious, meaning it has both male and female reproductive organs in separate flowers on the same plant (Richardson and Rundel 1998). Generally, hybridization is restricted because of early pollen release relative to other yellow pines (Gray 2001). There are no recognized varieties or subspecies of Table Mountain pine (USDA Natural Resources Conservation Service 2006). Table Mountain pine reportedly hybridizes with pitch and shortleaf pine (Krugman and Jenkinson 1974; Della-Bianca 1990; Carey 1992). Table Mountain pine populations establish through large-scale, synchronous germinations that reflect 25+ years of mating events (Gibson and Hanrick 1991).

Table Mountain pine cones ripen during the fall of the second season (Gray 2001) and can remain closed for up to 25 years and still remain viable (Lamb 1937; Sanders 1992). McIntyre (1929) found that Table Mountain pine had an average seed viability of 81% and that tree age had no effect on percent seed viability or cone size. McIntyre concluded that frosts, drought, and heavy rains influence cone growth, seed development, and viability more than tree age. However, Gray (2001) found that Table Mountain pine trees older than 11 years had viable seeds and that cones collected during the winter had a higher percentage of viable seeds than those collected during the other seasons. Percent viability of seeds is lowest during the summer. This is in line with the historic dominance of dormant season fires. Table Mountain pine as young as five years can produce cones although with poor seed viability (USDA Forest Service 1990; Gray 2001). Trees older than 76 years had the most viable seeds overall. Waldrop *et al*. (2002) reported that Table Mountain pines in the 5–10 year age group had 3-year-old cones with 23% viability. This suggested that Table Mountain pine was adapted to regeneration under low-intensity fire regimes that occurred every 5–10 years with seeds becoming viable every 2–3 years (Waldrop *et al*. 2002).

Table Mountain pine cones delay seed release by a minimum of two minutes to allow the hottest and most destructive flames of the forest fire to pass before the seeds are dispersed (Barden 1978; Armbrister 2002). Temperatures greater than 32 ºC are needed to melt resins that seal the cones (Barden 1978; Turrill 1998). Forty percent of 2-year-old cones do release seeds on an annual basis (Barden 1979; Gray 2001), but such releases generally do not result in regeneration (Sanders 1992) because release is not accompanied by a prepared seedbed, increased sunlight, opened canopy, and reduced competition. Gray (2001) also pointed out that high temperatures increase the rate at which cones open, but also reduce the production of viable seeds by desynchronizing the release of pollen with the female strobilus receptivity or by inhibiting germination. This could become more of a problem with global climate change.

Table Mountain pine maintains a symbiotic relationship with mycorrhizal fungi. This relationship allows Table Mountain pine to increase its ability to locate nutrients in the soil in a more efficient way (Barnes *et al*. 1998). Table Mountain pine grows more slowly without the presence of mycorrhizae and the number of mycorrhizal types was greater in limed soils compared to unlimed soils, although they were still present in unlimed soils (Zobel 1969). These fungi prefer dry habitats and are well adapted for survival in xeric Table Mountain pine habitats (Ellis *et al*. 2002).

Pisolithus tinctorius Coker and Couch, *Suillus granulatus* (Fr.) Kuntze, and *Cenococcum spp*. are the predominant symbionts forming mycorrhizal root tips on Table Mountain pines (Waldrop *et al*. 2002). Two years after a prescribed burn, seedlings that burned at medium-low to medium-high intensity had twice as many mycorrhizal root tips (40%) compared to seedlings that burned at high intensity (22%) (Waldrop *et al*. 2002). Ellis *et al*. (2002) suggested that mycorrhizal development begins in the first season after the fire event and continued into the second season. Findings also suggest that soil temperatures did not reach lethal levels, even with high-intensity burning (MacDonald *et al*. 1998). No soil sterilization was achieved although mycorrhizal populations did decrease at temperatures over 50 ºC and were virtually eliminated over 80 ºC. Temperatures that high are rare to any significant soil depth. Either the mycorrhizal fungi survived the intense fires, or recolonized the site extremely quickly (Ellis *et al*. 2002).

Fire-adapted and fire-dependent ecosystems are stable in the kinds of wildlife found both before and after fire events (Barnes *et al*. 1998). Most small birds and mammals remain in recently burned areas (Bendell 1974). These ecosystems are still able to sustain life after fire events because of the clonal capabilities of certain grasses and shrubs and the abundance of serotinous-coned pines, both of which are a relatively stable food source (Barnes *et al*. 1998). Table Mountain pine has tremendous ecological value in this respect. Table Mountain pine-xeric oak stands provide habitat for a number of Appalachian species, including economically-important white-tailed deer (*Odocoileus virginianus* Zimmerman), ruffed grouse (*Bonasa umbellus* L.), and wild turkey (*Meleagris gallopavo* L.), as well as scarlet tanagers (*Piranga olivacea* J.F. Gmelin), the northern pine snake (*Pituophis melanoleucus* Daudin), and slender glass lizard (*Ophisaurus attenuatus* Cope) (Turrill 1998). Table Mountain pine provides a valuable seed source that is available when other conifer cone crops and acorn crops fail and after fire events (*e.g*., Williams 1991; Armbrister 2002; Zobel 1969). Mollenhauer (1939) recommended that Table Mountain pine be added to a preferred list of game food trees because of its preference by wildlife and ability to grow on unfavorable sites where other species cannot survive. Besides wildlife species, certain plants, such as Heller's blazing star (*Liatris helleri* Porter), Peter's Mountain mallow (*Iliamna corei* Sherff.), white irisette (S*isyrinchium dichotomum* Bickn.), and running buffalo clover (*Trifolium reflexum* L.), all of which are endangered, are dependent in some way upon xeric, montane forests. Other rare plants restricted to xeric pine and pine-oak communities are the round-leafed serviceberry (*Amelanchier sanquinea* (Pursh.) DC), branched whitlow grass (*Draba ramosissima* Desr.) and witch-alder (*Fothergilla major* (Sims) Lodd.) (Hessl and Spakman 1996; Turrill 1998).

1.7 Previous Studies on Table Mountain Pine

1.7.1 Distribution and Ecology of Table Mountain Pine

The history of scientific research involving Table Mountain pine has resulted in two types of studies. The first type documents the distribution and general ecology of the species. The second type documents the history and role of fire and the effects of prescribed fire in Table Mountain pine stands. Braun (1950) noted that hardwood forests were fairly well understood, but pine ridge communities in the eastern deciduous community were not (Racine 1966). This slowly began to change in the succeeding decades.

Whittaker (1956) documented the vegetation of the Great Smoky Mountains, and gave limited focus to high-elevation Table Mountain pine stands. Table Mountain pine stands were described as being small and open with canopy stems 25.4–38.1 cm (10–15 in) in diameter, canopy height at 12.2–15.2 m (40–50 ft), and tree coverage at 70–80%. Whittaker noted pitch pine, chestnut oak, American chestnut (*Castanea dentata* (Marsh.) Borkh.), scarlet oak (*Quercus coccinea* Muenchh.), and black gum (*Nyssa sylvatica* Marsh.) in Table Mountain pine stands, as well as red maple (*Acer rubrum* L.), sourwood (*Oxydendrum arboretum* (L.) DC), black locust (*Robinia pseudoacacia* L.), and sassafras (*Sassafras albidum* (Nutt.) Nees) in smaller numbers. A well-defined shrub layer with 60–90% cover of mountain laurel (*Kalmia latifolia* L.) and *Vaccinioideae* spp. was also noted. Pines on southern slopes in the Great Smoky Mountains were said to be in a cycle of generations, in which the first generation is propagated by a severe fire and as these trees mature and die, a second generation of pines established (Whittaker 1956). However no evidence is given to show this phenomenon is not the result of repeat fires (Barden 1977).

Racine (1966) described Table Mountain pine stands of the Thompson River Gorge, North Carolina. The objective was to document Table Mountain pine distribution and its relationship to topography and soil, as well as explain the structure and composition of the community and its successional and climax relationships. Ten stands between 610 m and 914 m (2000–3000 ft) were selected that met the following criteria: dominated by hard pines, over 1.2–1.6 ha (3–4 acres), had mature pines 43–64 cm (17–25 in) dbh (diameter at breast height), and no indications of disturbance, including fire. Racine found that pines were more important at the lower end of the sampling range, but this could be explained by Racine excluding pine stands with fire scars, which are more likely at higher elevations. Table Mountain pine was only found at one of the 10 sites.

Zobel (1969) conducted the first complete study of the distribution, environment, and vegetation of Table Mountain pine stands. Twenty-nine Table Mountain pine stands were sampled in 1965 and another 19 in 1966 between 120 m and 1405 m (394–4610 ft) from Pennsylvania to Georgia to determine what physical characteristics allowed for the establishment of the species on a site. Samples of needles, cones, soil, and rock, as well as increment cores, were collected, and data on the associated vegetation, topography, and microclimate were recorded at each site. Zobel concluded that interference from other species likely excludes Table Mountain pine from sites it should be able to occupy, who also predict that the increase in fire prevention and a decrease in land abandonment was thought to reduce Table Mountain pine establishment in the future.

Barden (1977) reiterated that there may be the possibility that certain Table Mountain pine stands are self-perpetuating without fire (*e.g.,* Racine 1966; Whittaker 1956; Zobel 1969). Barden agreed with Zobel (1969) who believed certain stands of Table Mountain pine that exist on rocky outcrops or shale slopes where hardwoods do not compete successfully are permanent, self-maintained stands. This is an acceptable hypothesis because lightning fires are not frequent enough in the Southern Appalachians (Barden and Woods 1974; Barden 1977) or severe enough to remove canopy and disrupt succession from pines to hardwoods (Barden and Woods 1976; Barden 1977). However, the alternative hypothesis is that Table Mountain pine is maintained through a combination of drought and lightning-ignited fires historically (Barden and Woods 1976; Harmon 1982).

Barden (1977) examined self-perpetuating Table Mountain pine stands at Looking Glass Rock, North Carolina. Study sites were located where pines were growing in soil that was separated by exposed rock from the main cap of soil which covered the dome and where mountain laurel was nonexistent or sparse. These criteria could help explain why self-perpetuating stands were found, as mountain laurel is extremely pervasive at xeric sites and hinders Table Mountain pine establishment. Eight instances of “hen-chick” relationship were noted in which a large hen tree with a chick tree suppressed in the same soil pocket is released when the hen dies. The chick then takes advantage of the nutrients available from the decaying roots of the hen and the increase in the amount of soil moisture. Light would not be a limiting factor at these sites, as shade is essential to seedlings’ survival on such dry sites. Forty-two of the 43 trees younger than 11 years of age were growing in the shade.

Barden also argued that repeat fires can initiate cohort establishments of pines at other sites, such as in the Great Smoky Mountains. In this case, Barden disagreed with Whitaker (1956) who gave no indication that repeat fires had initiated cohort establishments of pines in the Great Smoky Mountains. Because of the history of large fires in the Great Smoky Mountains before the 1930s, polymodal size or age distributions should be attributed to repeated fires, unless proven otherwise (Barden 1977).

Barden (2000) revisited Looking Glass Rock to determine what affect the 1980s drought period had on Table Mountain pine recruitment. After the drought period between 1989–1996, the delayed effects of the drought reduced viable Table Mountain pine seeds. This resulted in greatly reduced seedling germination. Barden concluded that at this xeric site, precipitation and temperature are more important in the maintenance of Table Mountain pine stands than fire. That the 1980s drought had such a prolonged effect on the Table Mountain pine population on Looking Glass Rock may be an indication of climate change. Such xeric sites are well suited to signal climate change and the results from this research may be an indication of the beginning of the predicted northern retreat of southern pines (Iverson and Prasad 1998; Barden 2000). Indeed, Cook and Cole (1991) hypothesize that there will be changes in the range limits of several eastern North American tree species, changes in composition and importance, and in some cases decreases in biomass with climate change.

In the tradition of Zobel, Williams (1998) documented the history and status of Table Mountain pine and pitch pine in the late 20th century. Williams noted and discussed the importance of disturbances that affected successional dynamics in Table Mountain pine stands that Zobel did not, including fire, ice storms, southern pine beetle, and fire suppression. Williams also documented the land-use histories of current Table Mountain pine-pitch pine dominated stands and related such histories to the spread of Table Mountain pine. Williams also indicated that Table Mountain pine may be susceptible to ozone and sulfur dioxide damage (Scherzer and McClenahan 1989). These pollutants increased mortality of the species in its northern range (Whiton 1989; McClenahan and McCarthy 1990; Williams 1998). Williams and Johnson (1990) conducted age-structure analyses in Table Mountain pine stands on Brush Mountain, Virginia. In this study, the authors ruled out gap-phase dynamics as a form of disturbance that propagates Table Mountain pine stands that contain shade-tolerant species.

Lamb (1937) and Barden (1978) conducted analyses on Table Mountain pine cones and seeds to determine their viability. Gray (2001) completed a more thorough investigation of the same subject. Table Mountain pine seed viability and availability were studied to determine if those characteristics vary with tree age, cone age, and season. Table Mountain pine seed viability and availability were found to be dependent on tree age, cone age, and season, with trees older than 76 years and cones collected during the winter months having the most viable seeds. Cones increase with tree age; however the average number of seeds per cone decreases with age.

Gibson and Hamrick (1991) conducted analyses to estimate the levels of genetic diversity for Table Mountain pine and determine how genetic diversity is distributed among populations of the species. Table Mountain pine maintains a high level of genetic diversity, which is expected among conifers, but diversity varied among different populations. Environmental variation in species increases with the geographic range of the species, with heterogeneous environments enhancing genetic variation (Hedrick et al. 1976; Hedrick 1986; Gillespie and Turelli 1989; Mitton 1995). Differences in allele frequencies between populations could be the result of founding populations with differing genetic compositions, or similar populations could have been separated resulting in a change in allele frequency. Gene flow is relatively low in Table Mountain pine, which indicates that genetic drift may be more important when looking at genetic divergence between Table Mountain pine stands. Gene flow through seeds would be ineffective, but through pollen would affect the genetic composition of the seed pool, but not the mature populations. Genetic variation in the next generation of Table Mountain pine would depend on genetic variation in the seed pools of adults who existed at the time of the fire event. After a fire event, seeds are released that represent a genetic record of mating events spanning the past 25 years or more. This is important because it suggests that cone serotiny is a strategy to preserve genetic diversity within a population (Loveless and Hamrick 1984; Gibson and Hamrick 1991). Through serotiny, the seeds that establish on a newly burned site will represent genes from numerous individuals, which would reduce the severity of founder effects. However, regeneration of stands from only a few remaining Table Mountain pines would create significant genetic differentiation among the stands. Repeat burning is recommended by the authors to prevent the loss of individual genotypes and maintain intrapopulational genetic variation. Therefore, fire suppression policies in Table Mountain pine stands have caused a loss of genetic diversity within those stands, as well as decreases in regeneration (Sanders and Buckner 1988; Williams and Johnson 1990; Gibson and Hamrick 1991).

Pfeffer (2005) found that field counting of nodes on Table Mountain pine saplings is a viable method for estimating sapling ages, which corroborates the findings of Williams and Johnson (1990). However, Barden (1977) noted there was a relatively low correlation between dbh and age (r^2=.43 for trees taller than 2 m (6.6 ft), r^2=.01 for trees older than 40 years). Pfeffer also found low correlations between node counts and age for trees older than 40 years. This is likely because Table Mountain pine is a self-pruning species, and for older trees it would be more difficult to accurately count branch nodes that had been self-pruned decades earlier. Based on Table Mountain pine saplings collected from Griffith Knob, Jefferson National Forest, Virginia, Pfeffer determined that each node is equivalent to 1.2 years of growth. Sapling age can be estimated in the field using the following equation: estimated age = 0.7178 (nodes) + 7.3488.

1.7.2 Fire Ecology in Table Mountain Pine Stands

Harmon (1982) brought fire history studies to the Appalachian Mountains through his analysis of the fire-scarred pine stands of the Great Smoky Mountains National Park

(GSMNP). Fire history in Table Mountain pine stands of the GSMNP were analyzed to determine whether the majority of fires in the park were lightning-caused or anthropogenic in origin. His study represents the first fire history study that utilized fire-scarred Table Mountain pine in the eastern US. The 46 collected samples revealed the mean interval between fires in the park was 12.7 yrs between 1856 and 1940. Fires in the park were caused by both humans and lightning. Evidence of past fires was present in most of the forests in GSMNP regardless of aspect, slope, or elevation.

Harmon (1982) was a landmark study in the eastern US for two reasons. It was the first fire history that incorporated tree rings, which had just begun to be used in southwestern fire studies. The eastern US had lagged behind the western US in dendroecological research since the advent of the science. This study introduced fire history studies to the east early in dendropyrochronological research. Second, previous studies had associated fire with Table Mountain pine, but this study illustrated that repeat fire existed in these forests which set the stage for further fire history/ecology research in the Appalachians. Harmon also illustrated that tree rings could be used in fire history studies. However, samples were only ring counted and not crossdated, which could have caused errors in dating. Ring counting to derive dates for fire scars is not considered adequate for accurate dating (Studhalter 1955; Fritts 1976).

Since Harmon (1982), numerous other studies on fire in Table Mountain pine stands have been conducted in the southern and central Appalachian Mountains. Many studies have been conducted to document the relationship between fire intensity and pine recruitment, as well as the history of disturbance and pine recruitment and the disappearance of Table Mountain pine. Williams (1991) documented the role of fire in the perpetuation of Table Mountain pine at xeric sites in the central and southern Appalachians. Sutherland *et al*. (1995) conducted a limited dendrochronological fire-history study on Brush Mountain, Montgomery County, Virginia and recognized the link between fire occurrence and tree establishment. The study combined age-structure analyses with tree-ring analyses of fire scars to assess the relationship between age structure and historical fire patterns. Williams and Johnson (1990) had previously analyzed the stand composition and age structure in Table Mountain pine stands in Virginia, but did not incorporate fire into their analyses. The majority of fires on Brush Mountain were dormant season fires, occurring predominantly during the months of February, March, and April. A combination of fuel and climate conditions are thought to influence fire on Brush Mountain. Between 1978 and 1944, Brush Mountain had a fire return interval of 10 years. Fire exclusion contributed to the current regeneration failure of pine.

Turrill (1998) conducted a fire history study in shortleaf, Table Mountain, and pitch pine stands in six national forests in the southern Appalachian region. The past occurrence of fire was documented through the presence of macroscopic charcoal particles in the soil. Turrill concluded that one prescribed burn of any intensity was not enough to control hardwood resprouting and initiate pine regeneration. Welch (1999) determined that macroscopic charcoal was present at all field sites, which indicated that soils retain charcoal particles signaling past fire events in the Appalachian Mountains. However, Welch’s analyses provided information only on the past occurrence of fires, not fire frequency. Dendrochronological analysis is necessary to determine the fire return intervals of Table Mountain pine stands (Welch 1999).

Waldrop *et al*. (1999) found that fires that create moderate shade conditions and three-inch-thick duff in the seedbed resulted in the maximum pine recruitment. This conclusion agrees with Barden (1977) who concluded that pine seedlings need a certain degree of shade for survival. Mohr *et al*. (2002) also found that moderate shade conditions were needed for pine recruitment and that seedlings could penetrate up to 10.2 cm (4 in) of duff. Welch and Waldrop (2001) tested the effects of prescribed fire on recruitment of pine seedlings. Medium-high intensity fires were the most successful in allowing abundant pine regeneration while not causing excessive mortality in the overstory. High-intensity fires killed almost all overstory trees and some seeds, while lower intensity fires did not open the canopy enough. In Waldrop *et al*. (2002, 2003) and Waldrop and Brose (1999), high and medium-high intensity fires provided the conditions necessary for pine recruitment, whereas lower intensity fires did not. Prolific hardwood sprouting was observed after fires of all intensities and the highest intensity fires are actually detrimental to soils and new germinants (Waldrop *et al*. 2002).

Brose *et al*. (2002) looked at three mixed Table Mountain pine-pitch pine stands in Georgia to determine what role disturbance and drought played in establishment. The current canopy of these stands was propagated by logging, disease, and wildfire. Climatic variables played no role in pine recruitment and several low- to moderate-intensity disturbances would be needed in these stands to reduce fuels, shrubs, and hardwoods, and to prepare the site for pine recruitment. Randles (2002) suggests that multiple burns are more effective than single burns in the reduction of understory density, although single, high-intensity fires could theoretically produce the same outcome. Repeated winter burns at regular intervals do not seem to reduce shrub density as the first burn reduces shrub cover and subsequent burns maintain this state.

The current debate in fire management in yellow pine stands surrounds the severity of the prescribed fires required to mimic effects of historical fires that occurred prior to widespread anthropogenic alteration of fire regimes. The need to use medium-high severity, stand-replacing fires to regenerate yellow pine stands has been suggested because of apparent fire adaptations, such as serotinous cones, shade-intolerant seedlings, and the requirement of bare mineral soil for germination (Waldrop *et al*. 2003). Randles *et al*. (2002) argued that yellow pine regeneration is best facilitated through higher severity fires because fire intensity has more of an impact than burning repetition on the composition and structure of yellow pine stands. However, the results from seven previous studies that examined yellow pine regeneration suggested that multiple low-severity fires could maintain the overstory and seed source while reducing the duff layer and encouraging regeneration without exposing bare mineral soil (Waldrop *et al*. 2003). Sutherland *et al*. (1995) also suggested that Table Mountain pine can regenerate under low- and high-severity fire regimes. This disparity suggests that fire plays a more variable role in the yellow pine stands of the Appalachian Mountains than previously thought.

Armbrister (2002) used dendrochronological techniques to crossdate nine fire-scarred samples from five study sites within the Great Smoky Mountains National Park, Tennessee. Fire seasonality, fire intervals, and statistical descriptions were obtained from all samples. A Table Mountain pine chronology from 1837–2001 with a Weibull medium fire interval of 6.8 yrs and a Weibull modal fire interval of 4.8 yrs was constructed. The majority of fires occurred during the dormant season. Based on the stand composition and age structure data, little pine regeneration was taking place in the park and fire-intolerant species were gaining dominance. This has been the conclusion of all Table Mountain pine studies that have taken place since the 1990s (*e.g.*, Williams and Johnson 1990, Spurr and Barnes 1990; Williams 1991; Sanders 1992; Sutherland *et al*. 1995, Waldrop *et al*. 2003; Lafon and Kutac 2003).

Lafon and Kutac (2003) evaluated the potential of other disturbance types for regenerating Table Mountain pine stands on Little Walker Mountain, Virginia. Whitney and Johnson (1984), looking at southeast-facing slopes, found that ice storms killed 76% of mature Table Mountain pines in a stand within two years of the storm, which initiated pine regeneration (Lafon and Kutac 2003). Williams and Johnson (1990, 1992) and Williams (1998) argued that ice storms accelerate conversion of pine stands to hardwood dominance, and that tree damage is concentrated on east-facing slopes. Little Walker Mountain had suffered a southern pine beetle (*Dendroctonus frontalis* Zimm.) outbreak in 2001–2002 (USDA Forest Service 2001, 2002) and a wildfire in 2001 (Lafon and Kutac 2003). Hardwood sprouting was prolific after ice storms and fire events. Ice storms and the southern pine beetle infestation reduced pine abundance relative to hardwoods. Ice storms are an important disturbance on west-facing slopes; however, mortality of pines was only 39.6%, compared to Whitney and Johnson's (1984) finding of 76% mortality. Southern pine beetle outbreaks and ice storm events result in considerable pine regeneration only when combined with fire.

The most recent scientific study on the subject of Table Mountain pine and fire comes from Brose and Waldrop (2006), who investigated the possible role of stand-replacing fire in the formation of mixed Table Mountain pine-pitch pine communities.

Nine stands in Tennessee, Georgia, and South Carolina were analyzed. The silvical characteristics of the species indicate their need for high intensity fires and their location on steep, dry, south- and west-facing ridges and upper slopes places them in areas of the highest fire intensities (Zobel 1969; Williams 1998; Brose and Waldrop 2006). Previous studies were cited that showed that pine seedlings were more abundant in areas where intense fires had occurred (*e.g.*, Williams *et al*. 1990; Williams and Johnson 1992; Groeschl *et al*. 1992, 1993; Sanders 1992). However, Waldrop and Brose (1999) found that Table Mountain pine seedlings regenerated better in areas experiencing moderate-intensity fires with only partial canopy removal. Five of Brose and Waldrop's (2006) nine stands were mixed-aged rather than of unimodal age distribution. Low- to moderate-intensity surface fires apparently were initiating pine establishment because these fires were all recorded on chestnut oaks. Other disturbance events, such as hurricanes, droughts, ice storms, insect outbreaks, coupled with fire, could have perpetuated these Table Mountain pine-pitch pine stands. They present no evidence of stand-replacement fires initiating Table Mountain pine-pitch pine stands. Regeneration instead appeared to be caused by noncatastrophic surface fires and canopy disturbances (Brose and Waldrop 2006).

1.8 Dissertation Objectives

This study has four major components:

(1) Determine the historic and current fire regimes of yellow pine stands in the central Appalachian Mountains – A fire regime is characterized by the type, frequency, intensity, severity, size, and season (Barnes *et al*. 1998). Fire scars provide

information on frequency and season directly, and severity and size indirectly. Determining how often, during which seasons, and at what scale yellow pine stands burned in the past will help fire management officers gauge how often they need to burn in the future to maintain and rejuvenate Table Mountain pine stands.

2) Determine how cohort establishments are linked to past fires – How has fire initiated establishments of fire-tolerant and fire-intolerant species and maintained pine dominance at the expense of species such as black gum and mountain laurel?

3) Predict the future stand composition by analyzing the changes in forest composition data and seedling composition data – By inventorying the seedling and sapling strata, it is possible to predict the composition of future midstories and canopies. This approach can illustrate any probable movement of pine stands towards hardwood dominance and give a prognosis for the survival of Table Mountain pine in the central Appalachian Mountains.

4) Determine the relationship between climate and fire and how climatic variables affect Table Mountain pine growth. Are there particular months that affect growth? Can climatic analyses give a better indication of when Table Mountain pine stands should have prescribed burning? Does climate precondition these stands for wildfires?

1.9 Hypotheses

1) Fire scars on Table Mountain pine will be dateable and will yield critical statistics that define the regional fire regime by delimiting the historical range of variability. Furthermore I hypothesize that fire frequency during the pre-suppression period will be greater than previously reported.

2) Age-structure and stand-composition data will corroborate and supplement fire event data obtained from fire-scar analyses. I hypothesize that more severe fire events will be revealed in the age-structure data. The relationship between fire events and establishments of both fire-tolerant and fire-intolerant species will also be apparent.
3) I hypothesize that fire events have decreased in the 20th century such that fire-intolerant species, such as black gum and mountain laurel, will dominate the mid- and understories of Table Mountain pine stands.
4) Table Mountain pine has previously been used in dendrochronological research because the species produces one annual ring per year, has discernable ring boundaries, and is sensitive to fluctuations in certain climate variables. However, I hypothesize that tree rings from Table Mountain pines will contain only a minimal response to climate compared to other forest tree species that grow in the eastern US primarily due to the over-riding influence caused by stand dynamics (i.e., competition and disturbances). I hypothesize that climatic variables will show weak forcing of fire activity due to human augmentation of fire frequency in the pre-suppression period. I hypothesize that fire characteristics are more affected by topography than by climate variables.

1.10 Organization of Dissertation

This dissertation is organized into six chapters. The first chapter is an introduction to Table Mountain pine ecology, history, biogeography, silviculture, and relationship with fire. Relevant previous studies on Table Mountain pine are also presented in this chapter. A brief history of dendrochronology is presented as it is the main analytical tool used in this dissertation.

Chapter two discusses the settlement and land-use history of the central Appalachian Mountains of Virginia. The cultural uses of Table Mountain pine by Native Americans are discussed as the circumstances of Native American burning of Table Mountain pine stands. The four study sites, Little Walker Mountain, Griffith Knob, Brush Mountain, and North Mountain, are all discussed in detail in this chapter.

Chapter 3 is titled "Evaluating the dendrochronological potential of central Appalachian Table Mountain pine (*Pinus pungens* Lamb.)." This chapter establishes that Table Mountain pine can be used in dendroecological research. Even though numerous scientific studies have been conducted using Table Mountain pine, no study has decisively proven that Table Mountain pine is a suitable species for dendroecological research. This chapter discusses the life history of Table Mountain pine and the physical characteristics of the species, including ring formation. Chronology development and the relationship between dbh and age are also discussed. The main foci of this chapter are the climatic analyses, which illustrate which months are crucial in Table Mountain pine development, and how temperature and precipitation affect Table Mountain pine growth. Climatic analyses also give an indication of which month prescribed burning would be most beneficial for Table Mountain pine growth.

Chapter 4 is titled "Fire regimes in xeric yellow pine stands of the Jefferson National Forest, Virginia, U.S.A." This chapter presents all fire history data collected from the four sampling sites. Statistics such as Weibull median fire return interval, standard deviation, coefficient of variation, lower exceedence and upper exceedence intervals, and maximum hazard interval are all provided in this chapter. Age structure of the stands is also analyzed to determine if fire initiates cohort establishment and whether or not Table Mountain pine is regenerating at each site.

Chapter 5 is titled “Relationships between wildfire and climate in the central Appalachian Mountains.” This chapter illustrates the relationship between fire and climate statistically using superposed epoch analysis. This analysis will determine if Table Mountain pine stands in the Appalachians require preconditioning to burn.

Chapter six is the conclusions chapter and provides an overview of the research presented in this dissertation and recommendations for future research. It also gives a prognosis, taking all factors and research into account, on the continued survival of Table Mountain pine in the central Appalachian Mountains.

CHAPTER 2

DESCRIPTION OF STUDY SITES

Appalachia is named for the Apalachee Indians of northwestern Florida. To rid themselves of Spanish goldseekers, the Apalachee Indians told the Spaniards of the northern mountains that reportedly contained vast quantities of gold. “Apalache” first appeared on a European map for the Appalachian Mountains region in 1562. The eastern mountain chain officially became known as the Appalachian Mountains after the American Revolutionary War (Walls 1977; Milanich 1995; Williams 2002).

Six physiographic provinces occur within the Appalachian system: Piedmont, Blue Ridge, Great Valley, Ridge and Valley, Allegheny (or Cumberland) Mountains, and Appalachian Plateau (Williams 2002). The Great Valley of Virginia lies between the Blue Ridge Mountains to the east and the main Appalachian chain to the west. The upper and lower boundaries of the Great Valley are marked by the Potomac River to the northeast and the Virginia-Tennessee border to the southwest, a distance of 491 km (305 miles) (Stoner 1962). The Great Valley encompasses the Shenandoah, James, Roanoke, and a portion of the New River Valleys in Virginia (Williams 2002). Study sites for this research are located in the Ridge and Valley Province in the James, North Holston, and New River watersheds.

2.1 The Native American Question

A standard question in eastern fire history research seems to be “who was starting the fires?” Unfortunately, fire-scared trees provide no information on the origin of the fire event, whether it be lightning or human. The practices of native populations living in the vicinity of the species in question can shed light on the fire regime of an area. Often times, the arrival of Native Americans to an area is heralded by a change in the seasonality of fire events (Lewis 2003). Historical information on Native Americans in the region will improve understanding concerning their role in fire ignitions and maintenance of fire-dependent species. The question of who was starting the fires will never be confidently answered for the stands in question. However, the question of how local Native Americans were altering the landscape, including xeric pine-oak stands, and whether or not humans were regularly present in Table Mountain pine stands, can be answered.

To determine the historic fire regime of an area, the fire severity, fire frequency, the spatial extent of fires, and the seasonality of past fires are investigated. Knowledge of human influences on past fire regimes is also important in the interpretation of those characteristics of historic fire regimes. In many areas, fire regimes are dually influenced by anthropogenic and lightning-ignited fires. Most accounts of Native American burning indicate that fire was used to achieve mosaics, resource diversity, environmental stability, predictability, and the maintenance of ecotones (Lewis 1973; Williams 2000:10).

The constant presence of fire predates human settlement in the southern U.S. (Komarek 1964, 1974; Stanturf *et al*. 2002). Before Native American settlement of the Appalachians, fire was likely caused by lightning mainly during spring and summer thunderstorms (Robbins and Meyers 1992; Stanturf *et al*. 2002). Lightning fires are described as infrequent and of high intensity, whereas Native American fires were typically high frequency and low-intensity (Kay 2000).

Cultural burning is believed to have been present across the southern Appalachian landscape since 10,000 BC (Chapman 1985; Goudsblom 1992; Buckner and Turrill 1998; Welch 1999). Native Americans entered Virginia around 9500 BC (Barber 1999; Brown 2000). Native American agriculture, their use of fire to control vegetation, and landscape-scale burns began during the Archaic Period (8000–1000 BC) (Buckner 2000). Native American populations began to increase significantly during the Middle Holocene (4000 BC), when warmer climates and the final ablation of the Laurentide Ice Sheet (Delcourt and Delcourt 1981, 1983; Stanturf *et al*. 2002) increased food availability (Stanturf *et al*. 2002). After 1000 BC, permanent Native American societies were established in the eastern woodlands mainly in the rich bottomlands of river valleys and coastal areas (Fagan 2000; Stanturf *et al*. 2002). Villages in the southern Appalachians were generally two (0.40 ha) to three (0.80 ha) acres in size, although some were as small as one-quarter acre (0.10 ha) or as large as six acres (2.43 ha) (DeVivo 1990).

During the prehistoric and early-historical periods, the Appalachian Mountains and their drainages served as Native American areas for war, foraging, hunting, and ceremonial activities (Blanton *et al*. 1992; Phipps 1993; Gregory 2002). Although most Native American societies maintained settlements and agriculture in the valleys, hunting and gathering were essential and prominent in the mountains (Stanturf *et al*. 2002). Mountain forests provided turkey, deer, bear (*Ursus* spp.), and eagles (*Haliaeetus leucocrphalus* L.). Chestnuts, hickory nuts, hazelnuts, walnuts, chestnut oak acorns, butternuts, and chinquapins were collected along with mica, steatite, and quartz crystals, which were used in religious ceremonies and for medicinal purposes (Hudson 1976).

Human fires would have been most prevalent in the alluvial bottoms of major rivers and coves where camps/villages were established and crops were grown, and on the upper slopes and ridgetops where people hunted and gathered nuts seasonally. From these positions, human fires could have spread to the ridgetops to maintain communities of Table Mountain pine (Delcourt and Delcourt 1997), chestnut, and xeric oak (Van Lear and Waldrop 1989; Lafon *et al*. 2005). In more remote areas of the Appalachians, accidental ignitions from campfires near travel routes could have provided the ignition source of higher-elevation fires (Van Lear and Waldrop 1989; Lafon *et al*. 2005). Early surveyors of Virginia noted that Native Americans often left campfires burning, which sometimes ignited the surrounding forest, and that forests with high fuel accumulations burned more vigorously than areas burned regularly by Native Americans (Byrd 1841; Maxwell 1910).

Native American fires altered the Appalachian landscape in many ways. Fires ignited by Native Americans were generally not destructive, were relatively easy to control, and often stimulated new vegetation (Williams 2000). Native American burning took place mainly between snowmelt and vegetation flush in the early spring, or in late fall (Pyne 1995; Kay 2000). Annual burning was a standard practice in all areas, including mountain areas, where grazing animals were maintained (Stanturf *et al*. 2002). In addition, the ranges of preferred wildlife species including bison (*Bison bison*), bears, wild turkey, and white-tailed deer were modified to suit Native Americans (Jurney *et al*. 2004). The Great Valley was burned every fall to prevent the forest from encroaching upon the prairie (Fowke 1894; Stewart 2002) and to increase pasture lands for the animals they hunted (Stoner 1962). Trees that did encroach on pasture lands were felled with a ring of fire that encircled the tree. Fire was also inserted directly into the unwanted trees (Maxwell 1910). Native Americans also burned in the winter to reduce the threat of serious wildfires, replenish soil nutrients, reduce undesirable vegetation cover, stimulate growth of meadows and other plants for deer browsing, and make it easier for deer and turkey to forage for nuts (Martin 1973; Hudson 1976). Fires also stimulated production of black huckleberries (*Gaylussacia baccata* (Wang.) K. Koch), *Rubus* spp., and *Vaccinium* spp., important forage crops for wildlife (Elliott *et al*. 1999).

2.1.1 Native American Civilizations of the Great Valley and Appalachian Mountains

No evidence exists of long-standing ancient or permanent habitation of the Great Valley by Native Americans; however, numerous gravesites and mounds have been found (Stoner 1962). Certainly, the Valley had no permanent residents after the Iroquois conquest of 1672 (Maxwell 1910). The Cherokee were the strongest regional Native American tribe and claimed the mountain territory of Tennessee, the Carolinas, and southwestern Virginia (Stoner 1962), which included part of the Great Valley of Virginia. However, six nations of Iroquois of New York also claimed the Great Valley (Pendleton 1920). The Iroquois eventually conquered all southern tribes east of the Mississippi River and from the Ohio River to Georgia, including the Cherokee. The Iroquois depopulated many of these areas, including some Cherokee territory.

During peacetime, the Great Valley had served as the prime hunting ground and frontier settlement zone for the Cherokee (Biggers 2006). It also served as a route for Native Americans traveling north or south and continued to serve as such until Euro-American settlement in 1730 (Maxwell 1910). The Appalachian Mountains functioned as a corridor of conquest for the Native Americans between the Ohio River Valley and Atlantic Coastal regions, and the Iroquois nations to the north and Creeks to the south (Maxwell 1910).

In 1540, the Cherokee numbered 30,000 in the southern Appalachians (Williams 2002); however, others argue the Cherokee population was never higher than 22,000 (Mooney 1900; Swanton 1946; Kroeber 1939; Denevan 1976; Goodwin 1977; DeVivo 1990). Cherokee women lived in the valley clearings in villages adjacent to forests and water sources where they cared for the community and crops, and gathered nuts, berries, and herbs (Perdue 1988; Williams 2002). The Cherokee economy was based principally on agriculture, which helps explain the location of settlements in fertile valleys. It would have been impractical to locate farms on steep mountain slopes or at high elevations where erosion and severe climatic variables, such as wind, would have been detrimental to crops (DeVivo 199). The men were hunters, warriors, and diplomats. They lived in the forest, led war parties, and traveled distances to hunt and conduct diplomacy (Perdue 1998; Williams 2002).

2.1.2 Fire and Hunting

Fire was used as a tool in hunting white-tailed deer, the most important species for the Cherokee and many other Native American tribes. Deer reached their maximum weight after acorns fell in the fall, which is also when they began congregating for mating season. This began the most opportunistic season for deer hunting. Late fall/early winter was also the best time to kill animals for their furs and skins (Brickell 1737; Stewart 2002), because of the increased thickness of their winter coats. One technique for hunting deer was the “fire surround” technique used in the fall and early winter. Two- to three-hundred Cherokee would ignite leaves in a circular pattern up to five miles in circumference. Deer would be driven into the center where they were easily killed. This hunting technique was much more efficient and less time consuming than individual hunts (Brown 2000). Fire hunts also increased deer browse, which helped increase deer populations for future hunts (Brown 2000).

Hunting fires were carefully controlled brush fires that enabled hunters to contain the game and collect their skins without damaging them (Hammett 1992). Fire hunts, however, may have been the chief means by which Native Americans destroyed the forests (Beverley 1722; Maxwell 1910). Apparently, fires would start in this manner and spread, especially during droughts when the fires covered extensive areas (Maxwell 1910). Waselkov (1978) suggests that fire hunts were common only after European settlement, when trade in deer skins became economically important. Before that time, fire hunts were probably only held for special occasion feasts for large tribes (Hammett 1992). However, Hudson (1976) claims the practice of fire hunts became less common after the arrival of European firearms. Native Americans also used fire to hunt bears by driving them from trees and dens (Swanton 1911; Smith 1974; Hudson 1976). Whether intentionally or unintentionally, the Cherokee practiced advanced wildlife management techniques by using fire to create or eliminate habitat based on the importance of the animal to Cherokee survival.

2.1.3 Cherokee Religion and Fire

A large portion of Cherokee life centered around fire worship and the use of fire. They believed that sacred fire, like their primary god, the sun, was an old woman. To show her respect, they fed her a portion of each meal, fearing she would take vengeance in the form of a nocturnal bird otherwise (Whitthoft 1946; Hudson 1976). The Cherokee believed the world existed on different layers or realms, and it was forbidden to allow those layers to mix. If mixing was allowed to happen, an individual would create "pollution" in the sacred fire that presided in each village, and horrible diseases were usually the punishment. As such, the Cherokee could not pour water (Underworld realm) on a fire (Upper world realm). Animals also belonged to different realms with birds belonging to the Upper World, deer and humans belonging to This World, and snakes and fish belonging to the Underworld, for example. The Cherokee believed animals from different realms should not intermingle. The Cherokee also had rules regarding burning animals from the Underworld (Hudson 1976), which is of interest as many sources claim eastern Native Americans burned to control snakes near their villages (*e.g.* Tome 1854, Lewis 1973, Whitney 1994). For the Cherokee, this likely involved burning away brush and tall grasses that snakes could have used for concealment. It would have been forbidden to burn a snake on purpose because, based on Cherokee religion, this would have mixed two realms. Snakes were considered special and dangerous animals that could control plants and other animals. They were only killed for medicinal purposes, while using great caution and special rituals (Hudson 1976). This offers another explanation as to why burning was conducted from late fall to early spring when snakes would have been hibernating and less likely to get burned. After the Cherokee killed a deer, a special prayer had to be recited to ask the deer's pardon for killing it. If this was not done, the deer would take vengeance on the hunter and cause rheumatism or arthritis. If this happened, the hunter then had to set fire to the path between himself and the deer to keep the vengeful deer spirit from following him (Hudson 1976).

The Cherokee fire myth has important implications for present-day questions about the historic use of fire. The Cherokee believed that in the beginning, there was no fire and the world was cold. The Thunder Gods, who lived in the Upper World, sent lightning and put fire into a hollow sycamore tree that grew on an island. The animals were perplexed as to how to retrieve the fire. Eventually a black water spider solved the problem and fire was brought to the mainland (Mooney 1900; Hudson 1976). The Cherokee acknowledged the importance of lightning as an ignition-source for fire, and based on this myth, it appears the Cherokee understood fire was the result of lightning strikes. If the Cherokee, and other Native Americans, made this connection and witnessed the benefits of lightning-ignited fires, it only makes sense that they would begin to augment natural fire regimes by starting their own fires.

2.1.4 Flora for Cherokee Medicinal Purposes

Pine trees were important in Cherokee medicine and religion and enter into Cherokee mythology fairly early in the creation myth. When plants and animals were first created, they were told to stay awake for seven nights. Only the cedar (*Juniperus* spp.), pine, spruce (*Picea* spp.), holly (*Ilex* spp.), and laurel (*Kalmia latifolia* L.) were able to stay awake, and as reward, were allowed to be evergreen and hold medicinal properties. The other tree species were punished for falling asleep by being made deciduous

(Mooney 1900; Hudson 1976). Native Americans knew the food value of every weed, shrub, and tree in the forest (Maxwell 1910). When Cherokee women were pregnant, they drank an infusion of slippery elm bark (*Ulmus rubra* Muhl.), spotted touch-me-not stems (*Impatiens capensis* Meerb), roots of common speedwell (*Veronica officinalis* L.), and cones of Table Mountain pine. The Table Mountain pine cones were meant to convey health and longevity to the infant (Hudson 1976). Splinters collected from lightning-struck trees were collected and used in Cherokee religious ceremonies. In Cherokee mythology, some of the first humans used such splinters to invoke lightning and thereby escape cannibals (Mooney 1900; Hudson 1976). Other ceremonies required objects to be buried at the bases of these trees and a fire burned over the object (Hudson 1976); unfortunately, no information on the objects or purpose of such ceremonies is offered in historical accounts.

It is important to note that Cherokee would have been present in Table Mountain pine stands and ridgetops to collect cones, splinters, and conduct religious ceremonies. Because they were visiting the stands regularly and lighting fires at the bases of lightning-struck trees, it is plausible that the Cherokee could have perpetuated Table Mountain pine stands through regular burning. It also seems possible that the Cherokee could have augmented natural lightning-ignited fires in Table Mountain pine stands during years with no natural fires to keeps underbrush low and make cone collection easier. It is not possible to determine if fire scars on Table Mountain pines were caused by human activities or natural factors.

Through the use of fire, Native Americans in the Appalachians altered their landscape mainly to ensure an abundant and reliable food supply. Cherokee medicine and religion made use of fire-adapted species that thrived as a result of frequent and reliable anthropogenic burning. Native Americans maintained a functional landscape that met the needs of the inhabitants (Hammett 1992) with fire being fundamental to that maintenance. The arrival of Euro-American settlers to the region, however, displaced native populations and altered disturbance regimes that had been in place for thousands of years.

2.2 Euro-American Settlement

The first European settlers to Virginia encountered forests with little undergrowth and large, mature trees that produced a park-like setting (Bruce 1896; Maxwell 1910) created by Virginia natives who burned their forests (Brown 2000). By AD 1664, Euro-American traders in Virginia were fairly familiar with the Virginia backcountry, and trade routes to Native American settlements were established and traversed regularly (Kegley 1938). One of the first explorers into the Virginia interior was John Lederer, who reached the eastern slope of the Blue Ridge Mountains in 1669 and the falls of the James River by 1670 (Kegley 1938). Lederer referred to the Great Valley as a savanna with large populations of deer (Maxwell 1910). Lederer and other early explorers found vast areas of western Virginia and West Virginia vacant. In 1672, the Iroquois, who claimed the territory but never occupied it, depopulated this area with firearms they obtained from settlers on the Hudson River (Coldon 1747; Maxwell 1910). The Iroquois eventually lost the region through treaties and to land speculators (Maxwell 1910).

With the Treaty of 1685, the British claimed the entire Iroquois empire, including the Appalachians, and bypassed negotiations with tribes actually living in the area

(Williams 2002). In the Treaty of Lancaster (1744), six Native American nations renounced their claims to all lands in Virginia (Kegley 1938). The treaty gave Euro-American settlers rights to the west-flowing waters, the Great Valley, and Appalachian Mountains of Virginia (Williams 2002). Euro-Americans had already settled the Great Valley by 1719 (Williams 2002). Quakers attempted to purchase the Great Valley from the Native Americans, but could not do so because the Great Valley did not belong to an individual tribe and was considered common hunting ground for various tribes (Kegley 1938). Besides the Cherokee and Iroquois, Native Americans of the coastal areas and Piedmont also reportedly traveled west towards the Appalachians, and probably into the Great Valley, in the fall to hunt deer (Hammett 1992).

During initial Euro-American settlement, the Great Valley was reported to be a prairie with bison, elk (*Cerus elaphus* L.), deer, bear, panther (*Puma concolor* spp.), wildcat (*Puma* spp.), fox (*Urocyon cinereoargenteus* Schreber), wolf (*Canis lupus lycaon* Schreber), beaver (*Castor canadensis* Kuhl.), otter (*Lontra canadensis* Schreber), and fowl (*Anatidae* family) (Kegley 1938). The Great Valley, in particular the Shenandoah Valley, contained abandoned Native American agricultural fields that were still clear and fertile and were prized by the incoming settlers (Maxwell 1910). The first land grants west of the Blue Ridge Mountains were made after 1730 (Mitchell 1977; Williams 2002), and settlers entered the Shenandoah Valley in 1732 (Cooke 1973). The first permanent Euro-American settlement in the Shenandoah River Valley was established in 1733 at Massanutton (Kegley 1938).

In 1742, less than 50 Euro-American families lived in the region south of the James River and west of the Blue Ridge, with no more than 25 Euro-American families north of the James River (Kegley 1938). Land was first purchased around Craig Creek in 1742 (Kegley 1938) and settlement of the New River Valley began in 1745 (Kegley and Kegley 1980). The first settlement beyond the Great Valley was Draper's Meadow (modern Blacksburg, Virginia) in 1748 (Billings *et al*. 1986). In 1754, Native Americans abruptly disappeared west across the Appalachian Mountains, without objecting to settlement of the northern Great Valley (Kegley 1938). The Cherokee, however, were alarmed by settlement of the Holston Valley, because it threatened their abundant hunting grounds (Pendleton 1920). Burning to maintain hunting stocks was an investment that was generally defended by the groups maintaining the area (Brown 2000).

In 1753, a road that connected the Roanoke settlements to Craig Creek at the mouth of John's Creek (modern-day New Castle) was completed. Fort William was erected to defend this area against frequent Native American raids (Stoner 1962). In 1755, the Shawnee began to attack settlers in the New River Valley (Williams 2002). Many settlers abandoned the western settlements during the French and Indian War (1755–1763) because of frequent Native American attacks and kidnappings (Kegley and Kegley 1980). A string of forts guarding the western approaches were built before 1756 to guard mountain passes from Native American attacks (Stoner 1962). In 1761, Fort Chiswell was established in modern-day Wythe County, Virginia, (Kegley and Kegley 1980) to guard the lead mines and settlers of the area (Williams 2002). The Fort also marked the point where Shawnee, Cherokee, and Virginia land speculators' territorial claims converged, and where Native American raiding paths ended (Williams 2002).

Significant settlement and development of southwestern Virginia occurred between 1769 and the Revolutionary War (1775–1783) (Summers 1970). Numerous mills were established between 1770 and 1783 and several roads were built during this time (Kegley 1938). By 1769, 75 Euro-American families resided at Sinking Spring on the Catawba and James Rivers; 45 families resided at Craig Creek; 45 families at New Dublin, Pulaski County; 42 families at Boiling Spring, Wythe County; and 45 families at Unity, Wythe County (Kegley and Kegley 1980). Montgomery County was established in 1776 and Blacksburg by 1798 (Kegley and Kegley 1980).

The Euro-American men from the Great Valley and surrounding mountains spent most of the Revolutionary War fighting the Native Americans in the mountains (Stoner 1962). In 1776, the Cherokee and neighboring tribes enlisted with the British Government in the hopes they would be able to keep their lands. The British gave Native Americans permission to plunder the settlements of southwestern Virginia and promised the return of their lost hunting grounds (Pendleton 1920). Native American hostilities continued through the Revolutionary War, in particular in the mountains around Craig Creek Valley. Native American hostilities were not uncommon in the region because mountain passes in the area were popular travel routes for the natives (Kegley 1938).

After the Revolutionary War, Euro-American settlements in the mountains increased in mountain valleys. The loss of traditional hunting territories caused the displacement and absorption of the remaining Native American populations. During the late-Antebellum period (1840–1860), settlements expanded up into the tributaries and hollows (small valleys between mountains) from the lower slopes and bottomlands (Gregory 2002). Agriculture and grazing expanded upslope during this period. Compared to Native Americans, settlers had a reckless pattern of land usage (Billings *et al*. 1986). Farmers burned trees and brush to prepare cornfields as the Native Americans had done.

Euro-Americans, however, did not practice crop rotation or use natural soil fertilizers as the natives had. Euro-American farmers would utilize a plot of land until soil fertility was depleted, then additional forest was cleared to repeat the process (Campbell 1969; Howell 2002). Increased instances of agricultural burning on the foothills would have increased the likelihood of fires spreading upslope, which would have benefited the survival and propagation of yellow pines.

Like the Revolutionary War, the Civil War saw many local men remaining in the mountains to hold the territory. The Civil War did not initiate an exodus of residents like that associated with the French and Indian War a century earlier. In 1861, the Confederacy lost the western half of Virginia to Federal troops; this land became the state of West Virginia in 1863 (Morton 1924). By the summer of 1861, Virginia was threatened by the Federal Army from passes through the northwestern mountains (Morton 1924). Guerilla warfare occurred throughout the mountains along the Virginia-West Virginia border (Williams 2002). Between 1861and 1862, 30,000 men were stationed in western Virginia and another 30,000 in the Shenandoah Valley to protect against a Federal Army attack from the west (Morton 1924). It was important to hold the mountains to protect the Great Valley, which served as the Confederate granary (Williams 2002). In 1864, Federal troops began destructive raids on farms and towns in the Great Valley, and made the foothills of the Appalachians from the Allegheny Mountains to the Blue Ridge untenable (Morton 1924).

During the late 19th century, timber companies began purchasing large quantities of land in the remote southern Appalachians (Van Lear and Waldrop 1989; Stanturf *et al.* 2002). After land was cleared by lumber companies, settlers often moved in and burned the slash to clear the land for livestock grazing. Trees were considered weeds that livestock and humans could not eat (Komarek 1974). The amount of damage inflicted on the Appalachian landscape by early-20th century residents, however, was considered to be minimal compared to the damage inflicted by Native Americans. A perfect example of this attitude is the critique of Native American land management practices offered by Maxwell (1910).

Maxwell called the clearings made by the Native Americans, or "Savages," large and created accidentally, wantonly, and with wasteful destruction. Maxwell even insinuated that burning for hunting purposes was out of laziness. Euro-Americans were very destructive, but not quite as destructive as the Native Americans. If Virginia had been settled much later, it would have been pasture land or desert. The colonists stopped the Natives just in time (Maxwell 1910). Early-20th century Americans had not yet realized the importance of fire as a management tool in Appalachian landscapes.

Management in the Appalachians was first advocated by Gifford Pinchot, father of scientific forestry in the U.S. Pinchot promoted the protection of watershed resources against erosion and fire to prevent downstream flooding and navigation problems by protecting forested headwaters. He also advocated selective cutting (based on size and species) and argued against wasteful forestry, which was rampant at the time. Pinchot was instrumental in the passage of the Weeks Act in 1911 that authorized the federal purchase of forested and cutover lands in the name of watershed protection. In the southern Appalachians, 1.4 million acres (5666 km^2) were purchased in the first 15 months after the act was passed. In 1924, the act was broadened to include lands unrelated to navigation and flood control (Bradshaw 1992; Williams 2002). In 1916, President Wilson established the Pisgah National Forest in North Carolina. This was the first national forest to be established in the Appalachians (Bradshaw 1992; Williams 2002).

The passage of the Weeks Act also provided money for the passage of fire safety laws and provided machinery for the enforcement of these laws. The new laws challenged the traditional practice of early-spring burning by backcountry farmers to clean away leaves and underbrush, create forage for domestic and wild animals, and help control snakes and insects. However, during the early period of forest management, all fires were considered dangerous and locals were hired as rangers to end traditional burning in all areas (Williams 2002). These new fire suppression policies lasted for 70 years, and amazingly, fire-adapted Appalachian ecosystems that existed for 6,000 years alongside Native American populations became severely degraded in that short time frame.

2.3 Study Sites

2.3.1 Topographic Setting

The four study sites sampled for this research are located in the Ridge and Valley Province in the Appalachian Mountains, Jefferson National Forest, Virginia (Figure 2.1). These sites were chosen for their locations in the urban-wildland interface, for their abundance of fire-scarred Table Mountain pines, or at the request of the USDA Forest Service to help locate particularly critical sites in need of immediate rehabilitation.

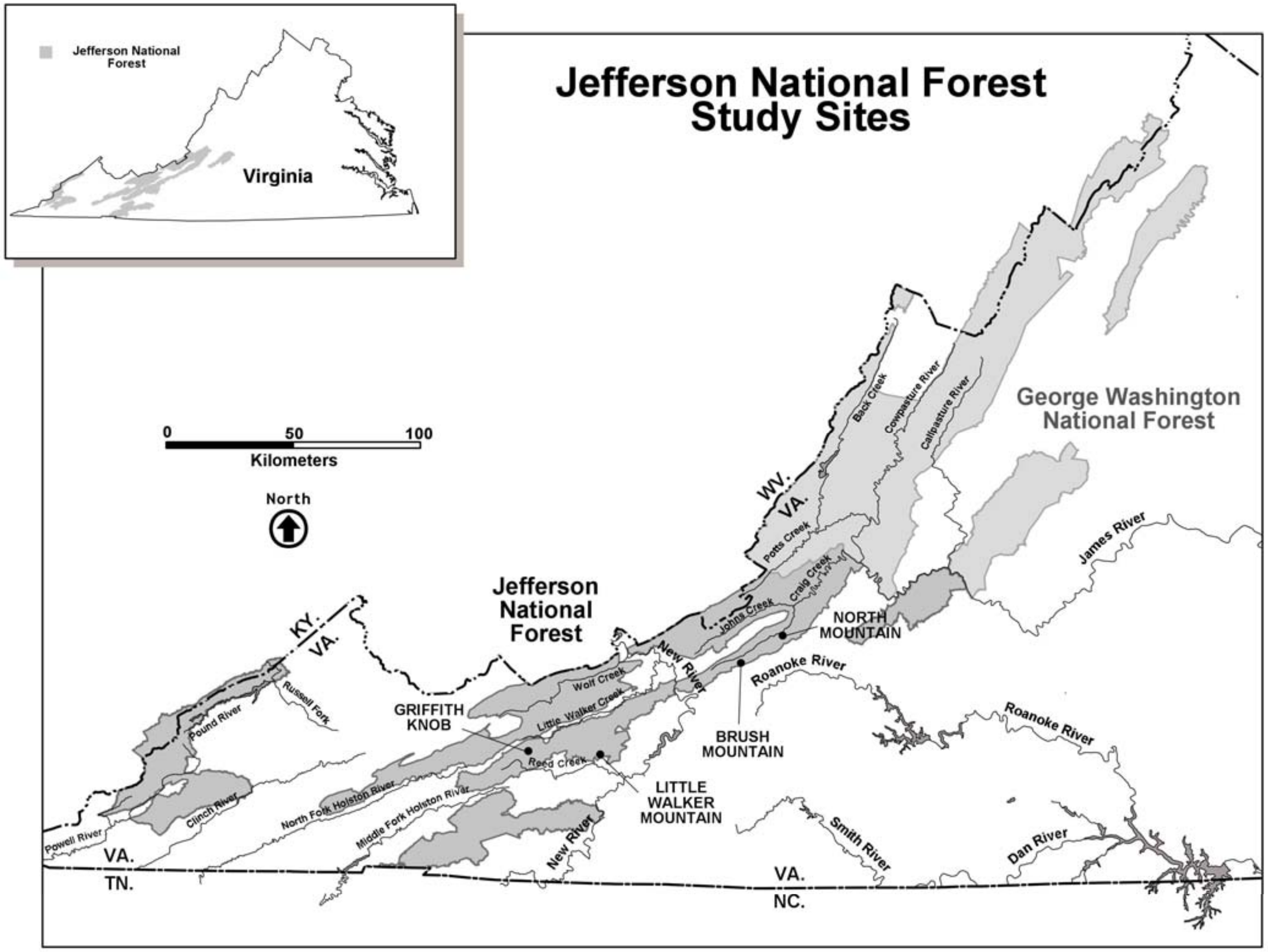

Figure 2.1: Location of study sites, Jefferson National Forest, Virginia, USA.

The central Appalachian Mountains are characterized by a humid continental climate (Bailey 1978; Lafon *et al*. 2005). Soils of southern Appalachian pine forests are sandy-loam Ultisols and Inceptisols (Welch 1999). Deep, dendritic fissures shaped by water erosion formed hollows on the ancient Appalachian tablelands (Hufford 2002) creating hollows, spurs, and distinct vegetation mosaics that vary with topography and microclimate. Appalachian terrain is steep and heavily dissected in many areas. For this reason, species composition in the southern Appalachians varies over relatively short distances in relation to environmental gradients (Waterman *et al*. 1995). Yellow pine stands cover the southwest-facing sides of spurs (side ridges perpendicular to the main ridge) in narrow bands that alternate between hardwood-dominated areas that lie between spurs (Lafon and Kutac 2003). The bedrock at all sites consists of sandstone and shale.

2.3.2 The Changing Vegetational Setting

In the short 250 years since initial settlement of the southern and central Appalachian Mountains, numerous changes in the vegetation composition of Appalachian forests have occurred due to: increased settlement, industry, fire suppression, livestock grazing, and natural and introduced pests and pathogens that have altered these forests. In the xeric pine-oak stands of the high-elevation Appalachian Mountains, fire suppression and the introduction of pathogens have quickly altered the health and composition of these stands and threatened the survival of important species. Introduced pathogens, such as the chestnut blight (*Cryphonectria parasitica* (Murrill) Barr), have benefited through accidental introduction by Euro-Americans into stands that have no natural resistance.

Chestnut blight, caused by a fungus of Asiatic origin, was introduced into eastern North America in 1904. The blight is cohosted and sustained by scarlet oaks. The southern and central Appalachians were the last places to be infected by the fungus, but its destruction of American chestnuts was complete by the 1930s (Dunn 1989; Jantz 2002). Chestnut trees contributed up to 40% of the overstory in xeric pine-oak stands and Appalachian ridgetops before the outbreak of the blight (Keever 1953). In the place of the chestnut, oaks and hickories have become dominant in Appalachian forests (Woods 1957; Jantz 2002). In particular, red oak and chestnut oak benefited through canopy openings caused by chestnut deaths on ridges (Abrams 2003).

Fire suppression has not only decreased the abundance of fire-adapted pine trees, but also made them more susceptible to southern pine beetle outbreak. The southern pine beetle has always been present in Appalachian pine forests. Before the advent of fire suppression policies, however, regularly occurring fires killed infected trees and thereby controlled the spread of the beetle. The beetle thrives in pine stands that are stressed by factors such as drought and over-crowding (Kalkstein 1981; Mattson and Haack 1987; Lafon and Kutac 2003). It has long been assumed that conifers under water stress are more susceptible to insect outbreaks because the stress increases the nutritional value of the conifers. This assumption has been proven by the positive relationship between water stress and the response of bark beetles and wood boring insects (Waring and Cobb 1992; Clancy *et al*. 1995). The primary defense in conifers against bark beetles is resinosis, however trees under water stress produce less resin (Clancy *et al*. 1995). Stressed loblolly pines maintain resin production, which does not benefit the southern pine beetle (Lorio and Sommers 1986; Clancy *et al*. 1995). Winters with mild temperatures, which are becoming increasingly more common, also increase the survival rate of the southern pine beetle (Lafon and Kutac 2003). Southern pine beetle outbreaks have caused significant population decreases in some stands (Lafon and Kutac 2003). Many of the living and recently killed Table Mountain pines collected for this project were victims of the southern pine beetle.

2.3.3 Brush Mountain

Brush Mountain (37º19'N, 80º20'W) is located in Montgomery County and is adjacent to the Craig Creek Valley (Figure 2.1), which is part of the James River watershed. The site on Brush Mountain is between 850–900 m (2800 and 2900 ft) in elevation. Brush Mountain receives 86.4 cm (34 in) of precipitation annually (NOAA 2005). Brush Mountain became part of the Jefferson National Forest in 1935 (Sutherland *et al*. 1995).

Samples were collected from the northern side of Brush Mountain, on the upper western and southwestern-facing spur slopes. The northern face of Brush Mountain is steep and difficult for logging equipment to reach and has been designated as unsuitable for timber by the United States Department of Agriculture Forest Service (Sutherland *et al*. 1995). The yellow pine stands on this mountain are fairly open with an understory sparsely populated with mountain laurel, serviceberry, black gum (*Nyssa sylvatica* Marsh.), red maple, white pine, and white oak. Table Mountain pine and chestnut oak dominate the canopy. Black gum, red maple, scarlet oak, Virginia pine, and black oak (*Quercus velutina* L.) are less commonly associated canopy trees.

2.3.4 North Mountain

The study areas on North Mountain (37º25'N, 80º10'W) are located in Craig County, adjacent to the Craig Creek Valley. The study sites are between 2200 and 2500 ft (670 and 760 m) in elevation. North Mountain receives 82.8 cm (32.6 in) of precipitation annually (NOAA 2005). The northwestern slope is heavily dissected by tributaries of Craig Creek, which create northwestern-running spur ridges and large breaks in vegetation. North Mountain is also traversed by maintained trails used for hiking, hunting, and biking.

The understory on North Mountain contains a thick cover of mountain laurel, blueberry (*Vaccinium corymbosum* L.), huckleberry (*Vaccinium ovatum* Pursh.), bear oak (*Quercus ilicifolia* Wangenh.), and greenbrier (*Smilax auriculata* Walt.). Understory trees include serviceberry, black gum, red maple, and hickory (*Carya* spp.). Chestnut oak, black gum, and Table Mountain pine dominate the canopy. Virginia pine, scarlet oak, black oak, northern red oak (*Quercus rubra* L.), and black locust (*Robinia pseudoacacia* L.) are less commonly associated canopy species.

2.3.5 Griffith Knob

Griffith Knob (37º01'N, 81º13'W) is located between Little Walker and Brushy Mountains in Bland County, adjacent to the Reed Creek Valley, which is part of the New River watershed. The sampling sites on Griffith Knob are located between 1100 and 1150 m (3600 and 3782 feet) in elevation. Griffith Knob receives 94 cm (37 in) of precipitation annually (NOAA 2005). The site is located on the western face of Griffith Knob. Griffith Knob has continuous vegetation.

Table Mountain pine dominates the canopy, while chestnut oak, scarlet oak, black gum, northern red oak, and white oak are less common canopy species. The understory is dominated by blackgum, Virginia pine, Table Mountain pine, bear oak, and mountain laurel, with a thick cover of blueberry. This is the only site that has any significant yellow pine regeneration in the form of seedlings and saplings.

2.3.6 Little Walker Mountain

Little Walker Mountain (37°03'N, 80°56'W) was named for Dr. Thomas Walker, surveyor and agent for the Loyal Land Company (Kegley and Kegley 1980). The sample sites are located on the northern face of Little Walker Mountain on the Bland County side, and are adjacent to Little Walker Creek, which is part of the North Holston River watershed. Sites are located between 800 and 920 m (2625 and 3018 ft) elevation. Annual precipitation is 81.5 cm (32.1 in) (NOAA 2005).

The understory on Little Walker Mountain contains numerous oak and American chestnut seedlings. The midstory is dominated by mountain laurel and striped maple (*Acer pensylvanicum* Pursh.) with a smaller number of rhododendron (*Rhododendron spp*.). Table Mountain pine and chestnut oak dominate the canopy. Black gum, white pine, red maple, scarlet oak, and northern red oak are less common associated canopy species.

CHAPTER 3

EVALUATING THE DENDROCHRONOLOGICAL POTENTIAL OF CENTRAL APPALACHIAN TABLE MOUNTAIN PINE (*PINUS PUNGENS* LAMB.)

Portions of this chapter referring to Table Mountain pine ecology and description of sample sites were taken from Chapters 1 and 2 of this dissertation. The use of "we" in this chapter refers to the many volunteers that helped conduct field work. These persons are listed in the Acknowledgements section of this dissertation. This research topic was originally formulated by Dr. Henri Grissino-Mayer, Dr. Charles Lafon, and Dr. Elaine Kennedy Sutherland. Dr. Grissino-Mayer assisted in the identification of relevant literature, location of sample sites, field collection, verifying the accuracy of dated samples, verifying climate analyses, and significant editing of this chapter. Dr. Lafon and Dr. Sutherland assisted in the location of sample sites and field collection. My contributions to this chapter include field collection, processing and dating of all samples, chronology development, conducting all analyses, and interpretation of results.

3.1 Introduction

In recent decades, studies concerning Table Mountain pine (*Pinus pungens* Lamb.) have focused on documenting the life history characteristics and ecology of the species (*e.g.*, Zobel 1969; Barden 1977, 2000; Harmon 1982; Sutherland *et al*. 1995; Waldrop *et al*. 2002, 2003). Some of these studies incorporated dendrochronological techniques. However, no study has conclusively demonstrated that the species is suitable for dendrochronological research. To add Table Mountain pine to the list of species acceptable for dendrochronological research, the annual ring structure and formation, relationship between climate and growth, quality of fire scars, and dendrochronological dating between trees in the same stands must be investigated. Douglass (1914) noted that crossdating must be demonstrated in a tree species before dendrochronological analysis can be used in ecological, archaeological, or climatological research in a region.

Demonstrating that Table Mountain pine has favorable characteristics for dendrochronological research is necessary for any future use of this species to reconstruct regional climate and fire regimes (*e.g.*, see Colenutt and Luckman 1995).

Beginning in the 1930s, Florence Hawley of the University of Chicago demonstrated that certain eastern tree species were useful for dendrochronological research (Hawley 1937, 1938, 1941), dispelling the myth prevalent at the time that eastern climates were not stressful enough to produce suitable tree-ring records. After Hawley, however, little research was conducted in the Southeast until the 1980s when foresters and ecologists saw that many commercially- and ecologically-important southeastern species were experiencing severe growth reductions (Sheffield *et al*. 1985; Sheffield and Cost 1987; Dell 1987; Cook 1988; Lucier 1988; Grissino-Mayer *et al*. 1989). These studies promoted more dendrochronological research in the region and showed that southeastern trees were likely experiencing combined effects of changes in climate or human-caused disturbances such as acid rainfall or air pollution. Additional studies later established the necessary role of fire in southeastern yellow pine ecosystems (Harmon 1982; Sutherland *et al*. 1995; Barden 2000; Brose and Waldrop 2006).

Since the 1980s, a considerable amount of research in the southeastern U.S. has been conducted using baldcypress (*Taxodium distichum* (L.) Rich.) to reconstruct climate. Stahle (1979) first proved that baldcypress could be dated against pine and eastern red cedar (*Juniperus virginiana* L.) chronologies in Arkansas. Stahle also constructed an 800-year-long baldcypress chronology from living trees and submerged logs in Missouri (Stahle *et al*. 1985). Baldcypress is a valuable tree in the Southeast because of its sensitivity to climate, longevity, resistance to decay, and long-term preservation potential. Long baldcypress chronologies have since proven useful in the reconstruction of southeastern climate regimes, for calibrating archaeological dates, and in providing seasonal to annual estimates of late Holocene climates currently provided only by pollen data (Stahle *et al*. 1985). For example, living baldcypress trees discovered by Stahle in southeastern North Carolina were found to be in excess of 1000 years in age (Stahle *et al*. 1988). June Palmer Drought Severity Index (PDSI) was reconstructed from A.D. 372 to 1985 for North Carolina using these baldcypress trees, and showed that a 30-year cycle of droughts during the growing season was recorded by the baldcypress. Baldcypress was also used to tie the disappearance of the Roanoke Island Colony and the abandonment of the Jamestown Colony in the early settlement history of Virginia to extreme drought periods (Stahle *et al*. 1998). A baldcypress chronology from southeastern Virginia was constructed from AD 1185 to 1984 and used to reconstruct growing-season Palmer Hydrologic Drought Index (PHDI) for southeastern Virginia and northeastern North Carolina. The Roanoke Colony disappeared during the most extreme drought period in 800 years (1587–1589) and the Jamestown Colony was abandoned during the driest seven year period in 770 years (1606–1612) (Stahle *et al*. 1998).

The lack of southeastern species capable of reaching ages over 500 years limits the length of climate reconstructions and quantity of climate analyses that can be conducted for the region. The habitats in which these living species grow also makes analyses difficult because environmental conditions are generally not limiting to tree growth, a necessary prerequisite for successful tree-ring dating. Other southeastern species, however, can be used to conduct climate analyses for several hundred years into the past when utilizing both living and remnant materials. One such species is Table Mountain pine, which can reach ages of 250 years (Zobel 1969).

3.2 Table Mountain Pine

The importance of Table Mountain pine lies in its ecological, not economic, value: increasing landscape diversity, protecting areas prone to erosion, and providing food and cover to a number of wildlife species (Gray 2001). Table Mountain pine plays a critical role in the regeneration of mountain forests after major fire occurrences (Zobel 1969; Williams and Johnson 1990; Armbrister 2002). Deterioration of xerophytic Table Mountain pine and mixed pine-oak stands has prompted concern about their continued survival in the central Appalachian Mountains. Fire ecologists and forest researchers predict that fire-intolerant species will eventually dominate traditional pine sites unless fire is restored to these ecosystems (Farrar 1998, Brose *et al*. 2001).

Table Mountain pine was historically prevalent on the xeric ridgetops and on south to southwest facing slopes of the Appalachian Mountains. This species does not maintain a continuous distribution, but occurs in isolated, high elevation stands (Sanders 1992) from Pennsylvania to Georgia (Zobel 1969). Table Mountain pine is a fire-adapted species, dependent on repeated fires to open serotinous cones for seed dispersal, prepare seed beds, increase sunlight reaching the forest floor, and eliminate hardwood competitors. Like other fire-dependent pines, Table Mountain pine evolved during periods of frequent lightning-ignited fires. Before the arrival of humans in the Appalachian Mountains, these fires would have been the only disturbance with enough frequency and intensity to influence the evolution and distribution of pines (Keeley and Zedler 1998).

For several thousand years, Table Mountain pine had benefited from Native Americans who augmented the natural fire regime until Euro-American settlement in the 18th century. Euro-American fires of the late 19th and early 20th centuries helped maintain populations of Table Mountain pine, but these fires were more destructive and eventually led to policies of fire suppression. The abundance and distribution of living pines and fire-tolerant hardwoods, as well as remnant fire-scarred materials, indicate that fire was a frequently occurring disturbance and primary influence on vegetation before the 1930s. In the past, fire acted as a natural disturbance process that altered successional dynamics, but after several decades of fire suppression, ridgetop pine communities of the central Appalachian Mountains are entering the later seral stages of forest succession and are disappearing (Waldrop *et al*. 2002). In 1996, the Southern Appalachian Assessment listed Table Mountain pine ecosystems as one of the 31 rare communities in the southern Appalachian Mountains (SAMAB 1996; Gray 2001). This is also the case in the central Appalachians where management agencies struggle to maintain Table Mountain pine-oak stands through the reintroduction of fire.

Understanding the complex relationships between climate, tree growth, and wildfire will further guide the management of Table Mountain pine. Knowledge of how Table Mountain pine responds to different climate variables is virtually nonexistent and therefore so is the ability to predict the response of this species to future changes in climate. Sutherland *et al*. (1995) conducted a limited climate analysis on Table Mountain pine in the central Appalachian Mountains and this is the only climatic research that involved Table Mountain pine to date. This research focused only on the relationship between fire years and climate, and not specifically on the influence of climate on tree growth. Later, Copenheaver *et al*. (2002) found that small-scale environmental variables, such as soils and land-use history, had more impact on vegetation distribution in Virginia pine-pitch pine stands in Virginia than climate. It is possible that no association exists between climate and tree growth in Table Mountain pines because of the stronger influence of competition and topography on the stands.

Over the last 25 years, interest in the relationship between fire and Table Mountain pine has increased (Harmon 1982, Turrill 1998, Waldrop *et al*. 1999, Welch and Waldrop 2001, Waldrop *et al*., 2002, 2003; Brose *et al*. 2002, Lafon and Kutac 2003), but only a few studies have used dendrochronology to examine the age structure and fire regimes in mixed hardwood-Table Mountain pine stands (e.g., Sutherland *et al*. 1995, Armbrister 2002, Pfeffer 2005). A need exists to thoroughly and comprehensively evaluate the dendrochronological potential of Table Mountain pine as it gains increasing importance for understanding past successional trends and past fire regimes, especially in light of anticipated future changes in climate.

The purpose of this study is to evaluate the dendrochronological potential of Table Mountain pine for use in ongoing fire history studies, climate analyses, and studies of stand dynamics. Specific objectives include (1) determine the crossdating potential of Table Mountain pine; (2) develop tree-ring chronologies for Table Mountain pine; (3) determine when climate exerts the most influence on growth of Table Mountain pines; and (4) develop a model of Table Mountain pine tree growth using climatic variables to eventually gain a better understanding of fire-climate relationships within these stands.

3.3 Study Sites

The four research sites are located in the Ridge and Valley Province in the Appalachian Mountains, Jefferson National Forest, Virginia. The central Appalachian Mountains are characterized by a humid continental climate (Bailey 1978; Lafon *et al*. 2005). Soils of southern Appalachian pine forests are sandy-loam Ultisols and Inceptisols (Welch 1999). The geology of all sites is sandstone and shale. Deep, dendritic fissures created by water erosion have formed valleys and spurs on the ancient Appalachian tablelands (Hufford 2002) with distinct vegetation communities that vary with topography and microclimate. Yellow pine stands cover the south-, west-, and southwest-facing sides of these spurs in narrow strips that alternate with hardwood-dominated areas in drainages and on north- and northwest-facing slopes (Lafon and Kutac 2003).

Sites on North Mountain (37º25'N, 80º10'W) are located on the northwest side of the mountain, which is located in Craig County, adjacent to Craig Creek Valley. Sites are between 670 and 760 m (2200 and 2500 ft) in elevation. North Mountain receives approximately 83 cm (32.6 in) of precipitation annually (NOAA 2005). The northwest slope is heavily dissected by tributaries of Craig Creek, which create northwest-running ridges and breaks in the otherwise continuous vegetation. The understory on North Mountain contains a thick cover of mountain laurel, blueberry, huckleberry, bear oak, and greenbrier. Understory trees included serviceberry, black gum, red maple, and hickory. Chestnut oak, black gum, Table Mountain pine, and to a much lesser extent Virginia pine, scarlet oak, black oak, northern red oak, and black locust, are present in the canopy.

Brush Mountain (37º19'N, 80º20'W) is located in Montgomery County adjacent to the Craig Creek Valley (Figure 2.1). The sites on Brush Mountain lie between 850 and 900 m (2800 and 2900 ft) in elevation. Brush Mountain receives approximately 86 cm

(34 in) of precipitation annually (NOAA 2005). Samples were collected from the northern side of Brush Mountain, on the upper west- and southwest-facing slopes. The yellow pine stands on this mountain are fairly open with an understory sparsely populated with mountain laurel, serviceberry, black gum, red maple, white pine, and white oak. Table Mountain pine and chestnut oak, and to a lesser extent black gum, red maple, scarlet oak, Virginia pine, and black oak, are present in the canopy.

Griffith Knob (37º1'N, 81º13'W) is located between Little Walker and Brushy Mountains in Bland County, adjacent to Reed Creek Valley. The sites on Griffith Knob are located on the western face between 1100 and 1150 m (3600 and 3782 ft) in elevation. Griffith Knob receives approximately 94 cm (37 in) of precipitation annually (NOAA 2005). Griffith Knob is very steep with continuous vegetation. Table Mountain pine dominates the overstory along with chestnut oak, scarlet oak, black gum, northern red oak, and white oak. The understory is dominated by blackgum, Virginia pine, Table Mountain pine, bear oak, and mountain laurel, with a thick cover of blueberry. This is the only site that has any significant yellow pine regeneration.

The Little Walker Mountain (37°03'N, 80°56'W) sites are located on the north face of the mountain, itself located in Bland County, adjacent to Little Walker Creek. Sites are between 800 and 920 m (2625–3018 ft) elevation. Annual precipitation is approximately 81.5 cm (32 in) (NOAA 2005). The understory on Little Walker Mountain contains numerous oak and American chestnut seedlings. The midstory is dominated by mountain laurel and striped maple, while Table Mountain pine and chestnut oak dominate the canopy along with black gum, white pine, red maple, scarlet oak, and northern red oak.

3.4 Methods

3.4.1 Field Methods

The field methods presented here are not those used in traditional dendroclimatic studies because our study was designed with a larger goal of analyzing the fire regimes of mixed hardwood/pine stands where Table Mountain pines form a major component. Nonetheless, the pines selected for climatic analysis were located on drier midslopes that had thin soils, conditions that promote sensitivity to climatic fluctuations. However, these sites are also prone to disturbances, such as fire and ice storms, that could diminish the strength of the climate signal.

Aerial photographs were used to locate potential sampling sites in yellow pine stands at all research sites. Aerial photos taken during winter months in leaf-off conditions were studied to distinguish between hardwood-dominated and pine-dominated stands. Sites were selected that minimized the effects of human-related disturbances so the effects of climate and fire could be assessed more accurately. In the eastern U.S., century-scale dendroecological investigations on forest dynamics are limited because of the prevalence of second- and third-growth forests and because of a long history of human disturbances. This makes it necessary to use remnant woody materials and to seek out areas that have not been logged, farmed, grazed, or urbanized.

Following the methods of Arno and Sneck (1977), cross-sections were taken from yellow pines on four ridges at each of the four research sites (Table 3.1). These cross-sections were removed from living trees, snags, stumps, and remnant logs. From

Table 3.1: List of sampling sites and number of increment cores and cross-sections taken from each site.

Research Site	Sampling Sites	Increment Cores	Cross-Sections
Brush Mountain	BMA	167	9
	BMB	116	13
	BMC	123	12
	BMD	*	14
Total		**406**	**48**
Griffith Knob	GKA	80	23
	GKB	*	42
	GKC	152	22
	GKD	65	24
Total		**297**	**111**
Little Walker Mountain	LWA	*	26
	LWB	93	14
	LWC	93	21
	LWD	124	21
Total		**310**	**82**
North Mountain	NMA	116	20
	NMB	*	9
	NMC	180	6
	NMD	114	18
Total		**410**	**53**
Total		**1423**	**294**

* Increment cores were collected from three macroplots at each research site. Macroplots were not established at BMD, GKB, LWA, or NMB.

each fire history plot (16 total), a range of six to 42 cross-sections (Table 3.1) were collected from yellow pines, mostly Table Mountain pine. In most cases, these cross-sections were fire-scarred, although some older non-fire-scarred samples were also collected for chronology development. Two fire-history plots at Brush Mountain previously collected by Sutherland *et al*. (1995) were used in this project.

Three 50 by 20 m plots (hereafter referred to as a "macroplot") were established at each site to determine forest successional status of these mixed hardwood/yellow pine stands based on stand information from the understory, midstory, and overstory. Using an increment borer at approximately 30 cm above ground, we extracted two cores at the base of the stem parallel to the slope contour from each inventoried tree. Because tree growth patterns can differ across the bole in the same tree (Fritts 1976; Cleaveland 1980), we cored through the entire trunk or extracted two cores that represent the diameter of the tree. In each, at least 40 yellow pine (Table Mountain pine, pitch pine, or Virginia pine) trees were cored at each macroplot. At some sites, this required moving outside of the macroplot to obtain additional yellow pines to core. These pine trees from outside the macroplot were used solely for chronology development and climate response analyses and were not included in any analyses of stand dynamics based on macroplot information.

3.4.2 Laboratory Methods

3.4.2.1 Crossdating and Chronology Development

Increment cores were stored in paper straws, dried, and mounted on wooden core mounts (Stokes and Smiley 1996). Cross-sections were frozen for 24 hours at –40 °C and then dried. All of the increment cores and cross-sections were progressively sanded with a belt sander beginning with ANSI 40-grit (500–595µm) and ending with ANSI 400-grit (20.6–23.6 µm) sanding belts (Orvis and Grissino-Mayer 2002).

Every tenth ring on all series were first dotted from the innermost complete ring to the outermost ring and marker rings identified (Stokes and Smiley 1996). Yellow pine increment cores were then crossdated using skeleton plots and verified using COFECHA software (Holmes 1983; Grissino-Mayer 2001a). COFECHA is a computer program used as a tool by dendrochronologists to gauge the quality of crossdating and measurement accuracy of and among tree-ring series (Grissino-Mayer 2001a). Individual series were analyzed in COFECHA using 40-yr segments lagged successively by 20 yrs. The tree rings on all yellow pine increment cores were measured to the nearest 0.001 mm using a Velmex measuring system interfaced with Measure J2X measurement software for chronology construction.

After the increment cores were measured, their measurement files were combined into one text file per site and used as a working data set to help crossdate the remnant wood collected for fire history analyses. Tree rings in all cross-sections were first dated visually using marker rings and using the patterns from the crossdated increment cores. Although some cross-sections could be dated graphically, we ensured crossdating accuracy by measuring the rings on all cross-sections along a radius that was well away from the fire scar area on the wood to avoid erratic growth patterns associated with the fire scars. After the tree rings on a cross-section were dated, the ring-width measurements were added into the working data set for that site. Not all collected increment cores and cross-sections were used in chronology development because of irregular growth patterns that caused many segments to have correlations that fell below the critical correlation coefficient of 0.37 ($p > 0.01$).

Each measurement series was then standardized to build a master tree-ring chronology for each site using the program CRONOL (Cook 1985). CRONOL standardizes the raw measurements by fitting a trend line or curve to the individual series being modeled using the ordinary least squares technique (Cook 1985). Standardization is the correction of ring widths for the changing age and geometry in a tree (Fritts 1976), and involves dividing the ring width measurement for each year by the value obtained from a negative exponential curve (used for this project), a regression line, or spline fit to the series (Cook and Kairiukstis 1992). Standardization forms a new time series by removing the trend and creating a mean and variance that are more homogeneous with respect to time (Matalas 1962; Fritts 1976). The standardized ring-width indices generally have no positive or negative linear trend, their mean value is one, and the variability exhibited in younger rings (juvenile growth) is made comparable to the slower mature growth (Fritts 1976). By standardizing, influences such as tree size, stand density, and competition within the stand are minimized (Friend and Hafley 1989). The STANDARD chronology type was used in this study because it retains low-frequency variation desirable for analysis of long-term climate trends better than the RESIDUAL chronology type, which has all low-frequency trends removed (Grissino-Mayer 1995).

The descriptive statistics used to characterize the tree-ring chronologies include mean sensitivity, a measure of year-to-year variability; standard deviation, a measure of the overall variability; and first-order autocorrelation, a measure of interdependence between the indices of successive years (Fritts 1976). It is desirable for the mean sensitivity and standard deviation to be high, and the first-order autocorrelation to be low (Dewitt and Ames 1978; Grissino-Mayer and Butler 1993). Values of mean sensitivity over 0.30 represent a sensitive measurement series (Grissino-Mayer 2001a). The most important indicator of the validity of both the crossdating accuracy and the strength of the climate signal of a tree-ring chronology is the average interseries correlation. The average interseries correlation gauges the strength of crossdating among all series for a site. For southeastern pines, interseries correlations greater than or equal to 0.40 are desirable (Grissino-Mayer 2001a).

3.4.2.2 Climate Methods

To assess the climatic influence on the annual tree growth of Table Mountain pine, correlation analyses were first performed between monthly and seasonalized precipitation and temperature data and the Table Mountain pine tree-ring chronologies from all research sites. Correlation analysis is the first step in understanding relationships between climatic variables and annual tree growth (Gholz 1982; Grissino-Mayer and Butler 1993). Correlation analysis employs Pearson correlation coefficients as a measure of the strength of the association between two variables and is used to determine the period of years when climatic factors are most influential in determining annual tree growth (Coile 1935; Fritts 1976; Grissino-Mayer and Butler 1993).

Climate analyses were run for each site individually using SAS (Schotzhauer and Littell 1987) to determine in which months climate variables had a statistically significant ($p < 0.05$) effect on tree growth. Several authors have found regional climate data to have higher correlations with tree-ring chronologies than single-station data (Briffa *et al*. 1988; Schweingruber *et al*. 1992, 1993; Stahle and Cleaveland 1992; Colenutt and Luckman 1995). Regional precipitation and temperature data (Region 5 in Virginia, henceforth called "4405") for North Mountain were obtained from the National Climatic Data Center web site (NCDC 2006). Because Griffith Knob, Little Walker Mountain, and Brush Mountain sites are closer to the boundaries of the climate zones than North Mountain, I averaged the Region 5 (4405) and Region 6 (henceforth called "4406") climate data together. If the average of Regions 5 and 6 did not correlate well with either site, data for individual nearby stations were averaged together. For Brush Mountain, the Covington, Hillsville, and Glen Lyn stations in Virginia were averaged together to obtain precipitation and temperature data. Data from Bluestone Lake and Meadows of Dan in Virginia were averaged together to analyze relationships with the Griffith Knob chronology. Data from Princeton and Bluefield Airport in West Virginia and Bland and Glen Lyn in Virginia were averaged together to analyze relationships with the Little Walker Mountain chronology. Precipitation and temperature data were analyzed for the period 1940–2002.

In addition to precipitation and temperature data, I also analyzed the relationships between Table Mountain pine tree growth and monthly and seasonal 4405 PDSI and PHDI (Palmer Hydrologic Drought Index) for the period 1940–2002. PDSI and PHDI values were obtained from the National Climatic Data Center (NCDC). PDSI is a monthly meteorological index that describes the severity of wet and dry periods while incorporating soil type, precipitation, and temperature (Palmer 1965). PDSI is often strongly correlated with tree-ring indices from the eastern US (Stahle *et al*. 1985; Jenkins and Pallardy 1995; Lafon 2000). PHDI is a hydrological index used to assess long-term moisture supply (Hayes 1996; NCDC 2004). PHDI responds more slowly to weather changes than PDSI, but more closely approximates subsurface hydrologic characteristics (Grissino-Mayer and Butler 1993). The NAO (North Atlantic Oscillation) indices for the period 1948–2000 and the Kaplan (AMO) indices for the period 1940–1991 were also investigated using correlation analysis. These indices were obtained from the Climatic Data Center web site (CDC 2006). To ensure consistency between sites, all correlation analyses were run since 1940, with the exception of NAO, whose data only extend to 1948.

Seasonalized variables were developed and analyzed using correlation analysis for precipitation and temperature and PDSI at Brush Mountain, temperature at North Mountain, PHDI and PDSI at North Mountain, Griffith Knob, and Little Walker Mountain, as well as for the Kaplan indices at Brush Mountain, Griffith Knob, and Little Walker Mountain.

All four tree-ring chronologies were combined and their relationship with precipitation, temperature, PDSI, PHDI, NAO, and the Kaplan indices evaluated. Seasonal variables were then created for precipitation, PHDI, and PSDI and investigated using correlation analysis.

NAO and AMO are teleconnections that affect climate and weather patterns over much of the eastern U.S., but their influence on the growth rates of individual tree species is poorly understood. The NAO is a redistribution of atmospheric mass between the Arctic and subtropical Atlantic mainly between November and April. NAO affects heat and moisture transport between the Atlantic Ocean and neighboring continents, storm frequency and intensity, and wind direction and speed over the Atlantic (Hurrell *et al*. 2003). The positive phase strengthens the subtropical high over the southeastern U.S., increasing subtropical airflow. The negative phase produces colder than average winters over the eastern U.S. (Bonan 2002). The effect of the NAO on ecosystems, surface temperature, and precipitation is greatest during the winter months (Hurrell *et al*. 2003).

AMO is a long-term oceanic phenomenon (Kerr 2000) that affects the entire North Atlantic Basin (Enfield *et al*. 2001). For example, between 1856 and 1999 sea surface temperatures in the North Atlantic varied 0.4 °C on a 65–80 year cycle (Kerr 2000; Enfield *et al*. 2001). During AMO warm phases, the U.S. experiences pronounced decreases in precipitation, particularly during the summer. A warm phase began ca. 1995 (Enfield *et al*. 2001). The Kaplan indices (Kaplan *et al*. 1998), specifically naives, which represent sea-surface temperature anomalies in the north Atlantic, are the original raw data that led to the eventual development of the AMO Index, and are used in this study.

Climate variables were lagged to determine if the climate of the previous growing season (beginning in the previous July) affected growth during the current growing season (through current September). The use of lagged climate variables is considered necessary because tree growth during the current year is partially dependent upon carbon uptake and production of photosynthates that occur during the growing season of the previous year and during the dormant season into the current year (Fritts 1976; Waring 1983; Grissino-Mayer and Butler 1993).

The PRECON (for factors that precondition tree growth) computer program was used to identify environmental conditions that influenced growth (Fritts *et al*. 1991; Fritts and Shashkin 1994; Grissino-Mayer and Fritts 1995). Unlike correlation techniques, PRECON uses multivariate techniques (Fritts 1962; Fritts and Shashkin 1994; Grissino-Mayer and Fritts 1995) to calibrate monthly precipitation and temperature with standardized tree-ring measurement series (Grissino-Mayer and Fritts 1995). PRECON determines the climatic variables to which the trees are most strongly responding (Fritts 1976; Buckley 1989; Fritts *et al*. 1991; Grissino-Mayer and Fritts 1995). The strength of the PRECON software is its ability to perform response function analysis, a multivariate biological model of tree growth. Response function analysis yields a rigorous evaluation of climatic effects on tree growth using principal components of the normalized climate data set to reduce the effects resulting from covariance among the independent variables. Response function weights represent the separate effects of temperature and precipitation on monthly tree growth (Fritts 1976: 356–370; Grissino-Mayer *et al*. 1989). Any weight with a significant ($p < 0.05$) negative or positive variation from the standardized index indicates a month when climate has a potentially strong impact on annual ring growth (Grissino-Mayer *et al*. 1989).

Using PRECON, tree growth was regressed on orthogonal transformations of 15 monthly precipitation and monthly temperature variables beginning with July of the previous year and ending with September of the current year (after Grissino-Mayer and Fritts 1995). Response function analysis was used in conjunction with correlation analysis to corroborate the results of the climate/tree growth correlation analyses (Grissino-Mayer and Butler 1993). I then used PRECON to develop time series plots that incorporate the results from a stepwise regression that uses only the months with significant climate effects to show those periods during the 20th century when tree growth was above or below that modeled from the observed climate variables. Any declines in growth could be caused by large-scale disturbances that affect all trees within a stand, such as ice storms. Such disturbances are expected to have some degree of influence on these forest-interior trees, thus reducing the strength of the overall climate signal.

3.5 Results

3.5.1 Ring Characteristics and Chronology Development

The use of dendrochronological techniques on Table Mountain pine was essential because, while the species typically has easily discernable rings with distinct boundaries between earlywood and latewood, ring counts are undependable due to false and locally-absent rings. A suppressed or stressed tree may only produce xylem for a fraction of the growing season (Kozlowski and Peterson 1962; Kozlowski and Pallardy 1997), which would explain the high number of locally-absent rings in Table Mountain pine.

Chronologies for the four research sites (Figure 3.1) extend well into the 1700s, which makes them the oldest Table Mountain pine chronologies for the region (Table 3.2). The interseries correlations were high at all four sites: Brush Mountain: 0.59; Griffith Knob: 0.58; Little Walker Mountain: 0.55; and North Mountain: 0.57. All sites had mean sensitivities greater than 0.30, standard deviations above 0.38, and low first-order autocorrelation (Table 3.2). The percentage of locally-absent rings was low at all sites. The most important marker rings included the years 1881, 1883, 1885, 1930, 1987, and 1994, and were used in visual crossdating. Some marker rings were common to all

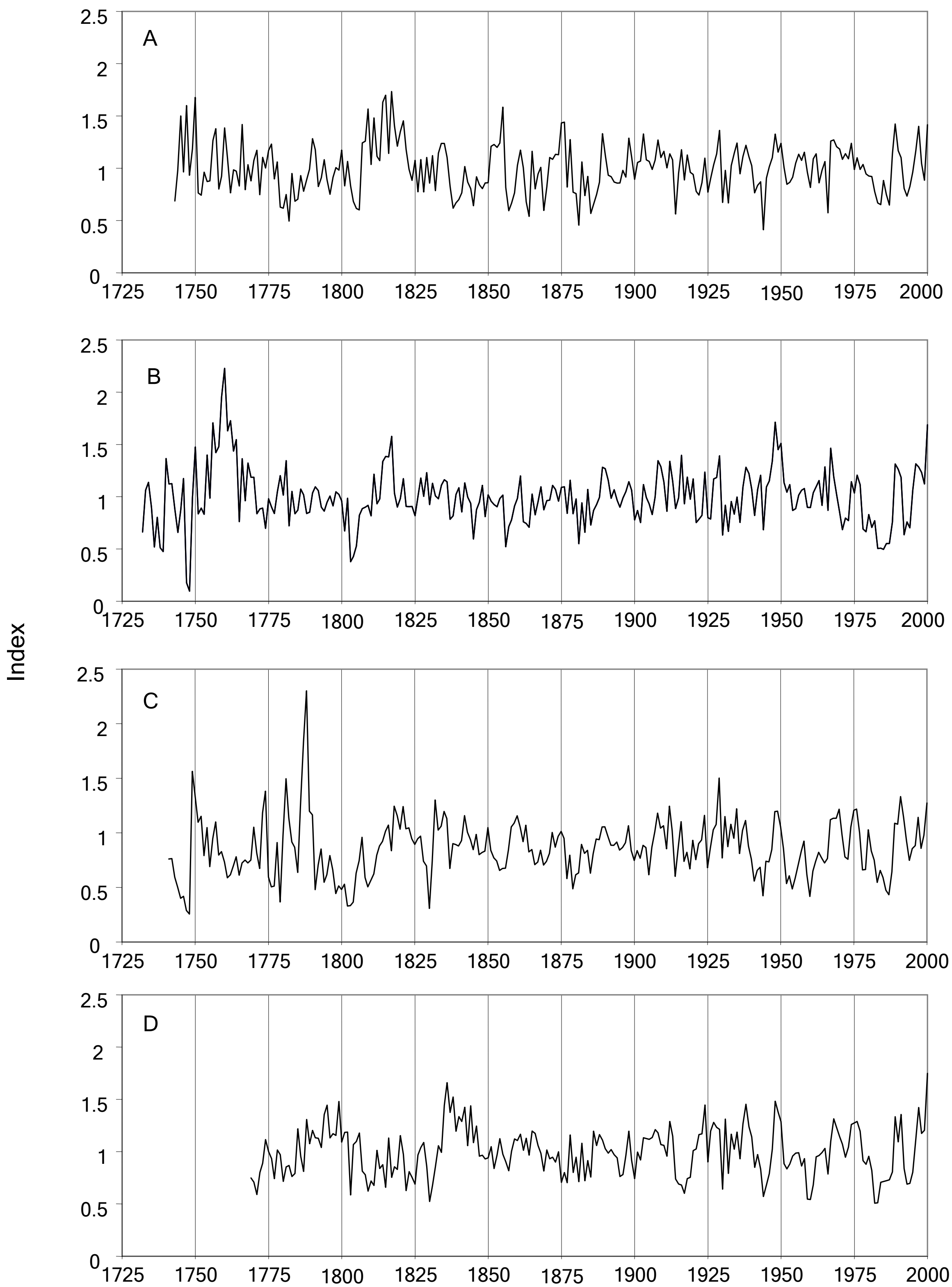

Figure 3.1: The North Mountain (A), Brush Mountain (B), Griffith Knob (C), and Little Walker Mountain (D) tree-ring index chronologies.

Table 3.2: Descriptive statistics for the Table Mountain pine chronologies developed for this study.

Site	Number of series	Range of Years	% Locally-absent rings	Interseries correlation	Mean sensitivity	Standard deviation	Auto-correlation
Brush Mountain	99	1732–2003	0.30%	0.59	0.30	0.47	–0.02
Griffith Knob	116	1741–2003	0.02%	0.58	0.32	0.38	–0.01
Little Walker Mountain	175	1694–2004	0.17%	0.55	0.32	0.47	-0.001
North Mountain	113	1743–2003	0.73%	0.57	0.34	0.37	–0.01

chronologies, but I found noticeable differences among the four chronologies, likely due to differences in topography and microclimate. The commonality of marker rings among individual series is a strong indicator of a regional climate signal and may be due to ice storms, which have been shown to coincide with the formation of narrow rings in the Ridge and Valley Province of Virginia (Lafon 2000) (Table 3.3). Suppression begins during the growing season following the ice disturbance, but release caused by removal of competing vegetation can lag a year or more (Lafon 2000). Ice storms affect Table Mountain pine growth through defoliation via limb breakage during the dormant season and early spring. Conifers store carbohydrates in foliage and are therefore severely affected by defoliation events (Kulman 1971; Clancy *et al*. 1995) such as ice storms. The removal of photosynthetic tissue by herbivores is known to negatively affect the mutualistic relationship with ectomycorrhizal fungi, which provide soil nutrients to the tree in exchange for a portion of photosynthates (Kozlowski 1992; Clancy *et al*. 1995). The same could be true for defoliation events initiated by ice storms. The disruption of this mutualistic relationship would be detrimental to Table Mountain pine in early spring and could affect tree development for the growing season.

3.5.2 Regional versus Multistation Climate Data

Three of the four study areas, Brush Mountain, Griffith Knob, and Little Walker Mountain, were located along the boundaries of climate regions 4405 and 4406. For this reason, correlations between the regional climate data and tree-ring data from these sites was extremely low. An average of 4405 and 4406 was also run against tree-ring data from each site with similar results. To rectify this problem, I created individual local

Table 3.3: Dates of known ice storms that affected southwestern and central Appalachian Virginia (Lafon 2000).

Research Site	Ice Event that caused Narrow Rings
Brush Mountain	January 1906
	March 1911
	November 1920
	March 1932
	April 1971
	March 1978
	January 1979
	December 1984
	February 1994
Griffith Knob	March 1911
	November 1920
	March 1932
	March 1978
	January 1979
	February 1994
	February 1998
Little Walker Mountain	January 1918
	March 1932
	March 1978
	January 1979
	February 1994
North Mountain	January 1906
	November 1920
	March 1932

climate data sets for each site combining records from individual climate stations. The climate signal became apparent through use of the station average (Figure 3.2), which justifies its use instead of regional climate data. North Mountain tree-ring data correlated well with regional climate data, therefore a locale-specific data set was not created for the site.

3.5.3 Response of Table Mountain pine to Climatic Variables

Results from the response function analysis showed that for North Mountain, 59% of the variance was explained by climate ($R^2 = 0.46$) and prior growth ($R^2 = 0.13$). 66% of the variability in the Brush Mountain chronology could be explained by climate ($R^2 = 0.26$) and prior growth ($R^2 = 0.40$). For Griffith Knob, 52% of the variance was explained by climate ($R^2 = 0.24$) and prior growth ($R^2 = 0.28$). For Little Walker Mountain, 59% of the variance was explained by climate ($R^2 = 0.21$) and prior growth ($R^2 = 0.38$). The adjusted R^2 is reported here because R^2 can overestimate the performance of the regression model (SPSS 1999; Lafon 2000).

Climate during the current and previous growing seasons had a more significant effect on Table Mountain pine growth at North Mountain than did the winter season, unlike the other sites. Response function analysis at North Mountain revealed a significant positive relationship with the previous year’s August and September and current year’s June through August precipitation (Figure 3.3A). A significant negative relationship was found with current year’s June temperature. The correlation analysis also indicated a significant positive relationship with the previous year’s September and current June and July precipitation, and a significant negative relationship with July

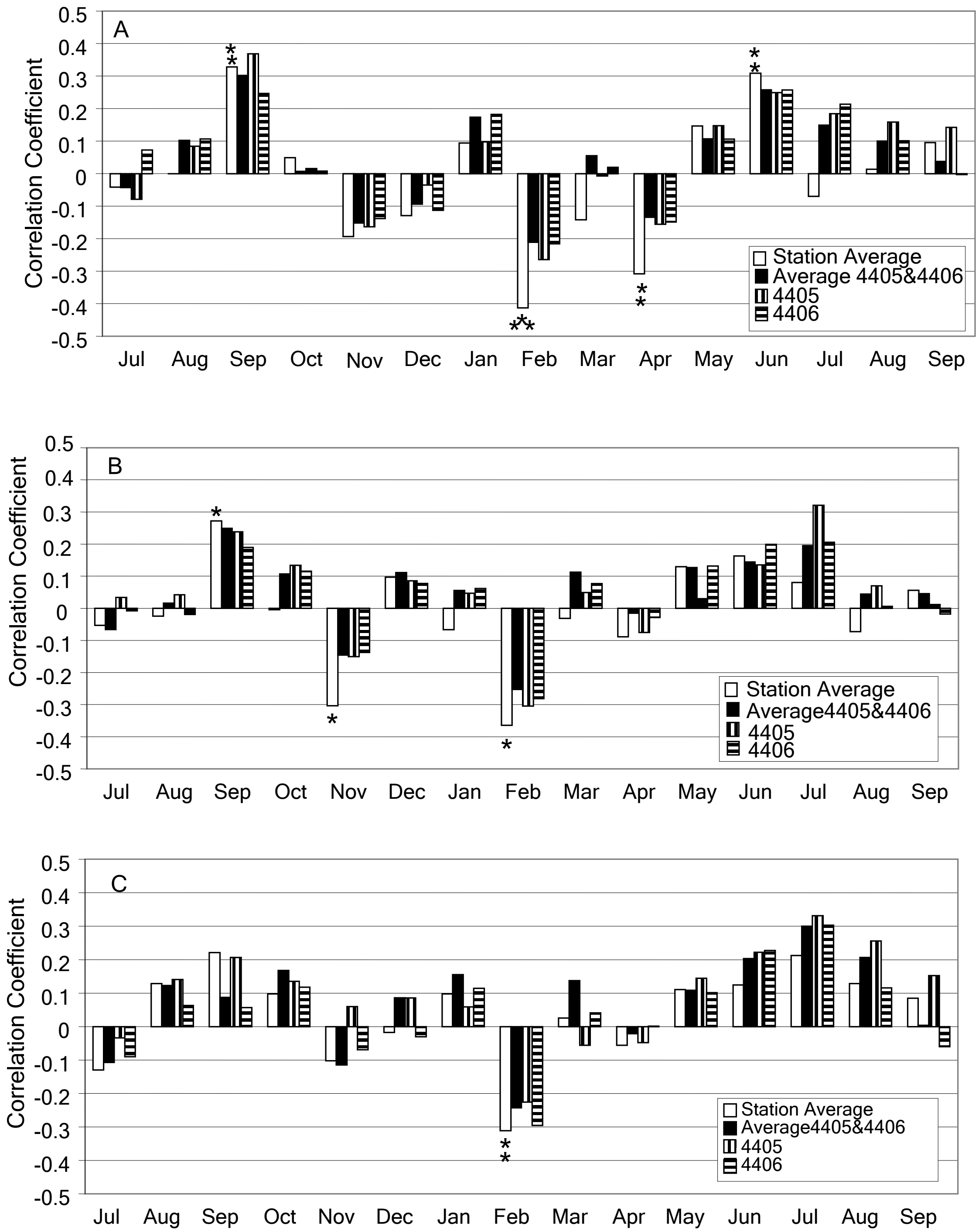

Figure 3.2: Results for the Brush Mountain (A), Griffith Knob (B), and Little Walker Mountain (C) correlation analysis, comparing precipitation for region 4405, region 4406, and the average of regions 4405 and 4406 with the tree-ring chronology. Statistically significant relationships are indicated by * ($p<0.05$), ** ($p < 0.01$) and *** ($p < 0.001$).

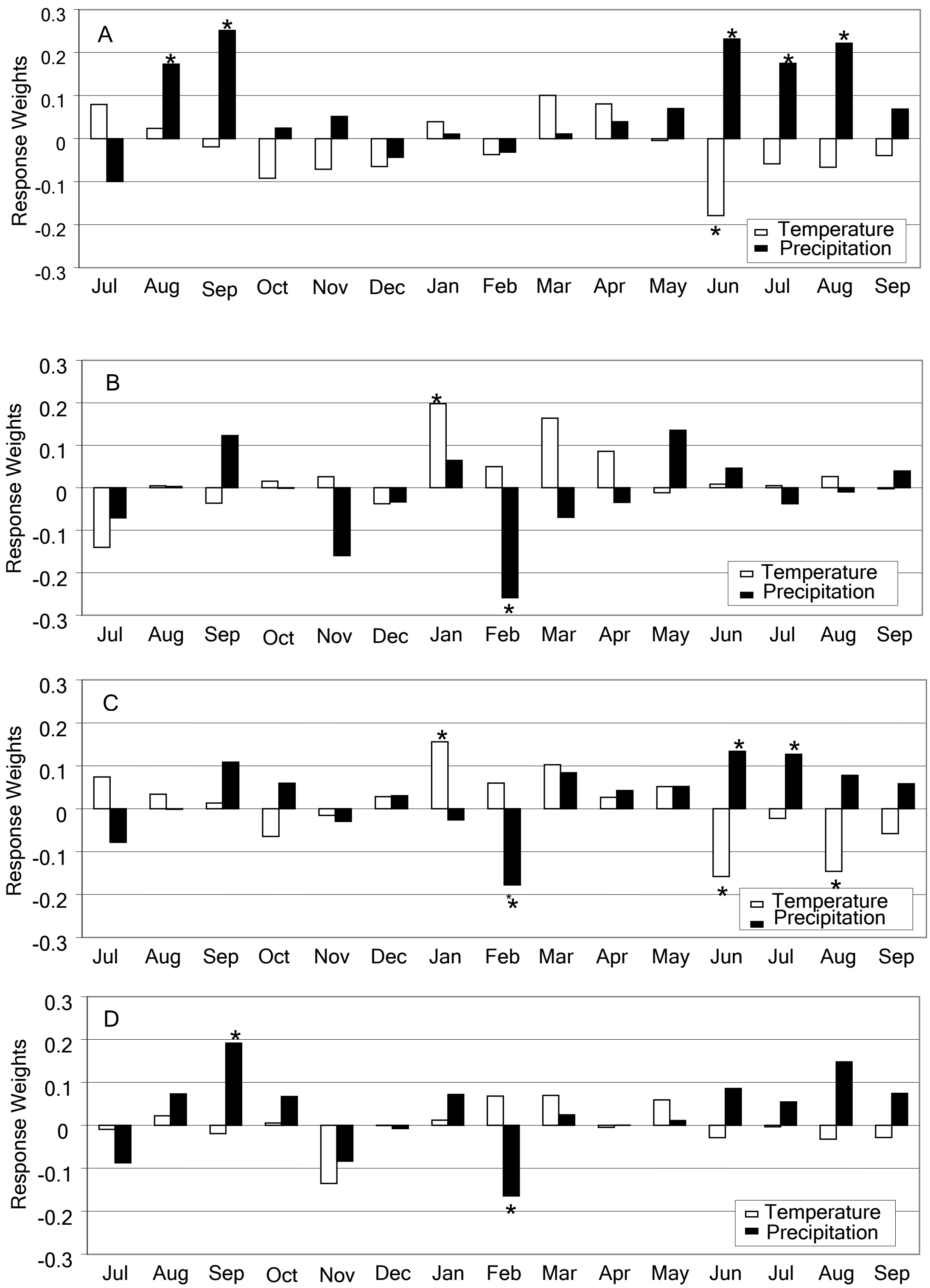

Figure 3.3: Results of response function analysis for North Mountain (A), Brush Mountain (B), Griffith Knob (C), and Little Walker Mountain (D) showing the effects of temperature and precipitation on Table Mountain pine tree growth. Statistically significant relationships are indicated by * ($p < 0.05$).

temperature (Figure 3.4A). Correlation analysis for seasonalized climate variables indicated no significant relationships with temperature. For precipitation, correlation analysis revealed a significant positive relationship with current May through August, with the strongest relationship found during June–July ($r = 0.41$, $p < 0.001$) (Table 3.4).

A statistically significant ($p < 0.05$) positive relationship was also found between the previous October through the current January and the current June through September PHDI and Table Mountain pine growth at North Mountain (Figure 3.5A). The previous September through December and the current June through September PDSI had a significant positive relationship with Table Mountain pine growth (Figure 3.5A). Correlation analysis for seasonalized climate variables showed the strongest relationship exists between July–September PHDI and Table Mountain pine growth at North Mountain during the current growing season ($r = 0.47$, $p < 0.001$) (Table 3.5). I also found significant positive relationships between seasonalized PDSI and tree growth during the previous September–October ($r = 0.45$, $p < 0.001$) and current July through September ($r = 0.46$, $p < 0.001$) (Table 3.5). A significant negative relationship was observed between Table Mountain pine growth at North Mountain and NAO during the previous August and previous December, while a significant positive relationship was found with current February (Figure 3.6A). A significant negative relationship was found between tree growth and the Kaplan indices for the current August (Figure 3.7A). The time series plot for North Mountain (Figure 3.8A) indicated that expected Table Mountain pine growth agreed relatively well with predicted growth, although an extended negative departure (indicating non-climatic growth suppression) was found in the 1980s.

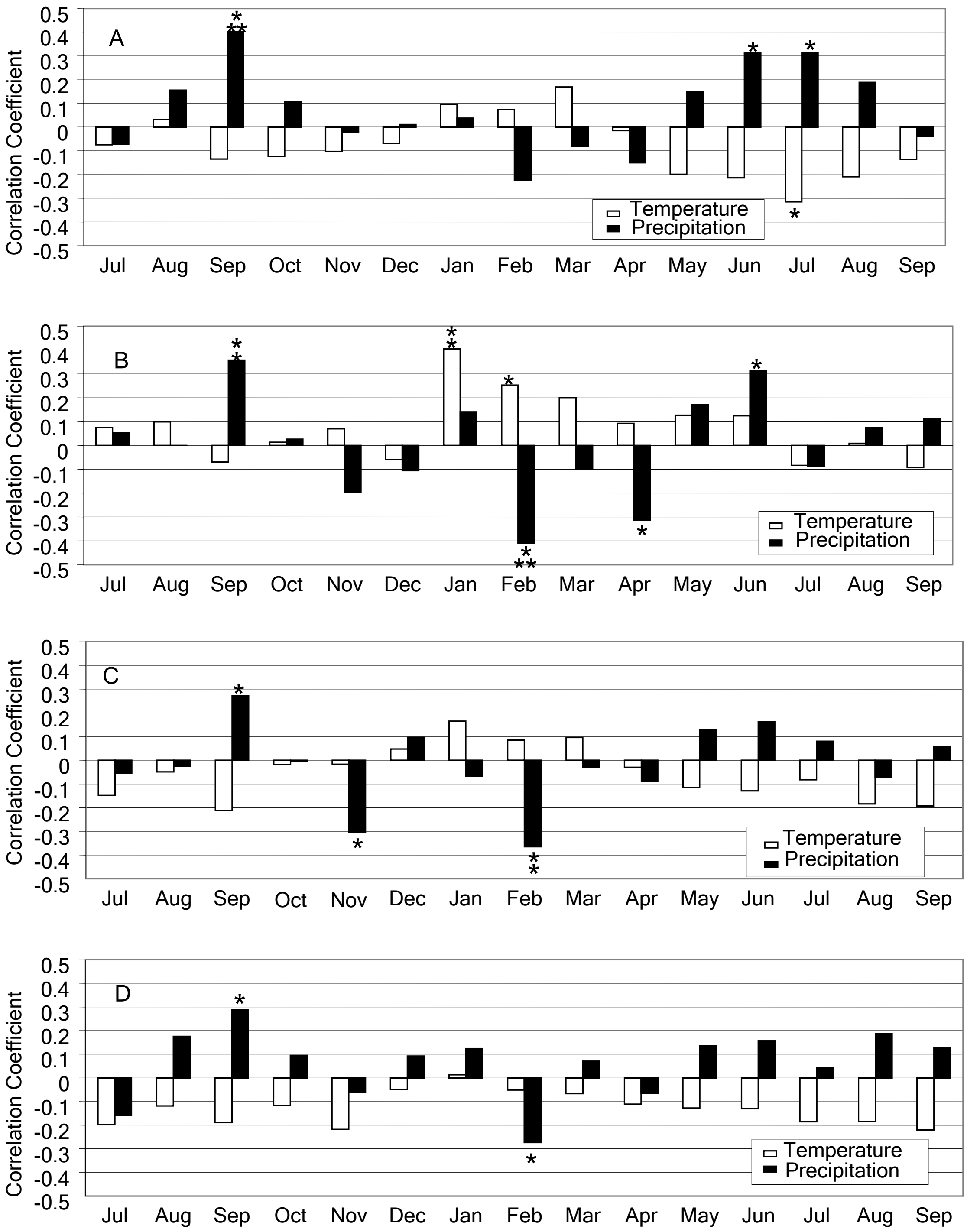

Figure 3.4: Results of correlation analysis for North Mountain (A), Brush Mountain (B), Griffith Knob (C), and Little Walker Mountain (D) comparing precipitation and temperature for the station average and Table Mountain pine tree growth. Statistically significant relationships are indicated by * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$).

Table 3.4: Correlation coefficients between tree-ring indices from North Mountain and seasonalized precipitation indices.

Season	Correlation
May-June	0.30*
May-July	0.39***
May-August	0.39***
June-July	**0.41*****
June-August	0.40***
July-August	0.30*

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

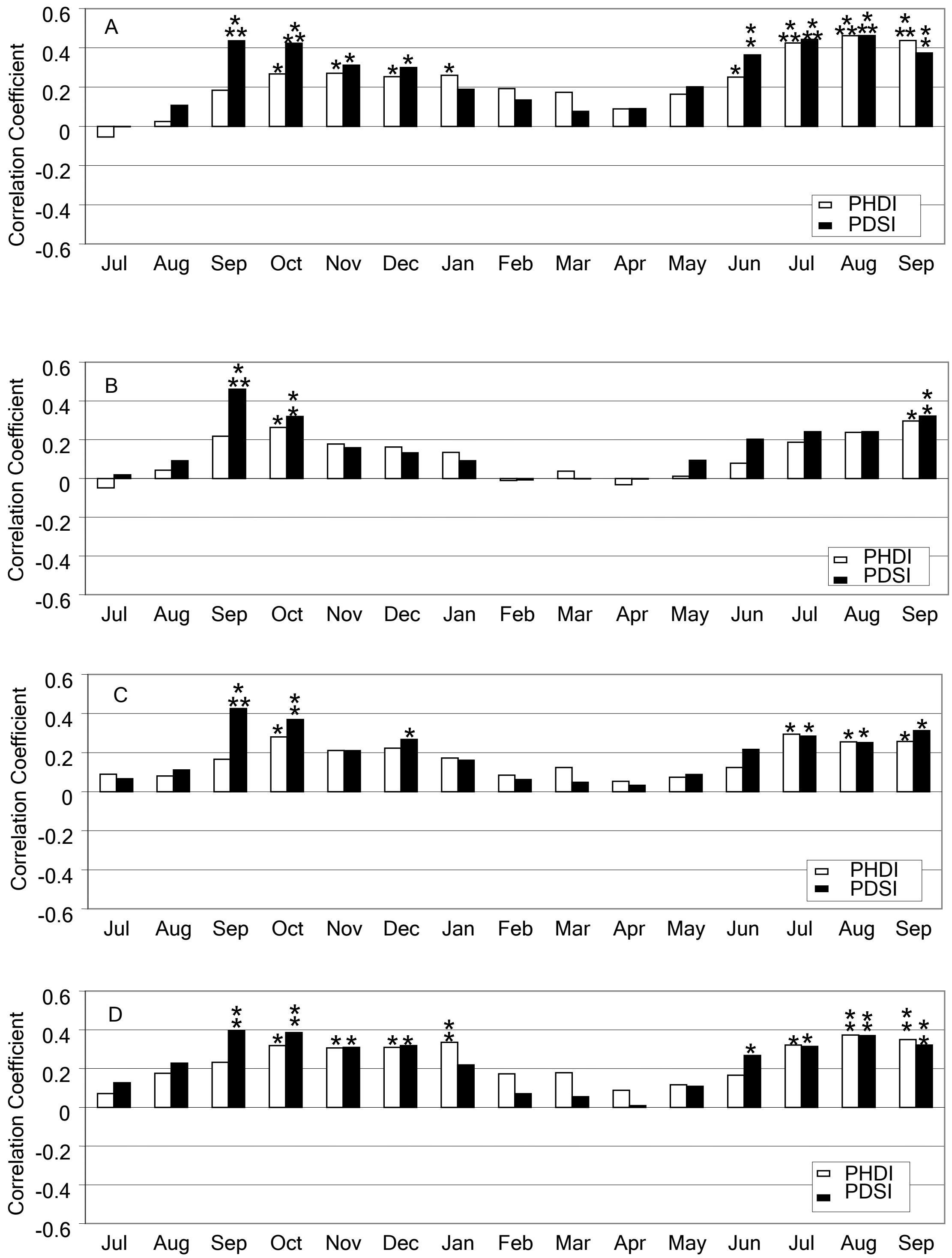

Figure 3.5: Results of correlation analysis for North Mountain (A), Brush Mountain (B), Griffith Knob (C), and Little Walker Mountain (D): PDSI and PHDI correlated against Table Mountain pine tree growth. Statistically significant relationships are indicated by * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$).

Table 3.5: Correlation coefficients between tree-ring indices from North Mountain and seasonalized climate variables.

Season	**Variable**	**Correlation**
May-July	PHDI	0.30*
May-August		0.36**
May-September		0.39**
June-July		0.35**
June-August		0.40***
June-September		0.43***
July-August		0.46***
July-September		**0.47*****
August-September		0.46***
Prev September-October	PDSI	0.45***
Prev September-November		0.42***
May-August		0.40***
May-September		0.42***
June-July		0.41***
June-August		0.44***
June-September		0.45***
July-August		**0.46*****
July-September		**0.46*****
August-September		0.45***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

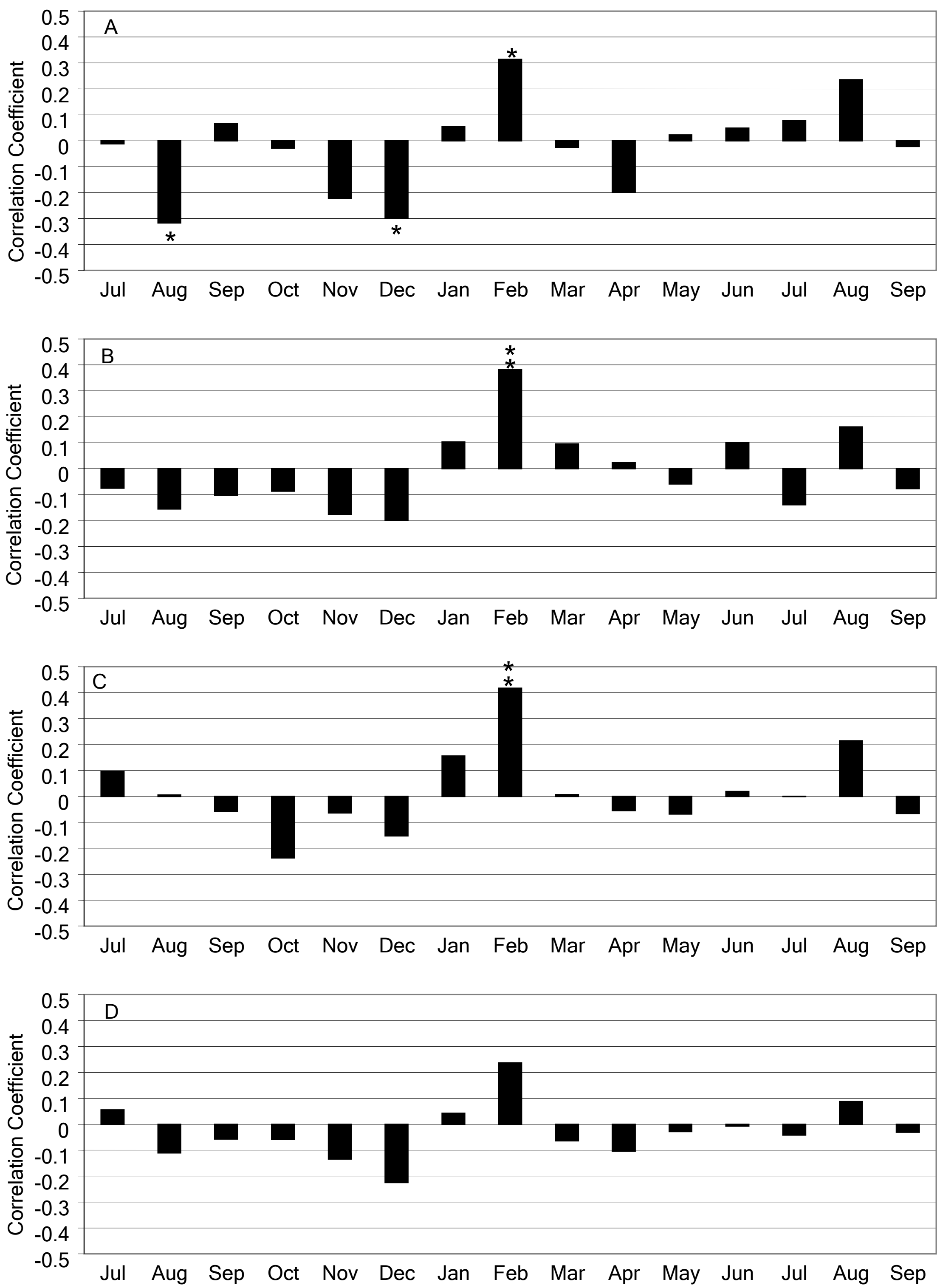

Figure 3.6: Results for correlation analysis of Brush Mountain (A), Griffith Knob (B), Little Walker Mountain (C), and North Mountain (D): NAO correlated against Table Mountain pine tree growth. Statistically significant relationships are indicated by * ($p < 0.05$) and ** ($p < 0.01$).

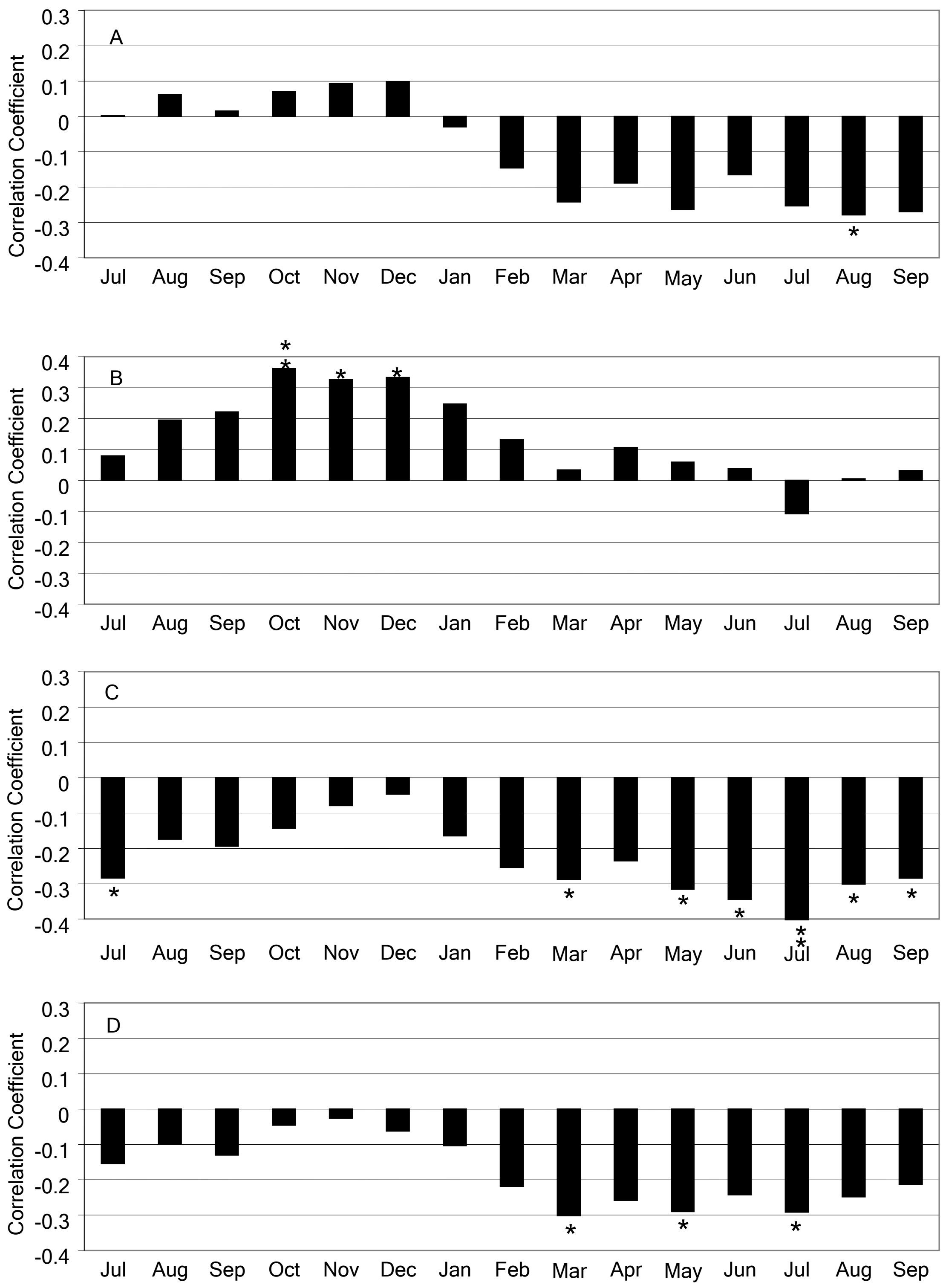

Figure 3.7: Results of correlation analysis for North Mountain (A), Brush Mountain (B), Griffith Knob (C), and Little Walker Mountain (D): Kaplan indices correlated against Table Mountain pine tree growth. Statistically significant relationships are indicated by * ($p < 0.05$) and ** ($p < 0.01$).

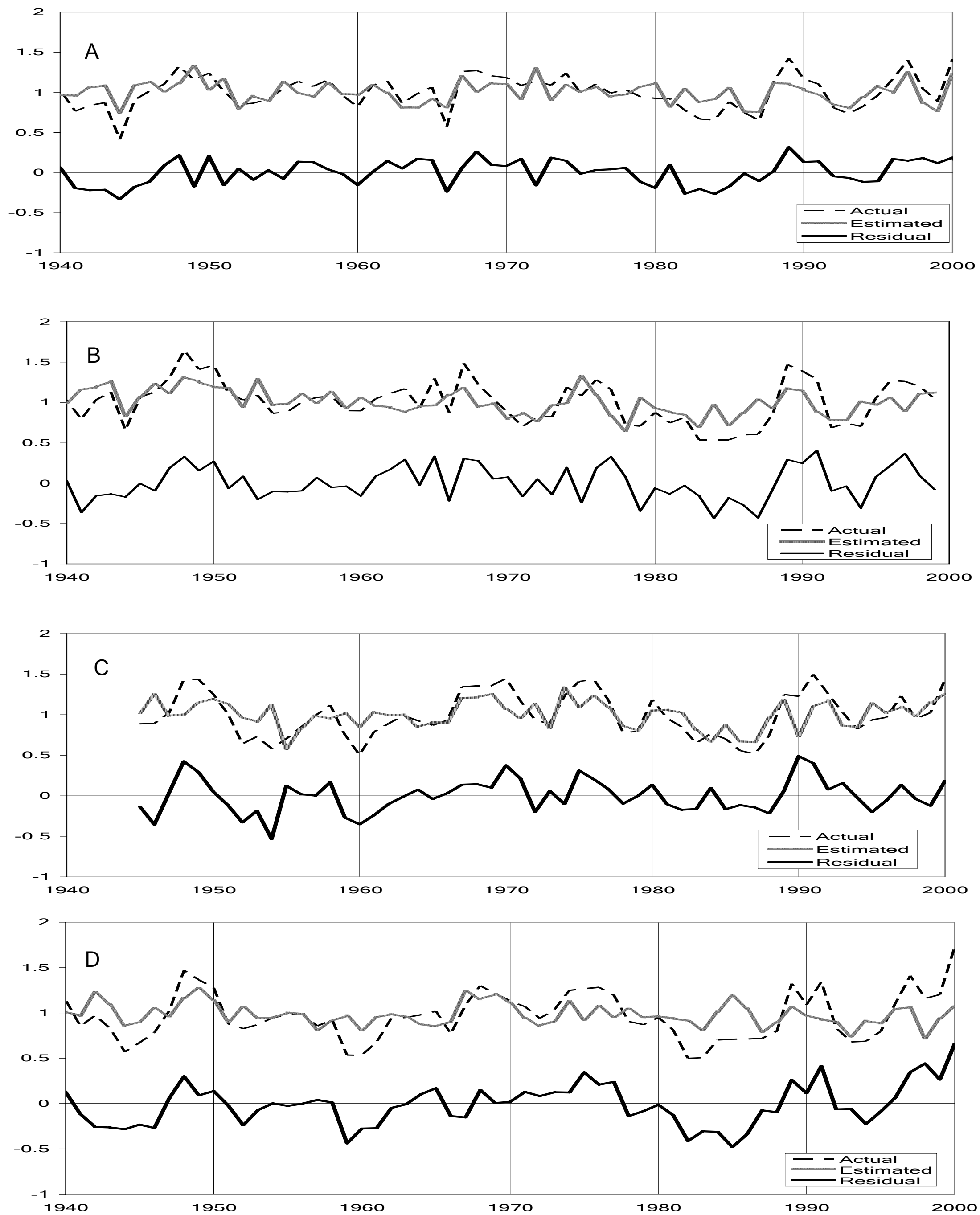

Figure 3.8: Results for North Mountain (A), Brush Mountain (B), Griffith Knob (C), and Little Walker Mountain (D) illustrating those periods in which tree growth was below that expected from the observed climate variables. "Actual" indicates the actual Table Mountain pine tree growth, "estimated" indicates the estimated annual Table Mountain pine tree growth based on the significant climate variables, and "residual" is the difference between the actual and estimated chronologies.

Results for Brush Mountain indicate that climate during the winter season (January–March) is the most influential on cambial growth of Table Mountain pine. Response function analysis for Brush Mountain indicated a positive relationship with January temperature and a significant negative relationship with February precipitation (Figure 3.3B). Correlation analysis for precipitation (Figure 3.4B) indicated a significant positive relationship with previous September and current June and a negative relationship with current February and April.

Temperature during the current January and February have a significant positive effect on Table Mountain pine growth at Brush Mountain. Correlation analysis on seasonalized climate variables at Brush Mountain indicated that the May through June season was the most significant for precipitation ($r = 0.33$, $p < 0.01$), while the January to March season was most significant for temperature ($r = 0.41$, $p < 0.01$) (Table 3.6).

PHDI during the previous October and current September has a significant positive effect on tree growth at Brush Mountain (Figure 3.5B). The previous September, October, and current September PDSI have a significant positive relationship with tree growth. I found no seasonal relationship between tree growth at Brush Mountain and PHDI. However, the previous September–October PDSI had a significant positive relationship with tree growth ($r = 0.41$, $p < 0.001$) (Table 3.7). Table Mountain pine at Brush Mountain had a significant positive relationship with February NAO (Figure 3.6). Correlation analysis also indicated a significant positive relationship between growth and the Kaplan indices from the previous year's October through December (Figure 3.7B). Seasonalized Kaplan indices showed a highly significant positive relationship between tree growth and Atlantic SSTs from the previous October through December ($r = 0.37$, p

Table 3.6: Correlation coefficients between tree-ring indices from Brush Mountain and seasonalized climate variables.

Season	Variable	Correlation
December-January	Temperature	0.26*
December-February		0.32*
December-March		0.35**
January-February		0.39**
January-March		**0.41****
February-March		0.28*
May-June	Precipitation	**0.33****
May-July		0.25*

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3.7: Correlation coefficients between tree-ring indices from Brush Mountain and seasonalized PDSI.

Season	Variable	Correlation
August-September	PDSI	0.30*
August-October		0.32**
August-November		0.29*
September-October		**0.41*****
September-November		0.34**
October-November		0.25*
June-September		0.28*
July-August		0.25*
July-September		0.29*
August-September		0.30*

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

< 0.01) (Table 3.8). The time series plot for Brush Mountain (Figure 3.8B) revealed that the expected Table Mountain pine growth deviated from actual growth beginning in the late 1970s and extending into the 1980s. Two positive departures in the 1990s indicated possible non-climatic growth release events.

Table Mountain pine growth at Griffith Knob is influenced by climate during both winter and summer seasons. Response function analysis revealed a significant negative relationship with the current year's February precipitation and a positive relationship with June and July precipitation. Analysis also indicated a significant positive relationship with the current year's January temperature and a significant negative relationship with current June and August temperature (Figure 3.3C). Correlation analysis indicated a positive relationship with previous September and a negative relationship with previous November and current February precipitation (Figure 3.4C). Unlike the response function analysis, correlation analysis did not reveal any relationship between temperature and Table Mountain pine growth. Because no evidence was found of a relationship over consecutive months for the Griffith Knob chronology, a seasonal climate analyses for precipitation and temperature were not performed.

The PHDI during the previous October and current July–September months has a significant positive relationship with Table Mountain pine growth (Figure 3.5C). When seasonalized, July–September PHDI had the most significant positive relationship with tree growth, but this relationship was not especially strong (Table 3.9). I also found a significant positive relationship between tree growth and PDSI during the previous September, October, and December, as well as the current July through September (Figure 3.5C). The correlation analysis revealed a significant positive relationship

Table 3.8: Correlation coefficients between tree-ring indices from Brush Mountain and seasonalized Kaplan indices.

Season	Correlation
September-October	0.31*
September-November	0.33*
September-December	0.36*
September-January	0.35*
October-November	0.35*
October-December	**0.37****
October-January	0.35*
November-December	0.34*
November-January	0.33*
December-January	0.31*

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 3.9: Correlation coefficients between tree-ring indices from Griffith Knob and seasonalized climate variables.

Season	Variable	Correlation
June-September	PHDI	0.25*
July-August		0.28*
July-September		0.28*
August-September		0.26*
August-September	PDSI	0.29*
August-October		0.33**
August-November		0.32**
August-December		0.32**
August-January		0.30**
September-October		**0.42*****
September-November		0.36**
September-December		0.35**
September-January		0.33**
October-November		0.30**
October-December		0.35**
October-January		0.28*
November-December		0.29*
November-January		0.27*

* p < 0.05, ** p < 0.01, *** p < 0.001

between tree growth and September–October PDSI ($r = 0.42$, $p < 0.001$) (Table 3.9). Current February had a significant positive relationship with NAO (Figure 3.6C). The Kaplan indices showed significant negative relationships with Table Mountain pine growth in the previous July, current March, and current May through September months (Figure 3.7C). Seasonalized Kaplan indices showed a highly significant relationship during June and July ($r = -0.39$, $p < 0.001$) (Table 3.10). The time series plot for Griffith Knob (Figure 3.8C) indicated deviations from expected growth for Table Mountain pine during the late 1940s (positive departure), early 1950s (negative departure), late 1950s–early 1960s (negative departure), and early 1990s (positive departure).

At Little Walker Mountain, Table Mountain pine growth is most significantly influenced by climate during the previous growing season and the current winter season. Response function analysis showed a significant positive relationship with the previous September precipitation and a significant negative relationship with the current February precipitation (Figure 3.3D). The negative relationship with February precipitation appears again in the correlation analysis (Figure 3.4D), as does a significant positive relationship with previous September precipitation. I found no relationship with temperature in either the response function or correlation analysis.

PHDI during the previous October–January and July–September has a significant positive relationship with growth at Little Walker Mountain (Figure 3.5D). PDSI during the previous September–December months and current June–September months also showed a significant positive relationship with Table Mountain pine growth. When seasonalized, the strongest relationships were found for the previous October–January

Table 3.10: Correlation coefficients between tree-ring indices from Griffith Knob and seasonalized Kaplan indices.

Season	**Correlation**
March-May	–0.29*
March-June	–0.32*
March-July	–0.34**
March-August	–0.36**
March-September	–0.36**
April-May	–0.28*
April-June	–0.31*
April-July	–0.36**
April-August	–0.36**
April-September	–0.36**
May-June	–0.34*
May-July	–0.38**
May-August	–0.37**
May-September	–0.37**
June-July	**–0.39****
June-August	–0.37**
June-September	–0.37**
July-August	–0.37**
July-September	–0.36**
August-September	–0.30*

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

PHDI ($r = 0.33$, $p < 0.01$) and previous September–October PDSI ($r = 0.41$, $p < 0.001$) (Table 3.11). I found a negative (though not significant) relationship with December NAO and a positive relationship (also not significant) with February NAO (Figure 3.6D). A significant positive relationship between February NAO and Table Mountain pine growth exists at all of the other sites (Figures 3.6A–C). The Kaplan indices during the current March, May, and July showed a significant negative relationship with tree growth (Figure 3.7D). When seasonalized, the Kaplan indices from March–August showed a statistically significant relationship ($r = -0.31$, $p < 0.05$) (Table 3.12). The time series plot for Little Walker Mountain (Figure 3.8D) indicated deviations from expected growth in Table Mountain pine during the entire period of analysis, especially the large negative departure from 1940–1948, 1958–1963, and 1976–1989, indicating major non-climatic events that caused multi-year growth suppressions.

The results of the correlation analysis between the composite chronology (all four tree-ring chronologies averaged together into one) and precipitation and temperature (Figure 3.9) revealed a significant positive relationship between tree growth and previous September precipitation, a significant negative relationship with February and April precipitation, and a significant relationship with temperature in the previous September and current August months. When seasonalized, a significantly positive relationship was found between June–July precipitation and tree growth, while a negative relationship was found with February–March precipitation, although these relationships were weak (Table 3.13). PHDI from the previous October through current January and again from July through September showed significant positive relationships with Table Mountain pine growth (Figure 3.10). PDSI from previous September–December and current June–

Table 3.11: Correlation coefficients between tree-ring indices from Little Walker Mountain and seasonalized climate variables.

Season	**Variable**	**Correlation**
September-January	PHDI	0.32**
October-November		0.32**
October-December		0.32**
October-January		0.33**
November-January		0.33**
December-January		0.33*
August-September	PDSI	0.37**
August-October		0.37**
August-November		0.38**
August-December		0.38**
September-October		**0.41*** **
September-November		0.39**
September-December		0.39**
September-January		0.37**
October-November		0.36**
October-December		0.36**
October-January		0.34**
June-August		0.33**
June-September		0.35**
July-August		0.35**
July-September		0.37**
August-September		0.37**

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3.12: Correlation coefficients between tree-ring indices from Little Walker Mountain and seasonalized Kaplan indices.

Season	**Correlation**
February-June	–0.29*
February-July	–0.30*
February-August	–0.30*
March-April	–0.29*
March-May	–0.30*
March-June	–0.29*
March-July	**–0.31***
March-August	**–0.31***
April-July	–0.30*
April-August	–0.30*
May-July	–0.29*
May-August	–0.29*

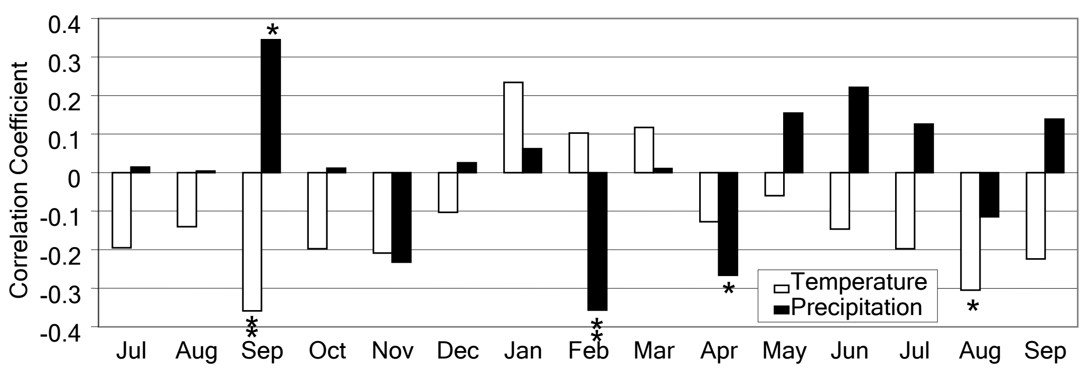

Figure 3.9: Results of correlation analysis for composite chronology, comparing precipitation and temperature Table Mountain pine tree growth. Statistically significant relationships are indicated by * ($p < 0.05$) and ** ($p < 0.01$).

Table 3.13: Correlation coefficients between tree-ring indices from the composite chronology and seasonalized precipitation.

Season	**Correlation**
February-March	–0.24*
February-April	–0.23*
May-July	0.24*
May-August	0.23*
June-July	0.27*
June-August	0.24*

* $p < 0.05$

September also showed significant positive relationships with growth (Figure 3.10). When seasonalized, the strongest relationship was found for PDSI from previous September–October ($r = 0.47$, $p < 0.001$) (Table 3.14). A positive relationship was found between February NAO and tree growth for the composite chronologies (Figure 3.11), a relationship found in all the individual chronologies as well. A significant negative relationship was revealed between growth and July Kaplan indices (Figure 3.12).

3.6 Discussion

3.6.1 Chronology Development and Ring Formation

Interseries correlations were high at all four research sites, with an average of 0.57. All sites had high mean sensitivities and high standard deviations, signifying that necessary variability exists in the tree-ring patterns due to climatic factors to ensure successful crossdating and extraction of the dominant climate signal. The commonality of marker rings across the region further indicates a regional climatic influence. First-order autocorrelation was low at all sites, indicating that the influence of the previous year's growth on the current year's growth was minimal (after Grissino-Mayer 1989). These low values would strengthen interpretations of past climates reconstructed from Table Mountain pine chronologies in this region as the tree ring for any given year reflects current climate and not climate from previous years.

3.6.2 Climate Analyses

Response function analysis for the four sites resulted in slightly different climate signals likely related to differences in elevation, topography, and microclimate at the

Table 3.14: Correlation coefficients between tree-ring indices from the composite chronology and seasonalized PHDI and PDSI.

	Correlation	
Season	**PHDI**	**PDSI**
August-September	NS	0.40**
August-October	NS	0.38**
August-November	NS	0.37**
August-December	NS	0.36**
August-January	NS	0.36**
September-October	0.26*	**0.47*** **
September-November	0.27*	0.42***
September-December	0.27*	0.39**
September-January	0.26*	0.36**
October-November	0.28*	0.35**
October-December	0.27*	0.33**
May-September	NS	0.34**
June-August	0.30*	0.34**
June-September	0.33**	0.37**
July-August	0.35**	0.36**
July-September	0.37**	0.39**
August-September	0.38**	0.40**

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, NS = not significant

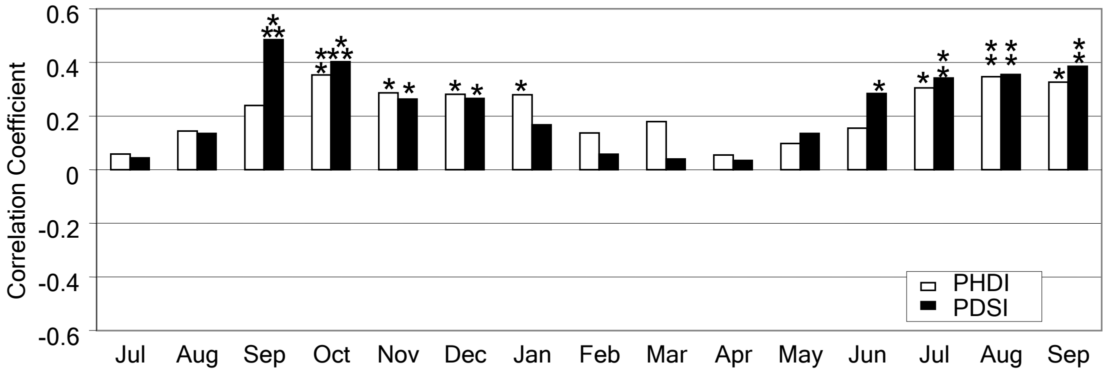

Figure 3.10: Results of correlation analysis for composite chronology: PDSI and PHDI correlated against Table Mountain pine tree growth. Statistically significant relationships are indicated by * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$).

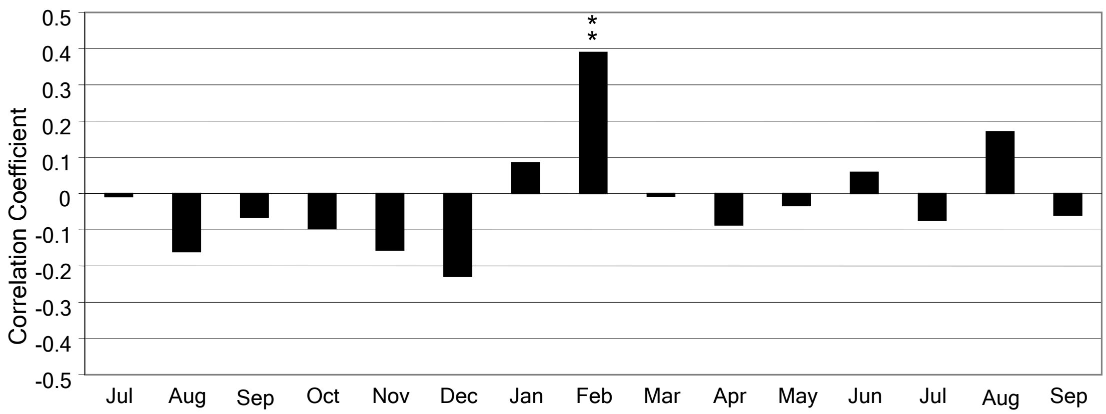

Figure 3.11: Results of correlation analysis of composite chronology: NAO correlated against Table Mountain pine tree growth. Statistically significant relationships are indicated by ** ($p < 0.01$).

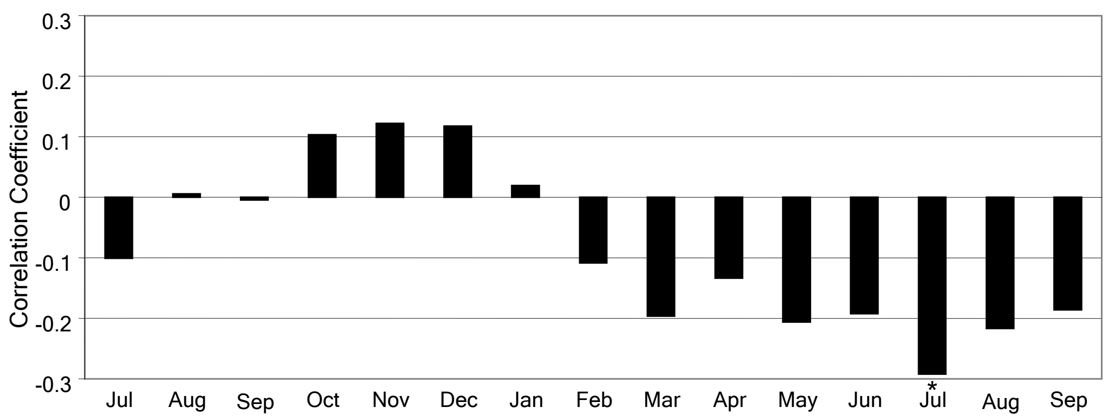

Figure 3.12: Results of correlation analysis for composite chronology: Kaplan indices correlated against Table Mountain pine tree growth. Statistically significant relationships are indicated by * ($p < 0.05$).

sites. In the eastern U.S., climate-response models typically explain 15–40% of the variance in ring-width indices (Travis *et al*. 1989; Travis and Meentemeyer 1991; Grissino-Mayer and Butler 1993; Lafon 2000), because tree growth is less directly tied to moisture availability than in the western U.S. The tree growth data from all sites had at least 21% of the variance explained by climate, which makes these data sets typical of other eastern U.S. sites. North Mountain, however, had 46% of the variance explained by climate, making it a more climatically sensitive site compared to the other research sites.

The synchronization of growth with a particular season does not assure that the amount of growth for that year will be correlated with the climate of that season (Fritts 1976). The climate of the prior growing season (the time when buds are formed) sometimes can exert a significant influence on growth that extends into the period in which the stem is elongating, i.e. in the current growing season (Fritts 1976). The previous growing season is important for carbohydrate uptake and photosynthate production, which explains the influence of climate during the previous year on Table Mountain pine growth, found for all four sites in this study. A wide annual ring generally forms when optimal conditions for photosynthesis occur during the fall of the previous growing season (Fritts 1976). For Table Mountain pine growth at all four research sites, I found a statistically significant positive relationship between Table Mountain pine growth and September precipitation during the previous year. This indicates wet conditions in the previous fall months enhance Table Mountain pine growth in the following growing season. In the case of North Mountain and Little Walker Mountain, the previous August through September precipitation also has a positive relationship with Table Mountain pine growth.

Table Mountain pine may have higher photosynthetic rates during favorable winter days than during hot and dry days of midsummer (Fritts 1966; Zobel 1969). This lengthened photosynthetic season would compensate for limiting conditions on dry, nutrient-poor sites (Zobel 1969) and increase the competitive abilities of Table Mountain pine. The preference of Table Mountain pine for south- and southwest-facing slopes would provide an advantage during winter months and prolong photosynthesis because of increased solar insolation. Conifers can continue photosynthesis on warm winter days and have positive carbon gains when their needles are not frozen (Cabot and Hicks 1982; Havranek and Tranquillini 1995; Pederson *et al*. 2004). This maintenance of foliage during the winter makes conifers more susceptible to needle damage from freezing, snow and ice, and winter desiccation (Pederson *et al*. 2004), which would explain the positive relationship that exists between winter temperature and tree growth at Brush Mountain and Griffith Knob. A warm winter would keep needles frost-free and allow photosynthesis to continue into the spring. Transpiration and photosynthesis can occur as long as needles do not freeze (Havranek and Tranquillini 1995).

At Brush Mountain, Griffith Knob, and Little Walker Mountain, the most significant relationship between climate and Table Mountain pine growth occurs during winter and early spring, i.e. January to April. During this time, Table Mountain pine growth is enhanced by conditions that are warmer and drier than normal. Warm air and soil conditions increase the rate of CO_2 uptake, which in turn increases photosynthesis (Kozlowski and Pallardy 1997) and the root length of Table Mountain pine seedlings (Zobel 1969). However, a wet winter (perhaps in the form of snow) could cause needle damage, a decrease in soil temperatures, and disrupt early photosynthesis, which may explain the inverse relationship between February precipitation and tree growth at Brush Mountain, Griffith Knob, and Little Walker Mountain. Another explanation for the inverse relationship with February precipitation is that Table Mountain pine initiates twig development and flowering earlier than other pines and is therefore more susceptible to frost damage that could be caused by frozen winter precipitation (Zobel 1969).

Winter temperatures may not have a significant relationship with pine growth at North Mountain because it is the lowest in elevation of the four sites (North Mountain 670–760 m, Little Walker Mountain 800–920 m, Brush Mountain 850–900 m and Griffith Knob 1100–1150 m) and so experiences warmer winter temperatures. Photosynthesis during the winter dormant season is critical for Table Mountain pine growing on nutrient-poor sites (Zobel 1969). These results suggest that the North Mountain sites may be more fertile sites because of the lack of a significant relationship between climate during the winter and early spring season and Table Mountain pine growth.

The significant relationships found between pine growth and dry February and warm January–February at Brush Mountain and Griffith Knob, and dry February at Little Walker Mountain, can be attributed in part to the relationship between Table Mountain pine and ectomycorrhizal fungi. Conifers are able to exist in warm climates, where better competitors exist, because of their association with ectomycorrhizal fungi. These fungi allow host conifers to obtain nutrients from sources normally unavailable to the pines (Havranek and Tranquillini 1995). When spring begins, ectomycorrhizae develop a strong carbohydrate sink in return for nutrients (Teskey *et al*. 1994; Woodward 1995), which stimulates photosynthesis in conifers (Dosskey *et al*. 1990; Woodward 1995). The abundance of the fungi is greatest when soils are dry because ectomycorrhizae lack competitive abilities in moist soils. During dry summers, populations can increase 10-fold (Walker and Oswald 2000). A dry winter would therefore increase ectomycorrhizae development, enhancing Table Mountain pine growth during the early portion of the growth season.

The third explanation for the significant relationship with a warm and dry winter is the influence of competition from oaks that also grow in the stands. In many gymnosperms, it has been proven that phloem production begins several weeks before xylem production (Evert 1963; Davis and Evert 1965; Alfieri and Evert 1968; Kozlowski and Pallardy 1997). Therefore, a dry and warm winter could stimulate the pines to break dormancy earlier, thus resulting in enhanced pine growth for that year.

At North Mountain, temperature does not become a significant influence until late spring and summer, when there is an inverse relationship with Table Mountain pine tree growth. High root temperatures during the summer can reduce photosynthesis (Kozlowski and Pallardy 1997), which may explain the significance of summer temperature at North Mountain and Griffith Knob. This is likely the case at North Mountain because lower elevation sites have higher humidity and temperatures during the summer months, plus soils at North Mountain are heavily insulated and may retain heat. This same trend is seen at Griffith Knob, which is likely because it is the highest in elevation and is the most exposed site. This relationship suggests cool summer temperatures enhance tree growth, while hot summer temperatures will cause lower than average tree growth, particularly at the extreme elevational limits of Table Mountain pine.

I found no positive relationship between Table Mountain pine growth at Little Walker Mountain and temperature. This is likely because the study sites at Little Walker Mountain were located on the sheltered side of the mountain adjacent to the Little Walker Creek Valley. Because these sites were located on the northern face of Little Walker Mountain, I can assume that the Table Mountain pine populations were mainly propagated by anthropogenic burning. The Table Mountain pines on Little Walker Mountain are not as old as the ones located at other sites; in fact, most pines at this site date only to the mid-19th century. This would have been an era of increasing human landscape alteration. Frequent burning on northern slopes can increase Table Mountain pine populations at the expense of the more mesic hardwoods that generally dominate the aspect.

PHDI and PDSI both showed significantly positive relationships with both the previous and current growing seasons at all sites. This suggests that climatic conditions during the growing season would need to be wet and cool for favorable growth. The current February showed a positive relationship with Table Mountain pine growth at all sites. Enhanced Table Mountain pine growth is dependent upon a warm, dry February and it is possible that climatic conditions associated with a positive phase of the NAO include such favorable conditions. Analyses of the Kaplan indices indicated a positive relationship between AMO during the previous October–December and Table Mountain pine growth at Brush Mountain. However, a significant negative relationship was found between pine growth at the other sites and AMO in the current growing season. Despite these differences in the correlations between the Brush Mountain results and those found for the other three sites, the pattern of the correlations over time is similar, but the pattern for Brush Mountain appears to simply peak earlier in the previous fall. This curious relationship between Brush Mountain and north Atlantic sea surface temperatures cannot be explained by these analyses.

The lack of synchronization between the expected and actual climate response in the time series plots, particularly at Little Walker Mountain, is most likely due to ice storm damage. The location of the Little Walker Mountain sites on a northern mountain face and the high elevation of the Griffith Knob sites would make Table Mountain pines at these sites more prone to ice storm damage. The time series plot for Brush Mountain indicated Table Mountain pine growth had fallen short of expected tree growth beginning in the 1980s. This is likely due to two factors, the first being the increase in senescence of existing Table Mountain pines, which are in decline and not being replaced by a new generation. The second reason is the increase in ice storms in the region during the late 1970s and early 1980s, which have a negative influence on Table Mountain pine tree growth, i.e. growth suppression. This departure from expected growth during the late 1970s into the 1980s is seen at all sites and is interpreted here as an indication of the regional influence of ice storms.

When relationships were explored between precipitation and temperature and the composite chronology, similar results were found as with the individual sites. A significantly dry February and April and wet September, as well as cooler conditions during the previous September and current August at all sites, indicate a regional climate influence. Significant positive relationships between PHDI and PDSI during the previous and current year and tree growth illustrate the influence of precipitation on Table Mountain pine growth. Because this species is prolific in areas where it has no access to the water table, growing season precipitation is the most important factor in its growth. The positive relationship between February NAO and the composite chronology is related to the influence of NAO on regional precipitation. The significant negative relationship between July Kaplan (AMO) indices and Table Mountain pine growth in the composite chronology is again likely due to the influence of the North Atlantic on Appalachian weather systems.

3.7 Conclusions

Based on the analysis of ring formation and the high quality of crossdating, Table Mountain pine would be an ideal species for climate reconstruction. Table Mountain pine adds only one ring per year, with the exception of a small percentage (between 0.02 and 0.70%) of false rings. Results of the correlation analyses and response function analyses are site specific and must therefore depend on elevation, local climate, and topography. Tree growth was highly correlated with precipitation and to a lesser extent temperature during the period analyzed. In the past, scientists have considered the application of dendrochronology limited in the southeastern U.S. where water is not considered to be a limiting factor (Phipps 1980). The eastern deciduous forest has largely been ignored for dendroecological analyses because forests in this region have been considered too complex for dendrochronological studies, with too many non-climatic factors (e.g., ice storms and insect damage) affecting tree growth (Phipps 1980). However, the results from this study indicate that precipitation is a limiting factor, and to a lesser extent temperature, at higher elevation sites with well-drained soils.

Another important finding of this research is the overall significance of PDSI on Table Mountain pine tree growth. If a climate reconstruction were conducted, PDSI would be the optimal index for central Virginia Table Mountain pine. The significance of PDSI in Table Mountain pine forests was previously identified by Sutherland *et al*. (1995) and this index has also been shown to be important in numerous western forest types (*e.g*., Cook *et al*. 1999, Pohl *et al*. 2002, Sheppard *et al*. 2002, Taylor and Beatty 2005). Drought preconditions fuels which is known to increase wildfire occurrence in the western U.S. The relationship between drought and fire occurrence is less well understood in eastern forests. However, the relationship between PDSI and fire occurrence in Table Mountain pine stands illustrated here provides insight into the role of drought and preconditioning in the eastern U.S. This is an important finding because with climate change, fire/climate relationships are expected to change. To understand past, current, and future fire/climate relationships, PDSI should be used in analyses of eastern yellow pine forests.

The importance of the North Atlantic Ocean on Appalachian weather systems and Table Mountain pine growth were confirmed through the NAO and the Kaplan indices at all sites. This implies that certain large-scale climatic events occurring in the North Atlantic impact regional Table Mountain pine growth: however, small-scale environmental differences, such as topography, competition, and seasonal variations in temperature and precipitation, also impact Table Mountain pine growth.

CHAPTER 4

FIRE REGIMES IN XERIC YELLOW PINE STANDS OF THE JEFFERSON NATIONAL FOREST, VIRGINIA, U.S.A.

Portions of the Introduction about Table Mountain pine ecology and fire regimes were taken from Chapter 1 of this dissertation. This chapter purposely omits detailed site information, which can be found in Chapter 2, portions of which will be included in any future publication. The use of “we” in this chapter refers to the many volunteers that helped conduct field work. These persons are listed in the Acknowledgements section of this dissertation. This research topic was originally formulated by Dr. Henri Grissino-Mayer, Dr. Charles Lafon, and Dr. Elaine Kennedy Sutherland. Dr. Grissino-Mayer assisted in the identification of relevant literature, location of sample sites, field collection, verifying the accuracy of dated samples, and review of this chapter. Dr. Lafon and Dr. Sutherland assisted in the location of sample sites and field collection. My contributions to this chapter include field collection, processing and dating of all samples, chronology development, conducting all analyses, and interpretation of results.

4.1 Introduction

Fire is the only pre-human disturbance that occurred with sufficient frequency and intensity in most climatic zones to be a consistent and strong selective pressure that influenced the evolution, distribution, and diffusion of pines (Keeley and Zedler 1998). The role of fire is apparent through the physiological adaptations of pines to fire, which include thick bark, cone serotiny, rapid development, and vegetative reproduction (Agee 1998). Fires not only facilitate regeneration and maintenance of yellow pine stands

(Zobel 1969; Williams 1998), but also prolong pine dominance in the forests of the southern and central Appalachian Mountains (Farrar 1998). In such humid climates, pines are poor competitors against hardwoods in seedling establishment, height growth, and reproduction, and therefore depend upon areas that have been disturbed by fire, areas with extreme climates, or areas that have nutrient shortages where hardwoods cannot compete (Bond 1989; Millar 1998).

Table Mountain pine, the yellow pine of principal interest, has a discontinuous distribution on xeric ridgetops on south- and southwest-facing slopes of the Appalachian Mountains from Georgia to Pennsylvania (Zobel 1969). Table Mountain pine is not restricted to xeric ridgetops, however, but is found where it competes successfully, including sites at lower elevations that have a history of burning (Illick 1928, Zobel 1969). The species is an Appalachian endemic that contributes to landscape diversity, and serves as a food source for many Appalachian wildlife species. Xeric oak-Table Mountain pine stands also help prevent erosion and promote forest regeneration after major fire events. Disturbance events and processes (such as farming, clearing, grazing, logging, mass wasting events, and wildfires) provide the needed site preparation for the regeneration of other Appalachian yellow pines (pitch, Virginia, and shortleaf pine), but wildfire is preferable for Table Mountain pine regeneration (Sanders 1992). Fire is needed to prepare seedbeds, open serotinous cones, eliminate hardwood competition, and open the canopy to ensure light can penetrate to the forest floor.

Fire ecologists and forest researchers predict that fire-intolerant species will eventually dominate and choke traditional southern pine sites unless fire is restored to these ecosystems (Farrar 1998, Brose 2001). This would decrease the aesthetic value of these forests, put a strain on plant and animal species dependent on xeric oak-pine communities, and increase the likelihood of catastrophic fires, mudslides, property loss, and potentially the loss of human life. This research will offer the data necessary for forest managers to reintroduce fire to yellow pine stands for the purpose of maintaining them in a healthy state.

The reintroduction of fire into wildlands, and predicting the behavior of those introduced fires, requires information on past fire regimes including fire frequency, seasonality, and the spatial characteristics of the fires (Swetnam *et al*. 1999; Grissino-Mayer *et al*. 2004). To gain a more precise understanding of historic fire regimes in pine stands, dendrochronological dating of fire scars on living trees, dead snags, cut stumps, and downed logs can be used. Fire history studies based on fire scars can provide information on the frequency and seasonality of past fires, and to some extent the spatial extent of past fires, but not how past fires affected vegetation (*i.e*., fire severity). Analyses on age structure and current stand composition (including the understory) are needed to help clarify the general effects of fire on stand development in an area (Sutherland *et al*. 1995). Fire history information, combined with age-structure analysis, can document the current composition of yellow pine populations, their relationships with past fire, and their prognosis for survival under the current fire regime.

Decades of successful fire suppression have resulted in important ecological changes in southeastern forests. In forests once dominated by fire-tolerant species, fire-intolerant species have established (Mutch 1994; Hesseln 2001), growing to size classes that make them resist fire damage because of thicker bark associated with age (Van Lear 1990). Fire suppression halts pine recruitment, stagnates pine stands (Hartnett and Krofta

1989), rapidly erodes the genetic diversity of pines, and increases outbreaks of southern pine beetle and the Table Mountain pine cone worm (*Dioryctria yatesi* Mutuura and Munroe) (USDA 1990; Gray 2001). Historically, fire was less impeded spatially by landscape fragmentation with fires spreading over large areas during drought years (Lafon *et al*. 2005).

4.2 Research Questions

Specific questions addressed by this chapter include:

1) Are fire scars on Table Mountain pines dateable and yield fire-return intervals similar to or shorter than those reported by Sutherland *et al*. (1995) of 10 years?
2) Will the majority of fires will be dormant-season fires? The majority of historical fires occurred in the fall after the growing season or late winter before the growing season.
3) Do age-structure and stand composition data indicate fire events not recorded by fire scars, and can such data help evaluate the overall successional status of the existing Table Mountain pine stands?
4) Will fire-intolerant species dominate the mid- and understories of Table Mountain pine stands?

4.3 Objectives

Scientific literature supports the hypothesis that natural disturbance is fundamental to the development of structure and function in forested ecosystems and therefore management of these ecosystems should be based on an ecological understanding of the processes of these natural disturbances (Attiwill 1994). Management agencies require information on disturbances, especially past fire regimes, which includes assessments of fire frequency, spatial extent, fire seasonality, and the response of fire to climatic factors (Swetnam *et al*. 1999; Grissino-Mayer *et al*. 2004). To reconstruct historic fire regimes in pine stands, dendrochronological dating of fire scars on fire-scarred trees, snags, stumps, and logs can be used. In addition to the fire dates, the frequency and seasonality of past fires can also be determined. The main objective of this research is to use fire-scarred Table Mountain pines collected from the central Appalachian Mountains of Virginia to determine the fire regimes of these stands. The overall health of the existing Table Mountain pine stands will be evaluated using age-structure and stand composition analyses of the overstory, midstory, and understory trees.

4.4 Methods

4.4.1 Field Methods

In the eastern U.S., dendroecological investigations are limited because of the prevalence of second- and third-growth forest and because of a long history of human disturbance. This makes it necessary to use remnant materials and seek out areas that were not logged, farmed, grazed, or urbanized to analyze the historic fire history of an area. Evidence of past fire events is lost over time and to current management strategies, such as prescribed burning (Allen 1994). For this reason, sites with minimal active management were selected to obtain the necessary materials.

Aerial photos taken during winter months in leaf-off conditions were used to distinguish between hardwood-dominated and pine-dominated stands and to help locate sampling sites. Forest Service personnel were also consulted to locate yellow pine sites with minimal human disturbance. Table Mountain pine was not favored by the lumber industry due to its poor form and short trunk with copious limbs (Walker and Oswald 2000), therefore allowing numerous living and remnant Table Mountain pine to be found. Another advantage to using Table Mountain pine for fire history studies is the species' inclination to repeated scarring. Cross-sections were collected according to Arno and Sneck (1977) and Baisan and Swetnam (1990). These cross-sections were removed from living trees, snags, stumps, and remnant logs. In most cases, these cross-sections were scarred by fire, although some older remnant samples without fire scars were collected for chronology development.

Before the 20th century, fires were rarely suppressed and generally burned in a patchy pattern depending on weather and fuel conditions. These fires would have scarred trees sporadically (Arno and Petersen 1983). This necessitates heavy collection to ensure that all fires are accounted for and to determine how patchy or widespread a fire was in a given year. We collected cross-sections from yellow pines on four ridges at each of the four research sites (Table 3.1). From each fire history plot (16 total), an average of 19 cross-sections were collected from yellow pines, mostly Table Mountain pine. Two fire history plots at Brush Mountain previously collected by Sutherland *et al*. (1995) were also used in this project.

Three age-structure plots were established at each site (12 total) to determine forest successional dynamics in the overstory of these yellow pine stands and also evaluate the health of the stands based on their mid- and understories. Plots measured 50 x 20 m (hereafter referred to as a "macroplot"). In each macroplot, all canopy tree species that measured > 5 cm diameter at breast height (1.4 m) were measured, inventoried, and cored. Using an increment borer placed < 30 cm above ground level, we extracted two cores at the base of the tree trunk parallel to the slope contour. Radial growth response can differ from radius to radius within the same tree (Fritts 1976; Cleaveland 1980), which necessitates coring through the entire bole or taking two cores that together represent the diameter of the tree.

To help develop a tree-ring chronology for dating purposes, and to ensure an adequate sample size was obtained for assessing pine age structure, at least 40 yellow pines (mostly Table Mountain pines, but also a few pitch pines and Virginia pines) were cored at each macroplot. At some sites, this required moving outside of the macroplot to collect cores from haphazardly selected yellow pines. These pine cores were used strictly for chronology development and for assessing pine age structure, and were not included in age-structure and stand composition analyses of the individual macroplots.

All trees that represented canopy species that were > 5cm dbh were measured, inventoried, and cored. Canopy species < 5 cm dbh and > 1m in height (saplings) were measured and inventoried, but not cored. To estimate the ages of yellow pine saplings, we counted the branch nodes seen on the main stem. This method has been used effectively to determine the age of Table Mountain pines too small to core (*e.g.,* Williams and Johnson 1990 and Pfeffer 2005). Canopy species less than 1 m in height were classified as seedlings and were inventoried in one randomly selected 10 x 20 m subplot within the larger macroplot. All cores were placed in labeled paper straws for safe storage during transport back to the laboratory.

The depth of the uppermost litter and duff layers of soil plays an important role in the successful regeneration of Table Mountain pine seedlings. Waldrop *et al*. (1999) found that fires that result in moderate shade conditions and a duff thickness of 7.5 cm (3 in) in the seedbed resulted in the maximum pine recruitment. Mohr *et al*. (2002) also found that moderate shade conditions were needed for pine recruitment and that seedlings could penetrate up to 10 cm (4 in) of duff. Preliminary studies conducted in the Great Smoky National Park indicate that a duff layer deeper than 3 cm (1.2 in) greatly reduces pine recruitment after fire events (Rob Klein, *personal communication*). In each macroplot, 20 haphazardly selected points were sampled to determine their duff depth. Duff was measured by inserting a sharp, thin, non-flexible steel rod through the duff and litter until the rod struck mineral soil. The depth was then recorded by measuring off the steel rod.

4.4.2 Laboratory Methods

<u>4.4.2.1 Sample Preparation</u>

Once dry, all increment cores were carefully extracted from the paper straws and mounted on wooden core mounts (Stokes and Smiley 1996). Cross-sections were frozen for 24 hours at –40 °F and then dried. All of the increment cores and cross-sections were sanded with a belt sander beginning with ANSI 40-grit (500–595μm) sanding belts and progressively using finer grade belts, until eventually we used ANSI 400-grit (20.6–23.6 μm) to polish the wood surface and ensure maximum ring definition (Orvis and Grissino-Mayer 2002). We began the crossdating process by marking the first complete ring formed in the tree as ring “0” and then dotted every tenth ring on all series with appropriate dots (1 dot for decade rings, 2 dots for every 50th ring of a century, 3 dots for the century ring, and 4 dots for the millennium ring). Marker rings were visually identified and recorded to aid in the crossdating process (Stokes and Smiley 1996).

4.4.2.2 Crossdating

Crossdating is especially necessary for fire history studies because small errors in dating fire events can result in the overestimation of fire frequency for a site (Stokes 1980; Lorimer 1985). Graphical (skeleton plots) and statistical (COFECHA) crossdating techniques were used to date all samples. Increment cores were crossdated graphically using skeleton plots and verified statistically using COFECHA software (Holmes 1983; Grissino-Mayer 2001a). The tree rings on all increment cores and cross-sections were measured to the nearest 0.001 mm using a Velmex measuring system interfaced with Measure J2X measurement software. COFECHA is a computer program used as a tool by dendrochronologists to gauge the quality of crossdating and measurement accuracy of and between tree-ring series (Grissino-Mayer 2001a). Series were analyzed using 40-year segments lagged successively by 20 years. For this segment length, the critical correlation coefficient needed for statistical significance at the 99% confidence level is 0.37. Segments of series that fell below this critical value were flagged by COFECHA to be re-inspected for crossdating accuracy. Often, these flagged segments occurred in the interior rings of the full measurement series due to erratic ring patterns that could have arisen due to local disturbances (such as windthrow). Because the segments on either side of these flagged segments were crossdated accurately, these segments had to be retained in the final analyses, although their influence on crossdating quality was diminished due to the large number of samples collected at each site (Grissino-Mayer 2001a).

Cores extracted at or close to the tree base often approximate the true age of the tree; I therefore did not use adjusted tree ages (Kulakowski and Veblen 2002). Standard pith estimators were used to estimate the number of years missing between the innermost curved ring on the core and the tree pith for cores that did not intersect with the pith (Applequist 1958; Armbrister 2002).

The tree rings on all cross-sections were dated visually initially using known marker rings and by using tree-ring chronologies developed from the increment cores. The rings on the cross-sections were then measured along a radius that did not intersect a fire scar to avoid the erratic growth patterns that sometimes can be associated with the fire wound. After the rings on a cross-section were dated, the ring-width measurements were added to the previously dated measurements from other series for that site. Not all collected increment cores and cross-sections were used in chronology development because of irregular growth patterns that occasionally caused correlation coefficients for particular segments to fall below the critical value of 0.37.

4.4.2.3 Dating Fire Events

After the tree rings from all fire-scarred cross sections were crossdated, calendar years were assigned to all fire scars. In addition, the seasonality of fires was determined by recording the intraannual position of the scar within the tree ring (Dieterich and Swetnam 1984; Baisan and Swetnam 1990; Grissino-Mayer *et al*. 2004). Bar graphs of the seasonality of fire events may show temporal shifts in fire season, and these shifts could be linked to human settlement in a region (Seklecki *et al*. 1996; Lewis 2003; Grissino-Mayer *et al*. 2004).

The seasonality of fire events is a critical component of the fire regime because managers can use this information in the development of prescribed fire plans in order to mimic the effects of past fires (Lewis 2003). We used the five categories of fire seasonality established by previous studies: dormant, early-early season, middle-early season, late-early season, and late season. Dormant season fires are located between the latewood of the previous ring and the earlywood of the following ring (Figure 4.1). This means the fire could have taken place in one of two years. In Virginia, however, most dormant season fires occur between February and April (Sutherland *et al*. 1995) and therefore the fire scars can be attributed to the current year, i.e. the earlywood of the following ring. Early-early season fire scars occur in the first third of the earlywood, while middle-early season fire scars occur in the middle third of the earlywood. Late-early season fire scars occur in the last third of the earlywood, while late season fire scars occur in the latewood portion of the tree ring (Baisan and Swetnam 1990; Grissino-Mayer 1995).

In this study, it was impossible to assign particular months during the growing season to particular fire scars as has been done in studies conducted in the western U.S. (Grissino-Mayer 1995, Grissino-Mayer *et al*. 2004), because no specific research has been conducted on the phenology of Table Mountain pine to determine the exact time of cambial growth. To complicate this type of analysis, the length of the growing season can vary depending on the site. We therefore chose to provide fire season information based only on the intraannual position of the fire scars.

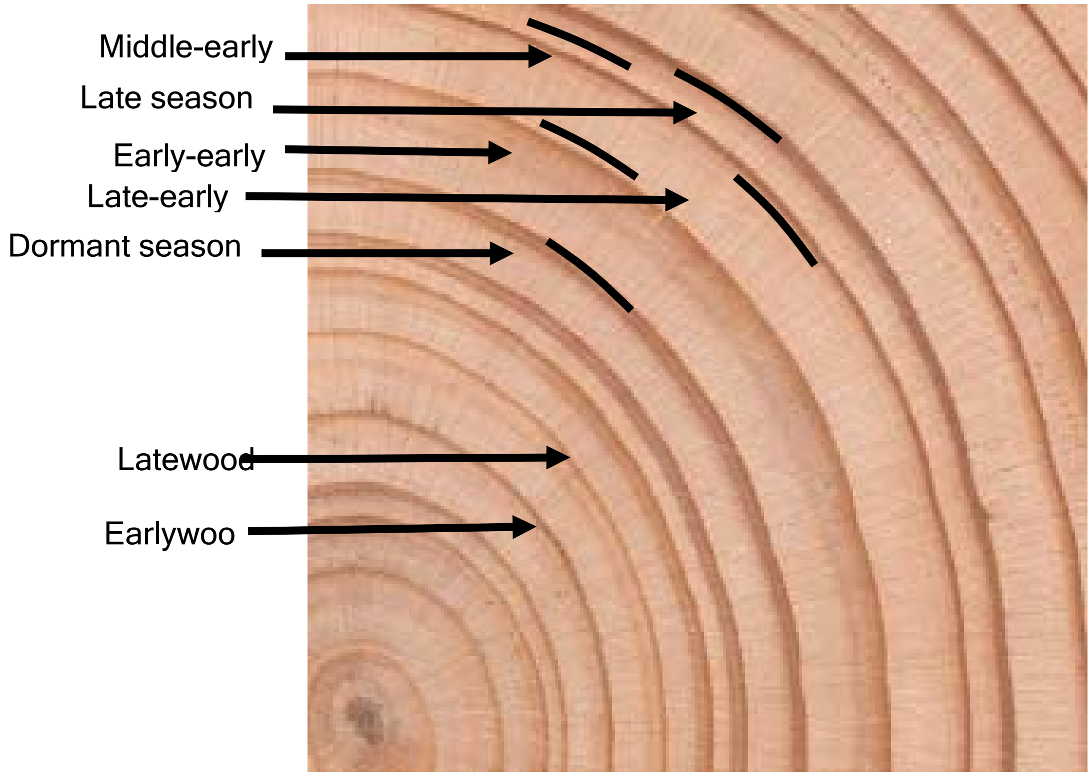

Figure 4.1: Illustration of fire seasons on a fire-scarred cross-section. Fire seasons include dormant season, early-early season, mid-early season, late-early season, and late season fires.

4.4.2.4 Statistics of the Fire Regime

To ensure the calculation of statistical properties of the fire regimes were robust, the periods of recorder and non-recorder years were also recorded on each sample. Recorder years are tree rings that are non-eroded and intact that form after the initial fire scar and contain or have the potential to record later fire events (Grissino-Mayer *et al*. 2004). Non-recorder years precede the first fire scar or are those areas of the cross-section that are too eroded or otherwise damaged to provide fire data (Grissino-Mayer 2004). All statistical analyses were preformed over segments of recorder years. All information regarding the fire-scarred samples (fire-scar date, season of fire, and inner ring/pith and outer ring/bark dates, recorder/non-recorder years of the sample) were input into FHX2 software (Grissino-Mayer 2001b) to create fire charts, generate descriptive statistics, and conduct statistical analyses. Statistical analyses were conducted over a period that began with the first year in which a fire scarred a minimum of two of our fire-scarred samples for the 10%-scarred class and a minimum of one for the all-scarred class, and ended on the year that the Jefferson National Forest was established, 1934. This period is called the "period of reliability" (Touchan and Swetnam 1995; Grissino-Mayer 1995) and is considered by fire ecologists as the period deemed suitable for statistical analyses of fire regimes at a particular site (Wong *et al*. 2004; Gonzalez *et al*. 2005; Arabas *et al*. 2006).

Statistics used to analyze the historical range of variability of fire regimes fall into three general categories (Grissino-Mayer 1995, 2001b). The first includes measures of central tendency. The mean fire interval (MFI) is the average of all fire intervals (the length of time between successive fire scars), but is generally not used in recent years to describe fire regimes because extremely long fire intervals can cause the distribution to be skewed, usually positively (Baker 1992; Grissino-Mayer 1995). To account for this skewness, the Weibull distribution is used to model positively (and negatively) skewed distributions that are common in fire history studies because it provides a superior fit to the distribution of fire intervals than the mean fire interval (Clark 1989; Johnson 1992; Baker 1992; Grissino-Mayer 1999). The Weibull Median Interval (MEI) is the interval associated with the 50th (midpoint) percentile of the distribution of fire intervals (Grissino-Mayer *et al*. 2004), and is less affected by extremely long fire intervals (Grissino-Mayer 2001b; Lewis 2003). Finally, the Weibull Modal Interval (MOI) represents the fire interval associated with the greatest area under the probability density curve (Grissino-Mayer 2001b; Lewis 2003).

The second major category includes measures of dispersion about the central value, such as the standard deviation (SD) and the coefficient of variation (CV). The CV is preferred because it allows comparisons of variability in fire interval distributions among sites by combining the SD and MFI in one statistic (Grissino-Mayer 1995; Lewis 2003). The SD alone does not facilitate easy comparisons because of the variability of the mean fire interval. The variability of the frequency of fire events can have profound implications on the resulting vegetation. For example, a fire regime with low variability suggests fire events that recur with regular frequency, which may allow enough time for pine seedlings to reach sapling height and therefore escape damage from a succeeding fire.

The third general category includes measures of range and these help further delimit the historical range of variability in fire regimes (Morgan *et al*. 1994). The

Minimum Fire Interval (MIN) and Maximum Fire Interval (MAX) represent the actual shortest and longest fire-free intervals in the distribution, respectively. The Lower Exceedence Interval (LEI) and Upper Exceedence Interval (UEI) of a distribution represent the intervals that delimit the shortest and longest fire intervals as modeled by the Weibull distribution. The FHX2 software by default uses the ±1.1 SD level to delimit these intervals because values above or below these two intervals represent 25% of the values considered statistically short (12.5%) or statistically long (12.5%). The Maximum Hazard Interval (MHI) is the maximum theoretical fire-free period that an ecosystem can sustain burning is highly probable (Grissino-Mayer 1995, 1999). For sites with high maximum hazard intervals, such as 1000+ years, the other statistical measures may provide a more accurate representation of the maximum sustainable fire-free interval. In this situation, the upper exceedence interval would be a more accurate representation of the maximum sustainable fire-free interval because it is not easily skewed by high variability or extremely long fire-free intervals (Lewis 2003). Together, the MAX, UEI, and MHI help assess the degree of fire hazard that currently exists at a site (Grissino-Mayer 1999; Grissino-Mayer *et al*. 2004).

Statistics were also generated depending on the spatial aspects of the fires by evaluating the percentage of sampled trees that had been scarred in any given fire year (Swetnam 1990, Grissino-Mayer 1995; Swetnam and Baisan 1996, 2003; Veblen *et al*. 2000; Veblen and Kitzberger 2002). The “all-scarred” class includes all fire years, including those fires that scarred only one tree in any individual site. These single-scarred trees, however, possibly represent a very isolated (i.e., patchy) and low-intensity/severity fire event that likely did not affect the whole stand (Kilgore and Briggs 1972; Lorimer

1985). To assess fire events that had greater impacts on the stands, we also evaluated the 10% scarred class in which at least 10% of the sampled trees were scarred in any fire history site. In general, such years are meant to represent spatially larger fires. For both scarred classes, the fire event had to scar at least two trees to be included in the fire statistics.

4.4.2.5 Age-Structure Analysis

To understand both the frequency and function of fires, recent studies have used age-structure analysis and fire-scar analysis together (Abrams *et al*. 1996; Armbrister 2002; Sibold *et al*. 2006). If only age-structure analysis is used, it may appear that only a few (or no) fires occurred because few (or no) cohorts may be discernible in the age structure of the stand. If only fire-scar analysis is used, effects on vegetation can not be evaluated (Sutherland *et al*. 1995). Fires do not create scars unless they are intense enough to kill a portion of the cambium on the living tree (Harmon 1982). Such fire events can also be assessed using age-structure data through cohort establishments. This makes the two types of analyses necessary and complementary.

Age-structure analysis itself includes the use of age-diameter graphs and stand composition plots, which include seedling plots and sapling plots. The age-diameter graphs show the relationship between size and age in the canopy species of each study area. These graphs also provide an indication of cohort establishments of the current overstory trees and how fire events may have initiated these establishment events when compared to the fire history plots. The seedling and sapling plots are important to determine the health and vitality of these xeric oak-yellow pine dominated stands and indicate the successional direction of these stands. Importance values, including the stand density and basal area, were also calculated to evaluate successional direction.

To evaluate the successional trajectory of pines, and to learn of the probable impacts of past fires on pine regeneration, we created frequency histograms of the ages of the pines collected at each macroplot and for each site by combining the information the macroplot age and size (dbh) data. These frequency histograms largely represent information on the ages of Table Mountain pine, although a few Virginia and pitch pines were included to assess yellow pines as a whole.

Additionally, cross-sections were taken from 20 mountain laurel stems in each macroplot to determine if their establishment, or resprouting, was tied to fire events and if their senescence was possibly tied to fire suppression efforts. The largest mountain laurel were sampled because I was interested in the establishment dates of the oldest shrubs. Cross-sections were cut from ground level with a hand saw to ensure the true age of the stem was obtained, i.e., the establishment year of the mountain laurel stem. All stems were sanded using progressively finer sandpaper until the surface was highly polished to reveal the cells of the wood under 10X magnification (Orvis and Grissino-Mayer 2002). The wood from mountain laurel would be classified as diffuse-porous, and as such the rings were not easily discernible until sanding with 320- to 400-grit sanding belts. Although crossdating the rings from this species may be possible in a future study, we simply counted the rings as we believe this to be accurate enough for age-structure analysis. This study represents the first use of a shrub species to help evaluate fire regimes in the Southeastern U.S.

4.5 Results

4.5.1 Crossdating Quality

Chronologies for the four research sites (Figure 3.1) extend well into the 1700s, which makes them the oldest Table Mountain pine chronologies for the region (Table 3.2). The interseries correlations were high at all four sites: Brush Mountain: 0.59; Griffith Knob: 0.58; Little Walker Mountain: 0.55; and North Mountain: 0.57. All sites had mean sensitivities greater than 0.30, standard deviations above 0.38, and low first-order autocorrelation (Table 3.2). The percentage of locally-absent rings was low at all sites. The most important marker rings included the years 1881, 1883, 1885, 1930, 1987, and 1994, and were used in visual crossdating. Some marker rings were common to all chronologies, but I found noticeable differences among the four chronologies, likely due to differences in topography and microclimate.

4.5.2 Fire Scars in Table Mountain Pine

Fire scars were surprisingly common on many trees at most sites that we visited in the Jefferson National Forest. Often, though, a considerable amount of time was needed during field reconnaissance to locate such trees among the dense understory that now exists in most locations of the National Forest, likely as a result of 20th century fire exclusion. Standing dead snags with fire scars contained the best preserved record of fire events, likely as a result of the high amounts of resin that exist in these snags due to excessive resin production by trees to seal off areas in the wood affected by high temperatures. A major finding of this study was the ubiquity of fire-scarred logs in the ridge and valley landscape that also contained fire-scar records, although these were not as well preserved as were the snags. In general, the high amount of rainfall and higher temperatures of the eastern U.S. are believed to cause rapid decay and deterioration of downed wood, but the resin produced in trees affected by fire events helps preserve the record in these downed logs longer than normal.

Fire scars are the most reliable indicators of past fire occurrence, although previous studies have cited the usefulness of excess resin ducts, expanded latewood, and trauma rings as indicators of fire events (Grissino-Mayer 1995). In Table Mountain pines, such alternative indicators of fire were uncommon. In some cases, growth suppression was seen in the rings after a fire scar, likely caused by loss of foliage and root damage due to the fire (Grissino-Mayer 1995). A more reliable indirect indicator of fire occurrence was observed on the age structure graphs, where the establishments of cohorts of trees are assumed to coincide with more severe fire events.

4.5.3 Reconstruction of Wildfire Events

This research provided information on the fire regimes of the 18th through the 20th centuries for four sites in the Jefferson National Forest, Virginia. It is unlikely that the history could be extended much farther back in time because the climate of Appalachian Virginia is not conducive to the long-term preservation (> 300 years) of relict pine wood, even after being impregnated by resin following repeated fire scarring events. The fire regime statistics presented here (including the mean fire intervals) represent the occurrence of fire somewhere within the study area. The sporadic fires recorded during the era of fire suppression (post-1934) are not representative of the pre-settlement fire regime and are therefore not used in statistical analyses of fire regimes.

Fire statistics were calculated for the historic period when fire was a regular disturbance on the landscape.

The fire history for each site is graphically represented by composite fire history chronologies. These chronologies provide information on the spatial and temporal distribution of fire events at each site. Samples from all four fire-history ridges for each of the four major sites and their identifications are listed on the right providing spatial information, while all recorded fire events appear at the bottom of the chronology showing the temporal aspects of fires at each site. The fire history charts also illustrate all fire events recorded by each sample. The dashed lines for each sample represent non-recorder years (*i.e.*, years when the tree had yet to be scarred or periods when rings were too eroded to faithfully contain a fire scar) while solid lines represent recorder years. Periods of reliability, the period used for statistical analyses, are listed in Table 4.1.

<u>4.5.3.1 Fire History of the Jefferson National Forest</u>

Between 1758 and 1934, Brush Mountain experienced a Weibull median fire return interval (MEI) of 3.3 years (Table 4.2) for the all-scarred class and 8.0 years for the 10%-scarred class. In general, the fire-free intervals I found at Brush Mountain were the longest found at my four study sites. For the all-scarred class, the LEI and UEI are 1.0 and 8.0 years, respectively. For the 10%-scarred class, the LEI and UEI are 2.3 and 18.6 years, respectively. Values for LEI and UEI were also the longest observed at all four sites. The maximum hazard interval for the all-scarred class was 479.0 years, but this

Table 4.1. Years of fire data for each site. Fire statistics were generated over the period of reliability.

Site Name	Begin Year	End Year	Earliest Fire	Latest Fire	Period of Reliability Begin	End	Length (yrs)
Brush Mountain	1732	2002	1758	1957	1758	1934	177
Griffith Knob	1750	2004	1764	1985	1810	1934	125
Little Walker Mountain	1694	2004	1778	1994	1789	1934	146
North Mountain	1736	2003	1742	1972	1779	1934	156

Table 4.2. Fire statistics (in years) for all sampling sites. The years in parentheses represent the period of reliability for each site.

	Statistic *	Brush Mountain (1758–1934)	Griffith Knob (1810–1934)	Little Walker Mountain (1789–1934)	North Mountain (1779–1934)
All-Scarred Class	**MFI**	4.09	2.25	2.84	3.21
	MEI	3.29	1.87	2.57	2.63
	MOI	1.18	0.83	1.85	1.09
	SD	3.48	1.98	1.84	2.92
	CV	0.85	0.88	0.65	0.91
	MIN	1.00	1.00	1.00	1.00
	MAX	13.00	9.00	10.00	17.00
	LEI	0.87	0.53	0.96	0.73
	UEI	7.96	4.32	4.96	6.19
	MHI	479.02	12.17	6.91	72.82
10%-Scarred Class	**MFI**	9.78	5.80	4.57	7.74
	MEI	8.01	4.33	4.12	6.50
	MOI	3.47	0.70	2.98	3.27
	SD	7.83	5.47	2.87	6.04
	CV	0.80	0.94	0.63	0.78
	MIN	1.00	1.00	1.00	1.00
	MAX	29.00	19.00	12.00	21.00
	LEI	2.27	0.97	1.54	1.95
	UEI	18.60	11.71	7.94	14.50
	MHI	>1000	>1000	22.12	822.10

* MFI = Mean Fire Interval; MEI = Weibull Median Interval; MOI = Weibull Modal Interval; SD = Standard Deviation; CV = Coefficient of Variation; MIN = Minimum Fire Interval; MAX = Maximum Fire Interval; LEI = Lower Exceedence Interval; UEI = Upper Exceedence Interval; MHI = Maximum Hazard Interval.

statistic could not reliably be calculated for the 10%-scarred class. The fires at Brush Mountain were spatially large, extending across several ridges, such as those fires that occurred in 1883, 1893, 1910, 1926, and 1934 (Figure 4.2). Brush Mountain also experienced numerous spatially-small, patchy fires that only scarred one or a few trees in our study area, such as the fires in 1821, 1831, 1866, 1873, 1907, and 1918. Few fires were recorded after the extensive fire in 1934, concurrent with the establishment of the Jefferson National Forest.

The MEI for Griffith Knob was 1.9 years for the all-scarred class and 4.3 years for the 10%-scarred class (Table 4.2). The LEI and UEI were 0.53 (essentially equal to 1.0 year because this is the shortest interval that can be recorded by fire scars) and 4.3 years, respectively for the all-scarred class, and 1.0 and 11.7 years for the 10%-scarred class. For the all-scarred class, the maximum hazard interval was 12.2 years but could not be reliably calculated for the 10%-scarred class. The maximum hazard interval was 12.2 years for the all-scarred class, but could not be calculated for the 10%-scarred class. This suggests that the Griffith Knob area is likely to burn after a fire-free period of 12.2 years, although the maximum interval sustained in the period of reliability was 9.0 years. The fires on Griffith Knob were also spatially large, extending across multiple ridges, such as the 1810, 1829, 1838, 1856, 1871, 1893, 1905, 1915, and 1926 fires (Figure 4.3). As with Brush Mountain, few fires were noted after the establishment of the Jefferson National Forest in 1934. The last extensive fire at Griffith Knob occurred in 1926, which was also a major fire year at Brush Mountain.

At Little Walker Mountain, the MEI was 2.6 years for the all-scarred class and 4.1 years for the 10%-scarred class (Table 4.2). The LEI and UEI were 1.0 year and 5.0 years

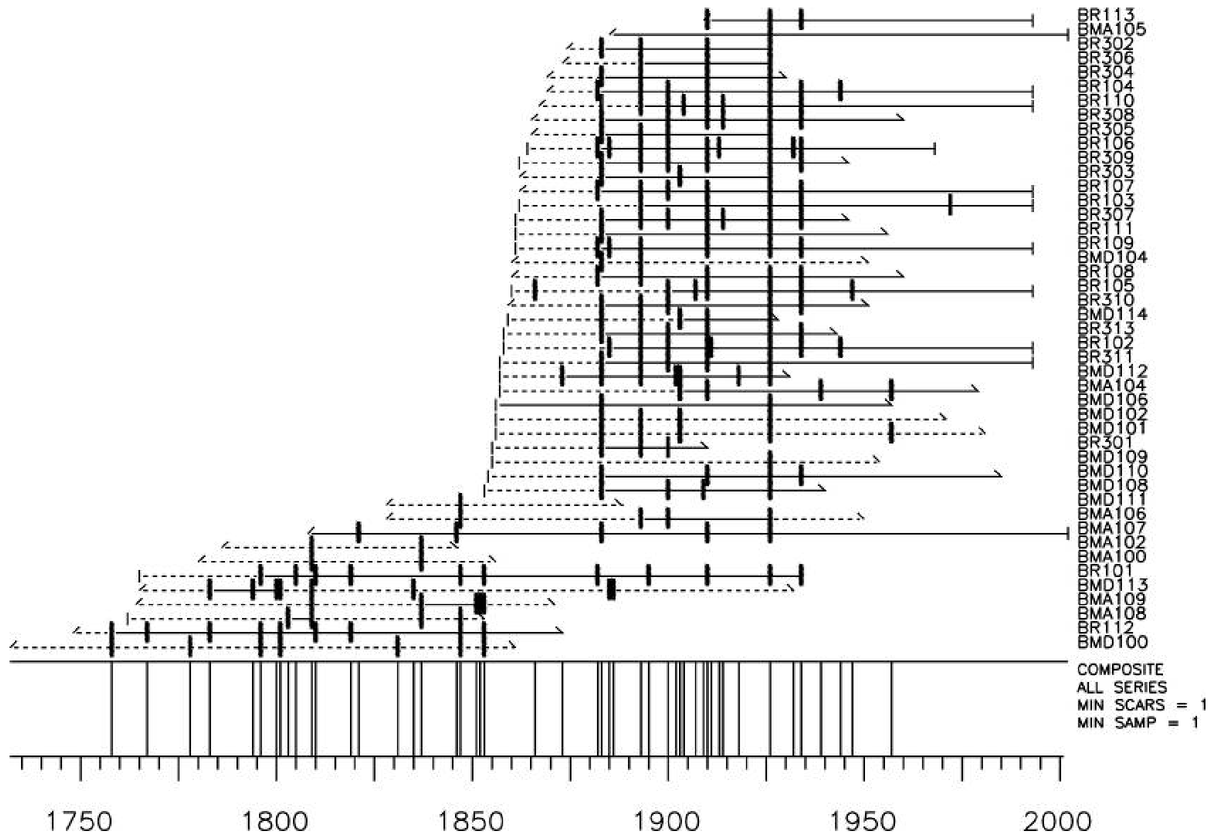

Figure 4.2: Brush Mountain composite fire history chronology. The spatial distribution of fire events is illustrated by the sample identifications on the right while the temporal distribution of fire events is illustrated by the composite axis at the bottom of the chart. Horizontal lines (dashed = non-recorder years, solid = recorder years) represent the range of years for the sample listed at the right. Each vertical bar shown on the horizontal lines is a fire event.

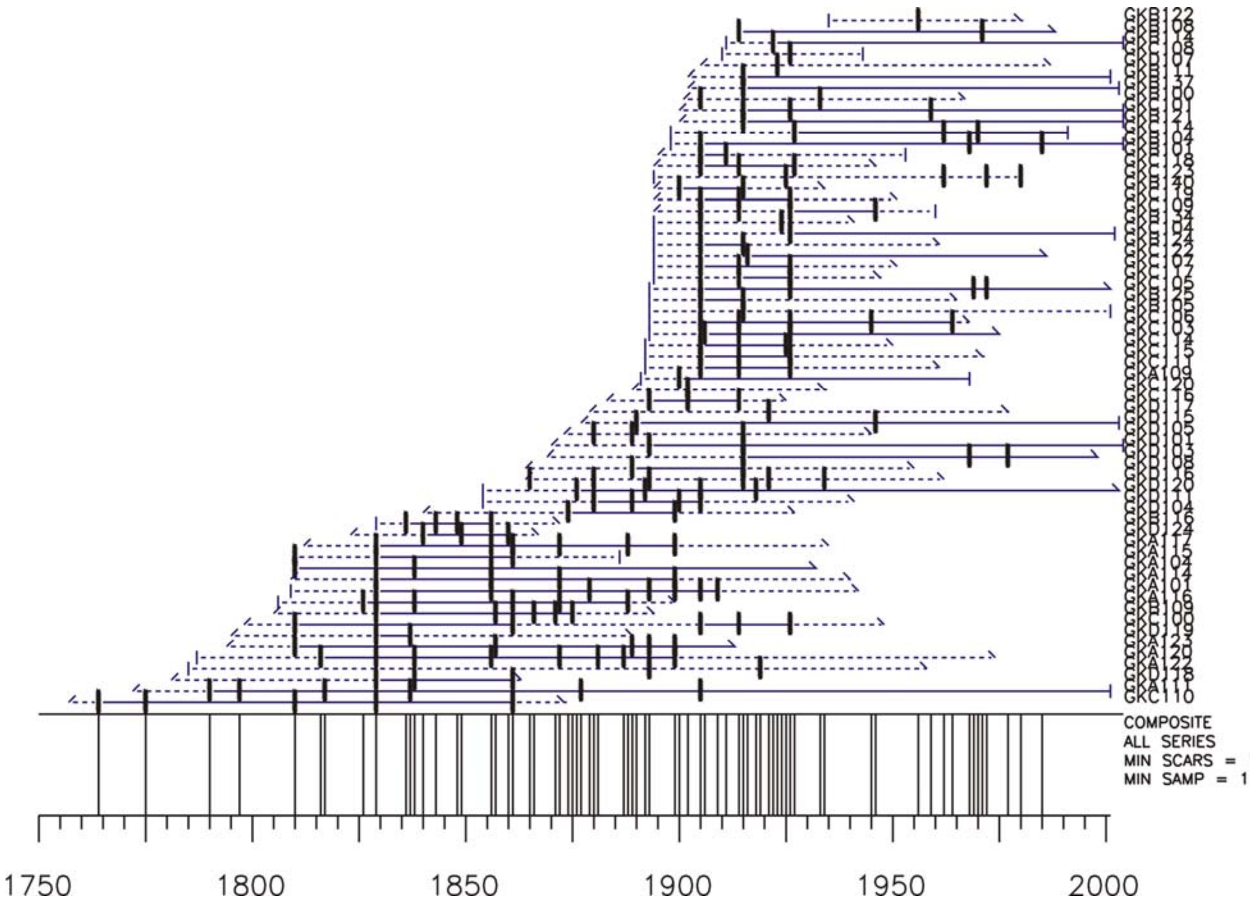

Figure 4.3: Griffith Knob composite fire history chronology. The spatial distribution of fire events is illustrated by the sample identifications on the right while the temporal distribution of fire events is illustrated by the composite axis at the bottom of the chart. Horizontal lines (dashed = non-recorder years, solid = recorder years) represent the range of years for the sample listed at the right. Each vertical bar shown on the horizontal lines is a fire event.

respectively for the all-scarred class, and 2.0 years and 8.0 years for the 10%-scarred class. The maximum hazard intervals were 7.0 years for the all-scarred class and 22.1 for the 10%-scarred class. These suggest that fire is likely to occur at some point after a fire-free interval of only 7.0 years, although a maximum interval of 10.0 years was observed during the period of reliability. Several larger-scale fires occurred in the years 1830, 1845, 1880, 1915, and 1934, but the number of samples scarred during these years was lower than at the other three sites. Instead, Little Walker Mountain displays multiple small-scale fires that suggest a patchier fire regime (Figure 4.4). Although smaller fires continued into the mid- and late 20th century, the last major fire year here occurred in 1934, similar to both Brush Mountain and Griffith Knob.

At North Mountain, the MEI was 2.6 years for the all-scarred class and 6.5 years for the 10%-scarred class (Table 4.2). The LEI and UEI were 0.7 years (equal to 1.0 year as this value is the absolute minimum that can occur) and 6.2 years respectively for the all-scarred class and 2.0 and 14.5 years respectively for the 10%-scarred class. The maximum hazard interval was 72.8 years for the all-scarred class and 822.1 years for the 10%-scarred class, but again these values are ecologically unreasonable. Instead, the maximum intervals of 17.0 and 21.0 years, respectively (all-scarred and 10%-scarred classes) are better measures of the maximum fire-free intervals that can be sustained by forests at North Mountain.

As with Little Walker Mountain, the fires on North Mountain had a much patchier distribution in contrast to the fire regimes at Brush Mountain and Griffith Knob. A few potentially larger-scale fires did occur in 1796, 1816, 1829, 1853, 1900, 1913, 1924, and 1963, but these fires scarred few of our sampled trees. Nonetheless, fires were still

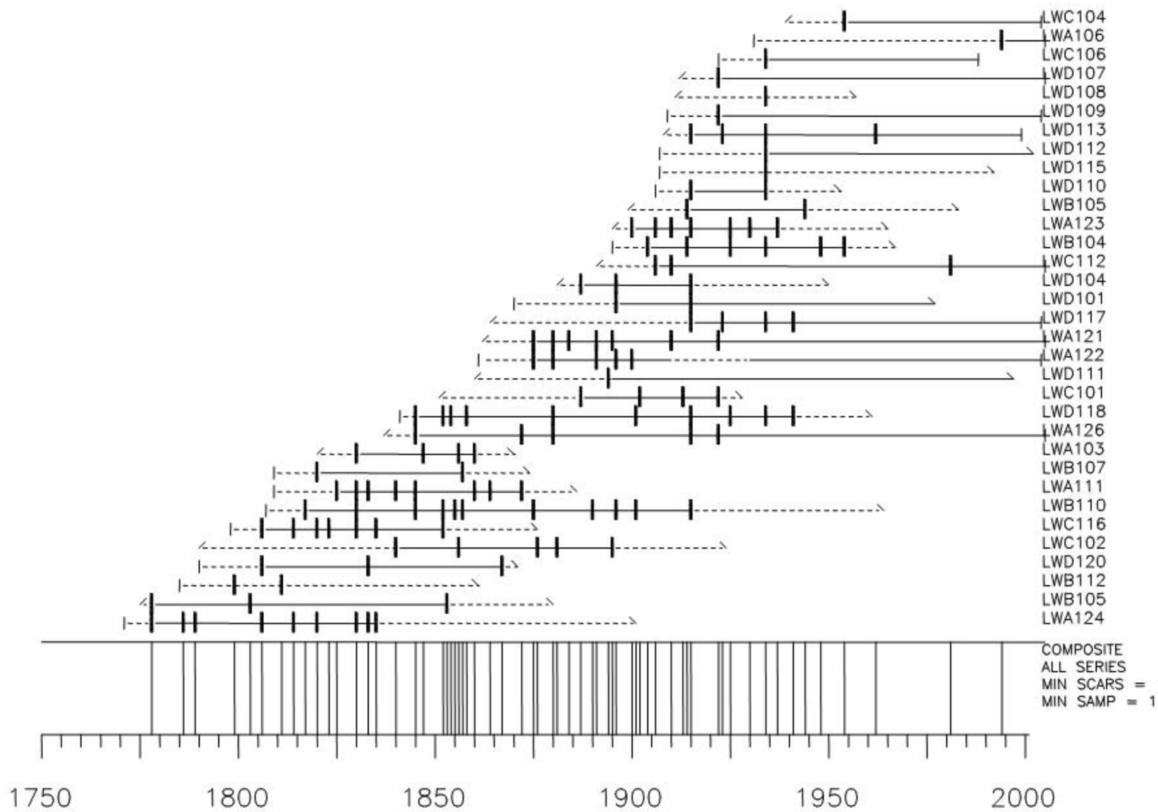

Figure 4.4: Little Walker Mountain composite fire history chronology. The spatial distribution of fire events is illustrated by the sample identifications on the right while the temporal distribution of fire events is illustrated by the composite axis at the bottom of the chart. Horizontal lines (dashed = non-recorder years, solid = recorder years) represent the range of years for the sample listed at the right. Each vertical bar shown on the horizontal lines is a fire event.

apparently able to spread to adjacent ridges. For example, the fire of 1900 was recorded at sub-sites NMA, NMB, and NMD, but not at sub-site NMC (Figure 4.5). NMC was lower on the slopes than the other four sites and, in addition, fewer samples were found that contained fire scars. The fire of 1963 was apparently confined to the upper areas of the slopes of North Mountain, as this fire was recorded only at sites NMA and NMB, the two highest of the four sub-sites.

Inspection of the MFI, MEI, and MOI for all four sites revealed that the MFI > MEI > MOI, a pattern suggested previously (Grissino-Mayer 1999) which occurs because the distribution of fire-free intervals is almost always positively skewed. This skewness causes the mean fire interval to be "dragged" to the right of the distribution towards the longer intervals and therefore makes this measure less reliable. In general, fires took place somewhere within the boundaries of the study sites between once every 2 to 3 years based on all fire-scarred trees, while potentially larger fires (10%-scarred class) occurred approximately once every 4 to 8 years (Table 4.2). The range of variation (LEI and UEI, as well as the minimum and maximum intervals) indicates that fires can return as soon as 1 year but can be delayed up to 8 years (all-scarred class), while more spatially extensive fires can be expected to return anytime from 1 to 19 years (10%-scarred class). However, Brush Mountain had a maximum fire-free interval during the period of reliability of 29 years (Table 4.2), but such durations were very uncommon at the four sites. Not surprisingly, the minimum fire interval at all sites was 1 year (Table 4.1), suggesting that either (1) fuels can build up quickly after a fire year enough to support a fire the following year, or (2) fuels burned incompletely during the previous fire year (Swetnam 1990; Grissino-Mayer 1995).

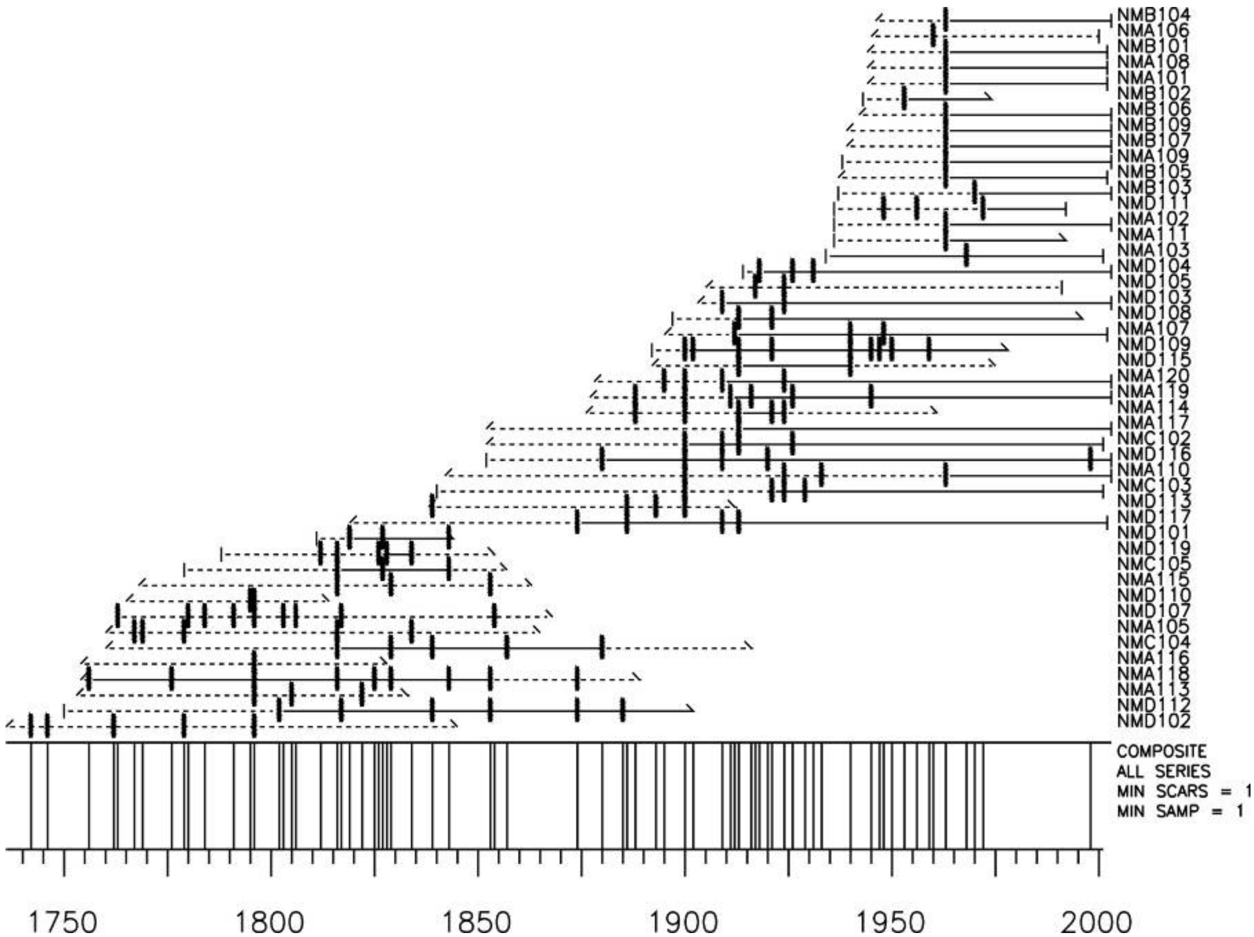

Figure 4.5: North Mountain composite fire history chronology. The spatial distribution of fire events is illustrated by the sample identifications on the right while the temporal distribution of fire events is illustrated by the composite axis at the bottom of the chart. Horizontal lines (dashed = non-recorder years, solid = recorder years) represent the range of years for the sample listed at the right. Each vertical bar shown on the horizontal lines is a fire event.

The standard deviation can be used to calculate the 95% confidence interval (CI) about the MFI (Grissino-Mayer 1995). However, the standard deviation cannot be used to calculate this CI for sites with very short values for the measures of central tendency, or for sites with skewed distributions, such as fire interval data, because these situations would yield negative values for lower bound of the CI. Instead, the coefficient of variation (CV) can be used to evaluate and compare the variability of fire-free intervals among the four sites. In general, the coefficients suggest that the variability about the mean fire intervals were fairly consistent for three sites: Brush Mountain: 0.85 (all) and 0.80 (10%); Griffith Knob: 0.88 (all) and 0.94 (10%); and North Mountain: 0.91 (all) and 0.78 (all). The variability of the lengths of fire-free periods at Little Walker Mountain was the lowest of the four sites: 0.65 (all) and 0.63 (10%), indicating fire intervals with durations that were more consistent. This property can be seen in the fire chart for Little Walker Mountain (Figure 4.4), which shows little variability as seen in the composite axis.

4.5.3.2 Fire Seasonality

The majority of fires at all sites were dormant season fires or occurred in the early-earlywood portion of the tree ring (Table 4.3), likely indicating fires that occurred in spring of that year. Dormant season burns occur after the last growing season’s pine needle fall and before hardwoods flush in the spring (Farrar 1998). Most dormant season fires historically have occurred in the early part of the current year between February and April (Sutherland *et al*. 1995). At Brush Mountain, 90% of fires were either dormant

Table 4.3. Seasonality of fire events (expressed as percent) for scars where season could be determined.

Study Area	**Dormant (D)**	**Early-Early (E)**	**D+E**	**Middle-Early (M)**	**Late-Early (L)**	**Late (A)**	**M+L+A**
Brush Mountain	84.0	5.9	**89.9**	3.6	4.7	1.8	**10.1**
Griffith Knob	29.7	42.6	**72.3**	23.6	1.4	2.7	**27.7**
Little Walker Mountain	35.1	44.3	**79.4**	13.4	3.1	4.1	**20.6**
North Mountain	76.3	7.9	**84.2**	14.5	0.0	1.3	**15.8**

season (84%) or early (6%) season fires, with only 10% of fires occurring from the middle of the growing season through the late portion of the growing season. At Brush Mountain, 20% of fire scars could not be assigned a season because these scars were too degraded to determine the season of the event.

Like Brush Mountain, North Mountain had 84% of fire scars indicate dormant season and early growing season fires (Table 4.3), the majority of which were dormant season fires (76%). Fire scars that occurred in the middle portion through the late portion of the growing season made up 16% of the total. At North Mountain, a large percentage of fire events (27%) could not be assigned a fire season in the tree-ring record because of the degraded state of the wood.

The seasonality of past fires at Griffith Knob was similar to the seasonality observed for past fires at Brush and North Mountains (Table 4.3). The majority of fires (72%) were dormant season and early growing season fires, but unlike Brush and North Mountains, the majority of those fires (43%) were early growing season fires. In addition, a larger proportion of fire events occurred during the middle growing season through the late growing season (28%), with 24% of those occurring in the middle season. I could not assign seasonality to 21% of the fire scars at Griffith Knob because of the advanced degradation of the wood samples.

This trend in seasonality continued at Little Walker Mountain, where the majority of past fires occurred early in the growing season (44%), followed closely by dormant season fires (35%) and middle growing season fires (13%) fires (Table 4.3). Less than 10% of fire events occurred in the latter portions of the growing season. I could not assign seasonality to 15% of the fire scars collected at Little Walker Mountain, again due to the advanced degradation of the wood.

Inspection of the fire seasonality over time (an analysis available in the FHX2 Statistical Module) revealed no dramatic shifts in the seasonality of fire events at any of the sample sites. Fire seasonality was more evenly distributed between dormant, early-earlywood, and middle-earlywood at Griffith Knob and Little Walker Mountain (Table 4.3). At North Mountain and Brush Mountain, the vast majority of fire events occurred during the dormant season, while early growing season fires dominated at Little Walker Mountain and Griffith Knob. In general, scars that occurred in the late-earlywood and latewood portions of the tree ring were rare at all sites, indicating that fires during the late growing season were rare in the past, just as they are today.

4.5.3.3 Spatial Characteristics of Fires

In general, the spatial aspects of past fires are of four types of fires: (1) spatially small fires that burned just one or two trees on each ridge, (2) local fires that burned several trees on a single ridge, (3) widespread fires that spread across multiple ridges at a single site, and (4) a fire that occurred at two or more of the four sites, although these fires may or may not have been connected. The first three types of fires occurred at Brush Mountain, Griffith Knob, and Little Walker Mountain. For example, a fire that occurred in 1885 on Brush Mountain was confined to the first ridge (BR1) in the original collection made in 1993 (Sutherland *et al*. 1995), while the spatially extensive fire of 1883 occurred across all ridges sampled on Brush Mountain (Figure 4.2). At Griffith Knob, a fire in 1829 burned all four ridges sampled (Figure 4.3). in 1926, a major fire was recorded at Brush Mountain, North Mountain, and Griffith Knob, but not at Little Walker Mountain. At North Mountain, fires appeared to be spatially small fires, scarring only a few trees per ridge, but no explanation can be offered to explain this as the forests and terrain on North Mountain resemble that found elsewhere, including the nearby Brush Mountain site. At both Brush Mountain and North Mountain, a clear gap in fire occurrence began in the early 1950s (Figure 4.2 and 4.5), again indicating fire regimes that may have been spatially similar.

4.5.4 Age-Structure Analyses

On Brush Mountain, a major cohort established almost immediately after the 1926 and 1934 dormant season fires (Figure 4.6). The oaks and other hardwoods established first after the 1926 fire, while the yellow pines soon followed after the 1934 fire. Not all canopy species established after these fires, as some oaks and pines had established as early as the 1820s. Although not obvious in the age structure analysis, a major cohort of pines clearly established in the period 1850 to 1865 as seen in the fire history chart (Figure 4.2). This cohort likely established after the 1853 fire, which was one of the few late season fires recorded in the seasonality analysis. In addition, one sample at Brush Mountain, BMA109, contained evidence of three fire events in back-to-back years, 1851, 1852, and 1853, the only instance of three fires occurring in consecutive years on one sample at any of the four study sites. These fire events in the early 1850s indicate a major alteration to the ecosystem on Brush Mountain that prevented

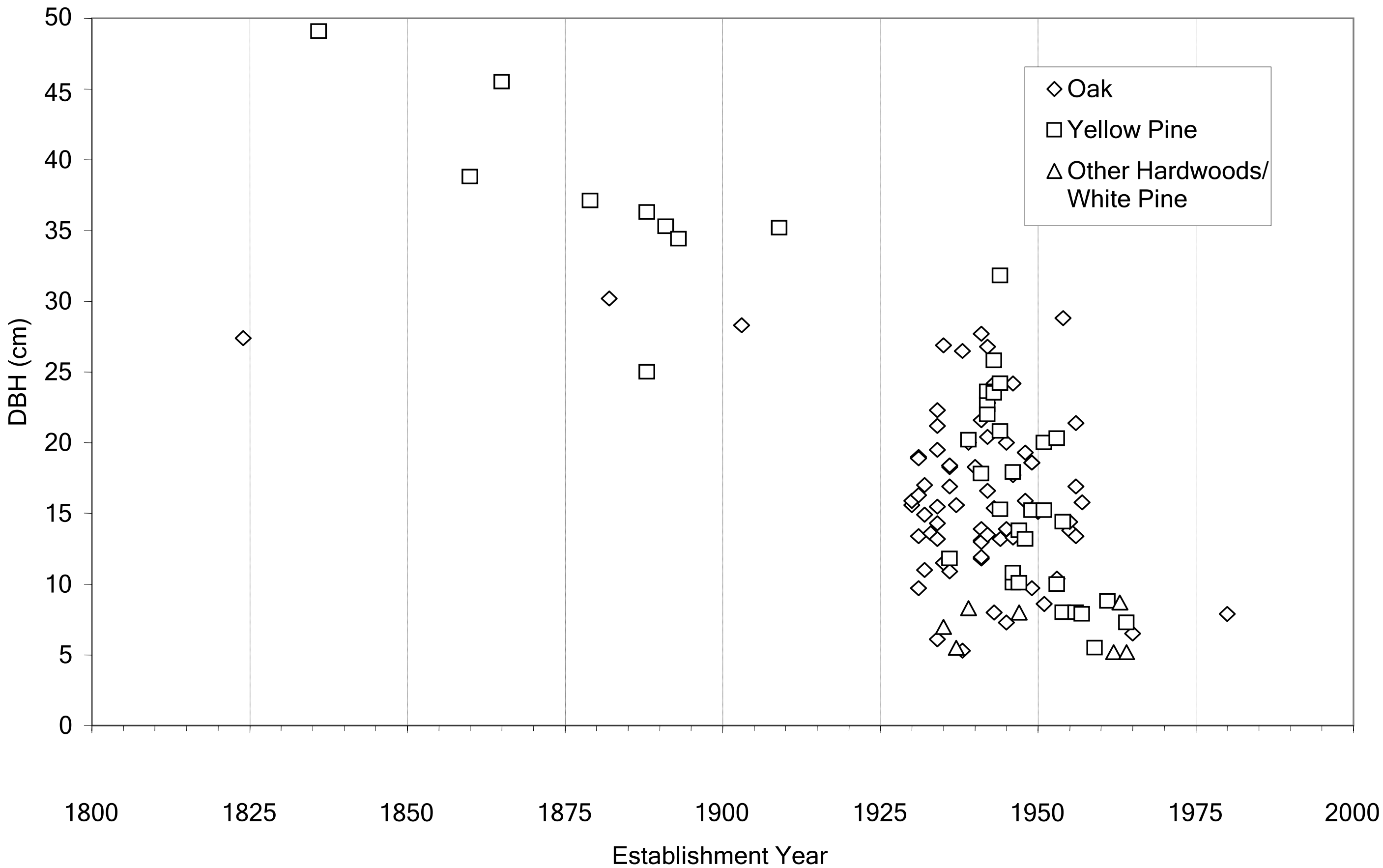

Figure 4.6: Brush Mountain age-diameter graph illustrating (1) the relationship between tree diameter and tree age and (2) the relationship between establishment dates and fire dates. Fire events in 1926 and 1934 immediately preceded the establishment of cohorts.

fires from occurring until the extensive fire year in 1882. During this relatively fire-free period, pines were able to establish.

Griffith Knob appears to have experienced three cohort establishment events, possibly indicating fires that were moderate in intensity and severity (Figure 4.7). One cohort of yellow pine established *ca*. 1890 and another between 1925 and 1930. The first cohort is also clearly seen in the fire history chart (Figure 4.3) as shown by the pith dates on numerous trees at this time. These trees are restricted to ridges GKB and GKC and indicate a possibly severe fire or series of fires, most likely in the late 1880s. The pines also established in a fire-free interval between 1893 and 1899, seen primarily on samples from ridges GKA and GKD in the fire chart. The second cohort established in the interval that followed soon after the major fire event in 1926, similar to the cohort that established after this fire year on Brush Mountain. A cohort of oaks established between 1910 and 1915 soon after the spatially extensive major fire in the year 1910. Other hardwoods established continuously, although not in the high numbers they did at other sites.

Little Walker Mountain experienced continuous establishment of oak and pine beginning around 1900 (Figure 4.8), although a small number of pines and oaks established between 1850 and 1900. Unlike Brush Mountain and Griffith Knob, the fire chart for Little Walker Mountain does not show that any pines sampled for fire history established in a clear cohort, although a few samples established at the LWD sub-site around 1900 (upper part of Figure 4.4). Therefore, the cohort establishment of 1900 can not conclusively be tied to any particular fire event. The cohort of pines that established in the early 1920s also can not be tied to a particular fire event, but this cohort coincides

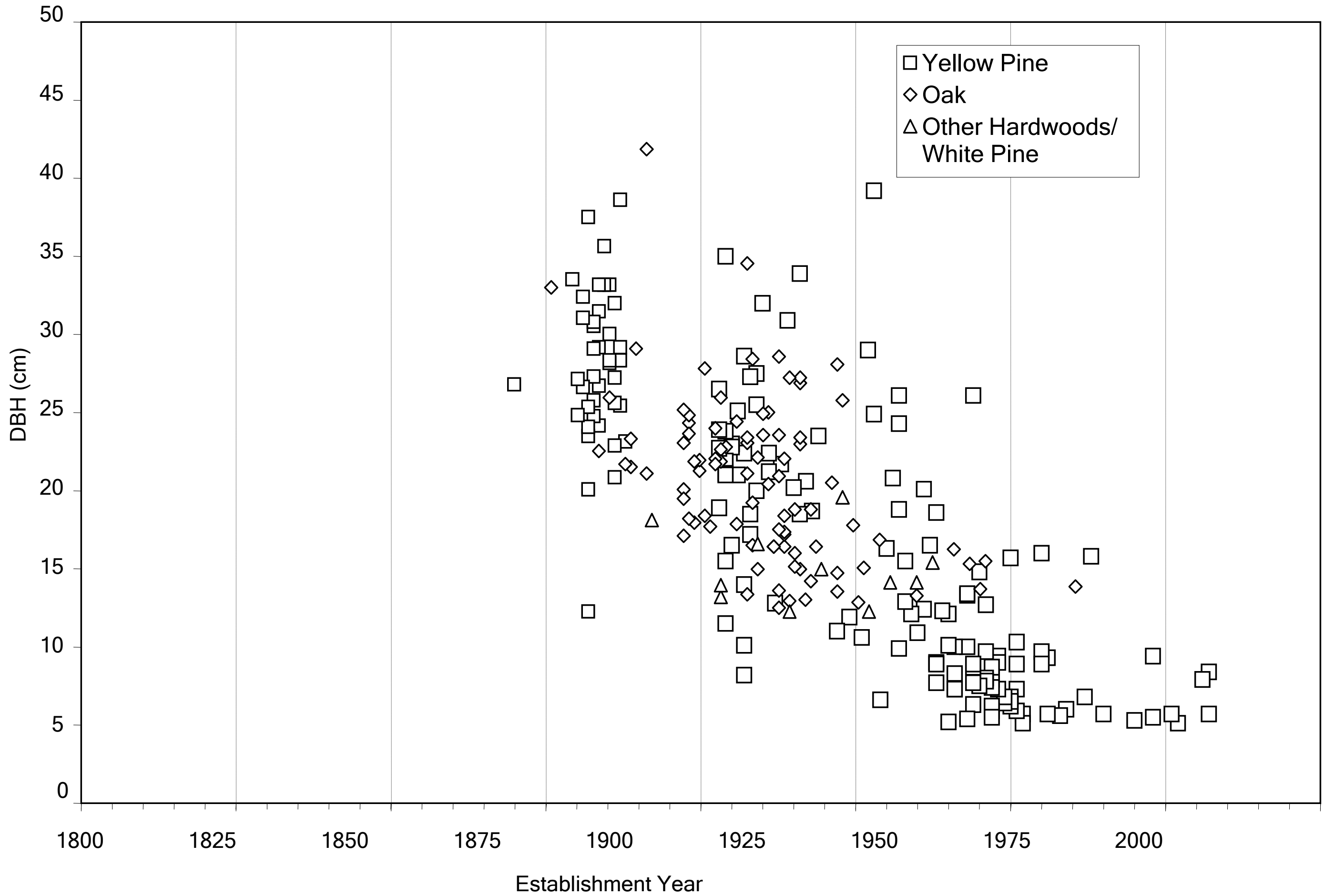

Figure 4.7: Griffith Knob age-diameter graph illustrating (1) the relationship between tree diameter and tree age and (2) the relationship between establishment dates and fire dates. Fire events in 1893 and 1916 immediately preceded the establishment of cohorts.

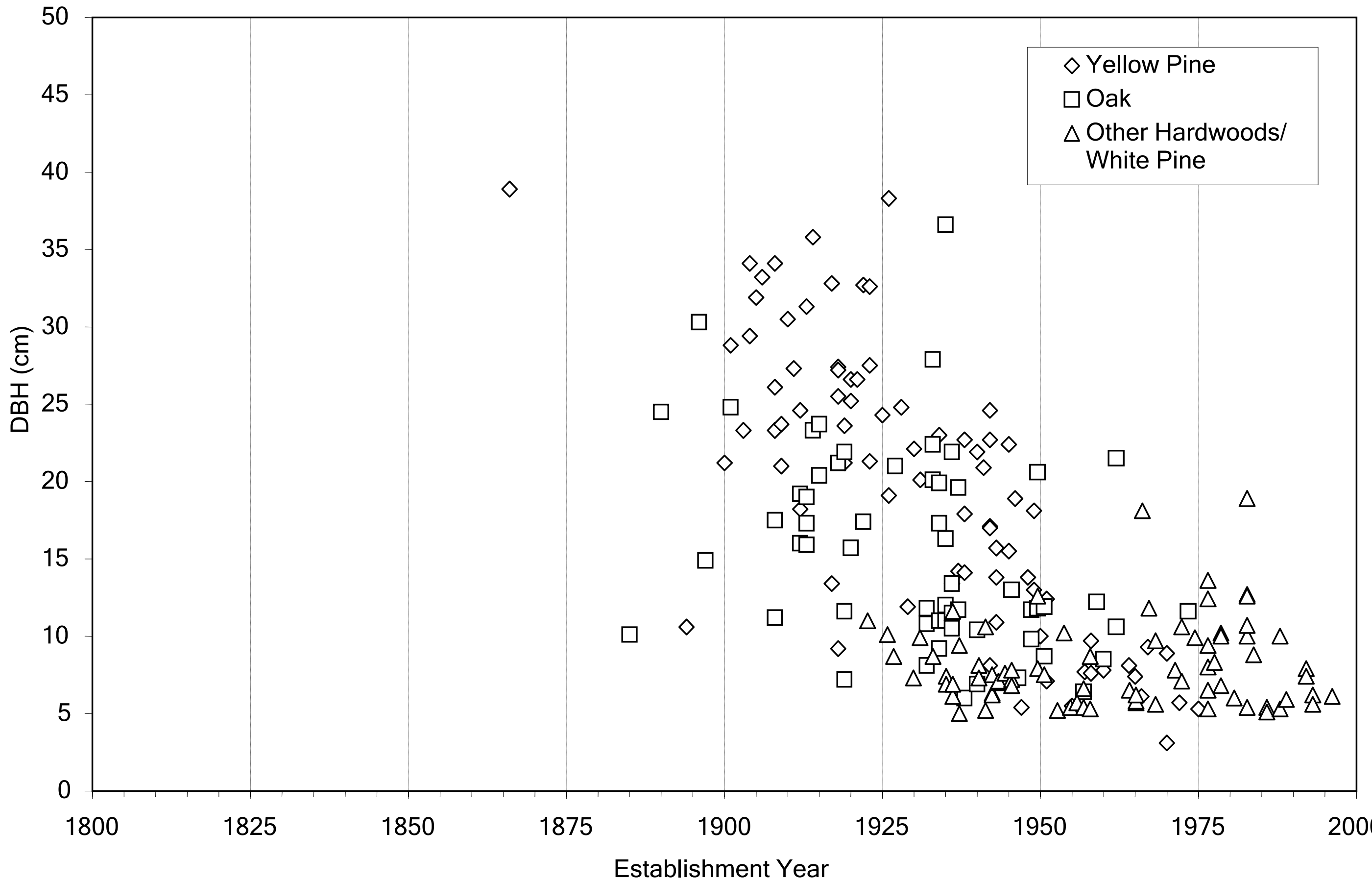

Figure 4.8: Little Walker Mountain age-diameter graph illustrating (1) the relationship between tree diameter and tree age and (2) the relationship between establishment dates and fire dates. The fire event in 1921 immediately preceded the establishment of the cohort.

with similar cohorts that established in the mid-1920s on Brush Mountain and Griffith Knob.

The age structure of trees on North Mountain showed a distinct clustering of establishment dates in the period 1920 to 1925 (Figure 4.9) that could not be clearly associated with any individual fire event. The fire chart for North Mountain also shows that many pines had innermost ring dates or pith dates soon after *ca*. 1925 (Figure 4.5). Like Brush Mountain, some oaks and other hardwoods exist that pre-date this cohort. The oldest trees in the North Mountain study area are chestnut oaks, which established in the late 1700s (these are not shown in Figure 4.9 which goes back to only 1800).

Brush Mountain currently has the oldest yellow pines with canopy trees that date back to the 1830s (Figure 4.10A), but the majority of yellow pines at Brush Mountain (> 60%) date only back to the 1930s–1940s. The other three sites have younger populations of yellow pines that became established beginning in the late 1800s (Figures 4.10B–D). The large pulse of regeneration of yellow pines on Brush Mountain occurred after the spatially large 1926 and 1934 fire events (Figure 4.2), perhaps indicating that these fires were more severe. North Mountain also has peak yellow pine establishment during the 1930s–1940s (Figure 4.10D), with over 50% of the current sample establishing in the period 1930 to 1960. These results demonstrate high numbers of Table Mountain pines younger than ca. 76 years in age, but Table Mountain pines older than 76 years are known to produce the most viable seeds (Gray 2001).

Little Walker Mountain and Griffith Knob have a more even age distribution of yellow pines between *ca*. 1890 and 1990 and also have the same general shape in the age structure distribution (Figures 4.10B and C), likely reflecting similar stand histories due

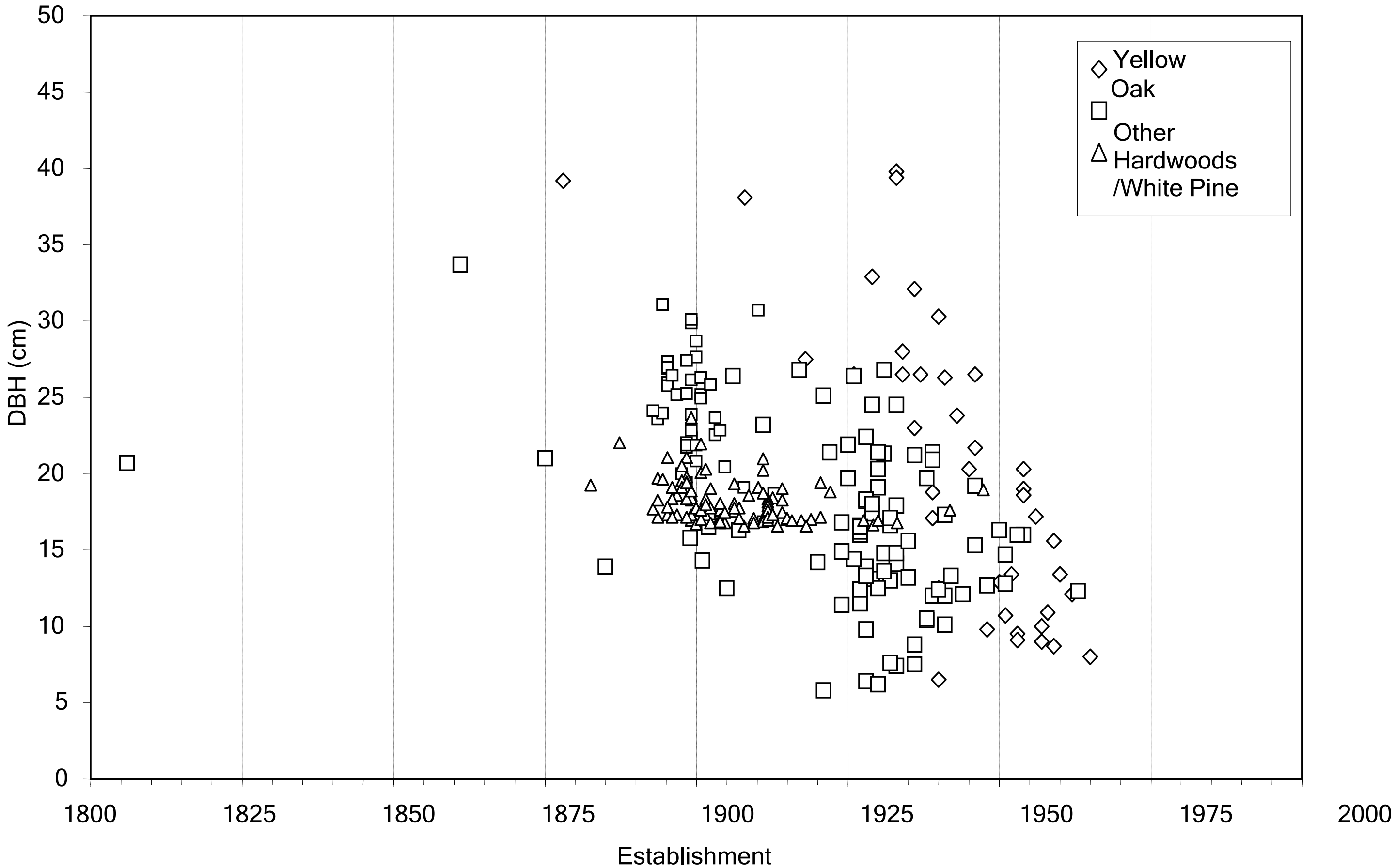

Figure 4.9: North Mountain age-diameter graph illustrating (1) the relationship between tree diameter and tree age and (2) the relationship between establishment dates and fire dates. Fire events in 1921, 1924, and 1926 immediately preceded the establishment of cohorts.

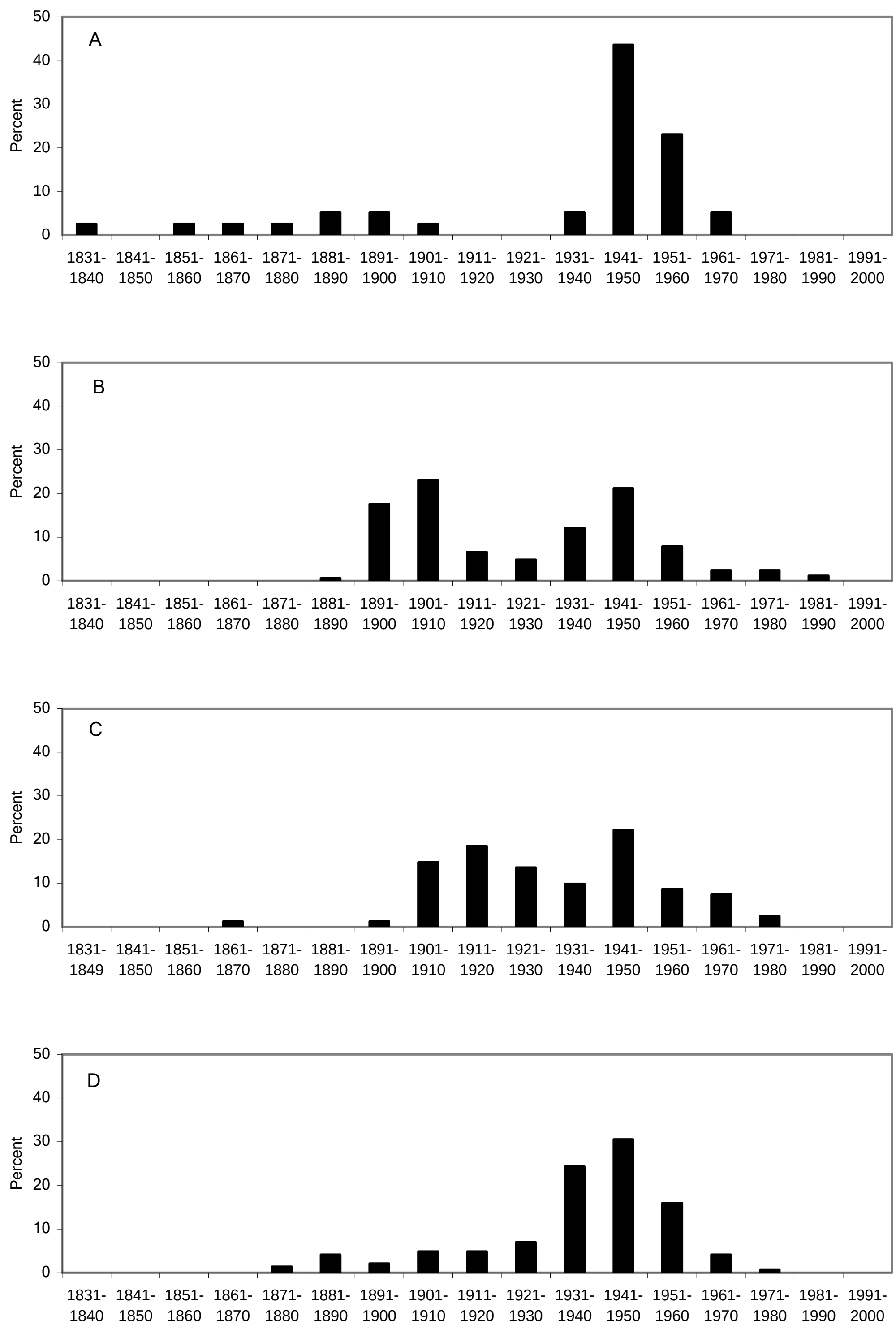

Figure 4.10: Age structure of yellow pines >5 cm from Brush Mountain (A), Griffith Knob (B), Little Walker Mountain (C), and North Mountain (D).

to their proximity to each other. The presence of older populations of Table Mountain pines at these two sites could suggest better regeneration ability because the older trees can produce higher numbers of viable seeds. Both distributions are bimodal with the first peak in establishment found between *ca*. 1890 and 1920 and the second between *ca*. 1930 and 1960. This latter peak was also observed at Brush and North Mountains farther to the north.

Combining the yellow pine establishment information provides an overall picture of the regeneration patterns throughout the study area. In general, yellow pine establishment had a bimodal distribution (Figure 4.11). The majority of yellow pines throughout the study area established between 1901–1910 and 1931–1950. The latter establishment pulse coincides with the last two significant fire events at the study sites, including the 1926 major fire (Brush Mountain, Griffith Knob, and North Mountain) and the 1934 major fire (Brush Mountain and Little Walker Mountain). Interestingly, these last two major fire events occurred nearly contemporaneously with the establishment of the Jefferson National Forest in 1934. The earlier establishment could be related to the extensive fire activity during the 1890s and early 1900s observed at all sites except Little Walker Mountain. Again, the age structure of pines at all sites shows that the majority of canopy yellow pines (> 55%) are less than 76 years in age, and Table Mountain pines greater than 76 years old are known to produce the most viable seeds (Gray 2001).

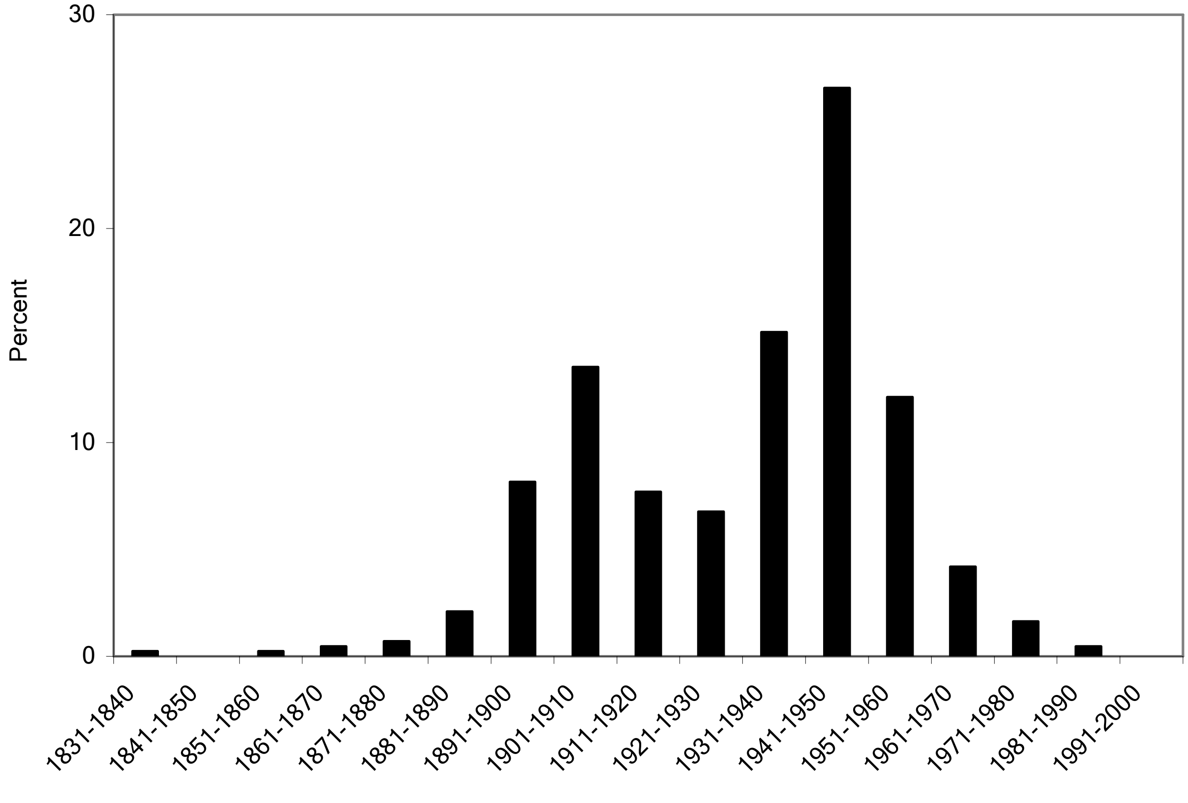

Figure 4.11: Age structure of yellow pines >5 cm from all sampling sites.

4.5.4.1 Current Stand Composition

Brush Mountain has seven tree species that currently occupy the canopy, dominated clearly by Table Mountain pine, which had the highest percentages for relative frequency, density, and basal area, resulting in the highest importance value (IV) of 48.0 (Table 4.4). The next most abundant tree species was chestnut oak which had an IV of 36.6, confirming that the stands largely consist of xeric pine/oak forests. Of lesser importance were black gum, red maple, scarlet oak, Virginia pine, and black oak.

Of the four study sites, Griffith Knob has the highest canopy diversity (12 tree species) although four species (red maple, American chestnut, pitch pine, eastern white pine, and scarlet oak) comprised less than 1% each of the current canopy (Table 4.5). Table Mountain pine again clearly dominates the canopy with the highest basal area, frequency, and density, resulting in the highest IV (70.03). Chestnut oak was the second most dominant tree species with an IV of 15.52. Other canopy species found include black gum, northern red oak, white oak, Virginia pine, and black oak.

Little Walker Mountain has seven tree species in the current canopy (Table 4.6). Table Mountain pine again dominated the canopy with the highest frequency, density, and basal area, resulting in an IV of 41.79. Like Brush Mountain and Griffith Knob, chestnut oak was the second most important tree species with an IV of 19.42. Unlike the previous two sites, however, Little Walker Mountain had two other tree species that would be considered codominants: black gum (IV = 13.36) and eastern white pine (IV = 12.12). Little Walker Mountain contained the greatest numbers of eastern white pines seen in our four study areas, indicating a likely change in the fire regime here because

Table 4.4. Stand composition of trees > 5 cm dbh at Brush Mountain.

Species	Basal Area (m^2/ha)	Frequency	Density (stems/ha)	Dominance (basal area/site area)	Relative Frequency (%)	Relative Density (%)	Relative Dominance (%)	Importance Value (%)
Acer rubrum	0.106	3.7	36.7	0.35	2.90	3.10	0.040	2.0
Nyssa sylvatica	3.19	16.3	163.3	10.63	12.90	15.17	1.170	9.7
Pinus pungens	165.4	56.0	560.0	551.17	44.10	41.18	58.750	48.0
Pinus virginiana	0.025	0.7	6.7	0.08	0.52	0.62	0.009	0.4
Quercus coccinea	2.98	8.7	86.7	9.93	6.80	1.24	1.100	3.0
Quercus montana	105.06	41.3	413.3	350.2	32.50	38.4	38.900	36.6
Quercus velutina	0.009	0.3	3.3	0.03	0.26	0.31	0.003	0.2

Table 4.5. Stand composition of trees > 5 cm dbh at Griffith Knob

Species	Basal Area (m^2/ha)	Frequency	Density (stems/ha)	Dominance	Relative Frequency (%)	Relative Density (%)	Relative Dominance (%)	Importance Value (%)
Acer rubrum	0.008	0.67	6.67	0.027	0.74	0.74	0.003	0.49
Castanea dentata	0.012	0.67	6.67	0.04	0.74	0.74	0.004	0.49
Nyssa sylvatica	0.121	2.70	26.70	0.40	2.96	2.96	0.056	1.99
Pinus pungens	228.6	53.70	536.70	762	59.63	59.63	90.88	70.03
Pinus rigida	0.021	0.33	3.33	0.07	0.37	0.37	0.008	0.25
Pinus strobus	0.001	0.33	3.33	0.003	0.37	0.37	0.0004	0.25
Pinus virginiana	0.061	1.67	16.67	0.20	1.85	1.85	0.024	1.24
Quercus alba	0.219	2.33	23.33	0.73	2.59	2.59	0.080	1.75
Quercus coccinea	1.75	0.67	66.70	5.83	7.40	7.40	0.69	5.17
Quercus montana	22.27	17.30	173.30	74.23	19.26	19.26	8.04	15.52
Quercus rubra	0.38	2.30	23.30	1.27	2.59	2.59	0.15	1.78
Quercus velutina	0.163	1.33	13.30	0.54	1.48	1.48	0.64	1.00

Table 4.6. Stand composition of trees > 5 cm dbh at Little Walker Mountain.

Species	Basal Area (m^2/ha)	Frequency	Density (stems/ha)	Dominance	Relative Frequency (%)	Relative Density (%)	Relative Dominance (%)	Importance Value (%)
Acer rubrum	0.31	4.00	40.00	1.03	5.51	5.78	3.17	4.82
Nyssa sylvatica	1.98	11.67	116.67	6.6	16.06	16.00	8.01	13.36
Pinus pungens	79.76	27.30	273.30	265.9	37.62	36.89	50.86	41.79
Pinus strobus	2.41	10.00	100.00	8.03	13.76	13.78	8.83	12.12
Quercus coccinea	0.44	2.33	23.33	1.47	3.21	3.56	3.76	3.51
Quercus montana	13.3	13.67	136.67	44.33	18.81	18.67	20.77	19.42
Quercus rubra	0.65	3.67	36.67	2.17	5.05	5.33	4.59	4.99

eastern white pine is considered very fire intolerant due to its thin bark. Other tree species found in the canopy include northern red oak, red maple, and scarlet oak (Table 4.6).

The current stand composition of canopy tree species at North Mountain is unlike that found at the other three sites. Nine species compose the canopy, dominated by chestnut oak which had the highest value for basal area and the second highest values for frequency and density, resulting in an IV of 35.36 (Table 4.7). Not far behind is black gum, which had the highest values for frequency and stem density, resulting in an IV of 31.92. Table Mountain pine, which dominated the canopies at the three other sites, ranks third in importance (IV = 16.28), followed by scarlet oak (IV = 12.06). Other canopy tree species include northern red oak, Virginia pine, red maple, black oak, and black locust (Table 4.7).

Combining the stand composition information for all four sites can provide some indication of the overall stand composition of these xeric pine/mixed hardwood sites of the Jefferson National Forest as a whole (Table 4.8). Table Mountain pine has the highest basal area, frequency, tree density, and dominance values resulting in the highest IV of all canopy species (44.03). Chestnut oak is the second most common tree species with an importance value of 26.73. The third most common canopy tree species is black gum IV = 14.25) which was found in very high numbers on North Mountain especially. A clear break can be seen with the other tree species as the next two most common species are scarlet oak (IV = 5.95) and red oak (IV = 2.22). Combined, the oaks have an IV of 35.53. Combined, the oaks, Table Mountain pine, and black gum account for nearly 94% of all canopy tree species in the four sites studied based on their importance values.

Table 4.7. Stand composition of trees > 5 cm dbh at North Mountain.

Species	Basal Area (m^2/ha)	Frequency	Density (stems/ha)	Dominance	Relative Frequency (%)	Relative Density (%)	Relative Dominance (%)	Importance Value (%)
Acer rubrum	0.011	1.00	10.00	0.037	1.07	1.07	0.01	0.72
Nyssa sylvatica	17.22	34.67	346.67	57.4	37.01	37.00	21.74	31.92
Pinus pungens	17.67	12.33	123.33	58.9	13.17	13.17	22.50	16.28
Pinus virginiana	0.11	1.00	10.00	0.37	1.07	1.07	0.13	0.75
Robinia pseudoacacia	0.001	0.33	3.33	0.004	0.36	0.36	0.002	0.24
Quercus coccinea	17.18	14.00	140.00	57.3	14.95	17.95	3.29	12.06
Quercus montana	42.29	26.00	260.00	141	27.76	27.76	50.55	35.36
Quercus rubra	1.48	4.00	40.00	4.9	4.27	0.36	1.77	2.13
Quercus velutina	0.014	0.33	3.33	0.047	0.36	0.36	0.02	0.24

Table 4.8. Stand composition of trees > 5 cm dbh at all four sites combined.

Species	Basal Area (m^2/ha)	Frequency	Density (stems/ha)	Dominance	Relative Frequency (%)	Relative Density (%)	Relative Dominance (%)	Importance Value (%)
Acer rubrum	0.11	2.33	23.33	0.09	2.55	2.67	0.81	1.51
Castanea dentata	0.003	0.17	1.70	0.0008	0.74	0.19	0.001	0.23
Nyssa sylvatica	5.63	16.33	163.33	4.69	17.22	17.78	7.75	14.25
Pinus pungens	122.85	37.33	373.33	102.37	38.63	37.71	55.75	44.03
Pinus rigida	0.005	0.08	0.83	0.0008	0.09	0.09	0.002	0.047
Pinus strobus	0.60	2.58	25.83	0.5	3.53	3.54	2.21	2.32
Pinus virginiana	0.049	0.83	8.33	0.04	0.86	0.88	0.04	0.45
Robinia pseudoacacia	0.003	0.08	0.83	0.0008	0.36	0.09	< 0.001	0.11
Quercus alba	0.05	0.58	5.83	0.0008	0.65	0.65	0.02	0.33
Quercus coccinea	5.59	7.92	79.17	4.66	8.10	7.54	2.21	5.95
Quercus montana	45.73	24.58	245.83	38.1	24.59	26.02	29.57	26.73
Quercus rubra	0.63	2.50	25.00	0.52	2.98	2.07	1.63	2.22

Quercus velutina	0.019	0.50	5.00	0.016	0.70	0.54	0.02	0.31

4.5.4.3 Sapling Composition

The composition of saplings (< 5 cm dbh) in the four sites can provide some indication of the possible future overstory stand composition. At Brush Mountain, the most populous species was black gum with 95 saplings (Table 4.9). Other saplings included red maple (n = 12 saplings), Table Mountain pine (n = 5), northern red oak (n = 3), American chestnut (n = 1), white oak (n = 1), and white pine (n = 1). Brush Mountain had the fewest number of Table Mountain pine saplings, as well as the fewest number of saplings in general, of the four sites sampled.

Table Mountain pine dominates the sapling composition at Griffith Knob with 131 saplings. Griffith Knob had the most extensive cover of Table Mountain pine saplings of the four sites studied. These saplings often were grouped together in what could be considered "doghair" thickets of pines, similar to the unhealthy doghair thickets of ponderosa pines found throughout the western U.S. (Covington and Moore 1994). The other yellow pines, Virginia and pitch, have 16 and 2 saplings respectively. Other dominant saplings are scarlet oak (n = 99), white pine (n = 18), northern red oak (n = 11), and black oak (n = 11). Scarlet oak had its greatest numbers at Griffith Knob of the four sites.

The sapling species composition at Little Walker Mountain is also dominated by Table Mountain pines with 92 saplings, followed by white pine (n = 43), black gum (n = 35), chestnut oak (n = 15), black locust (n = 15), and red maple (n = 13). No other yellow pine saplings were present. The presence of large

Table 4.9. The number and species of saplings documented at each site. Saplings were recorded across the entire 50 x 20 m macroplot, three macroplots per site.

Species	**Brush Mountain**	**Griffith Knob**	**Little Walker Mountain**	**North Mountain**	**Total**	**Percent**
Acer rubrum	12	8	13	46	79	7.14
Carya glabra	0	2	0	0	2	0.18
Castanea dentata	1	2	5	1	9	0.81
Fagus grandifolia	0	0	0	0	0	0.00
Nyssa sylvatica	95	5	35	338	473	42.77
Pinus pungens	5	131	92	9	237	21.43
Pinus rigida	0	2	0	0	2	0.18
Pinus strobus	1	18	43	0	62	5.61
Pinus virginiana	0	16	0	0	16	1.45
Quercus alba	1	7	1	10	19	1.72
Quercus coccinea	0	99	1	0	100	9.04
Quercus montana	4	4	0	39	47	4.25
Quercus rubra	3	11	6	1	21	1.90
Quercus velutina	0	0	15	1	16	1.45
Robinia pseudoacacia	0	4	15	0	19	1.72
Tsuga canadensis	0	3	1	0	4	0.36
Total	**122**	**312**	**227**	**445**	**1106**	

numbers of white pines at Little Walker Mountain clearly indicates changes in fire regimes because white pines are not fire tolerant. White pine has thin bark that makes the species especially vulnerable to even low-intensity fires.

At North Mountain, we found extensive numbers of black gum in the understory, so much so that they made traversing through the stands difficult. In the macroplots, we found 338 black gum saplings. Other dominant saplings are red maple (n = 46 saplings) and chestnut oak (n = 39), and we found only 9 Table Mountain pine saplings. Both Brush Mountain and North Mountain had similar percentages of black gum, Table Mountain pine, and red maple, although North Mountain had many more chestnut oaks than did Brush Mountain.

Combined, the four sites show that the future composition of the overstory in the Jefferson National Forest could be dominated mostly by black gum (42.3%) and Table Mountain pine (21.4%). Together, the oaks currently comprise about 19% of the sapling composition. Chestnut oak, which is the second most common species in the current overstory, is only the sixth most abundant species among the current saplings. If the four sites are split, however, with Brush Mountain and North Mountain making up the northern sites, and Griffith Knob and Little Walker Mountain making up the southern sites, the northern sites could be dominated by black gum in the future while the southern sites would continue with Table Mountain pine as the dominant overstory species.

4.5.4.2 Seedling Composition

Although some natural mortality of the current seedling population will no doubt occur, examination of the composition of the seedlings can provide information on what the composition of the forest could look like well into the future. The seedling tally for Brush Mountain (Table 4.10) was dominated overwhelmingly by chestnut oak, with 150 seedlings (68%). Red maple had the second highest number with 44 seedlings (20%), while scarlet oak (n = 8), black gum (n = 7), northern red oak (n = 7), and black oak (n = 5) were found in relatively small numbers. We found no Table Mountain pine or any other yellow pine seedlings.

At Griffith Knob, the oaks in general dominated the seedling category (77% of all seedlings) (Table 4.10). Northern red oak dominated the seedling tally with 94 seedlings (32%), followed by black oak (n = 45, 15% of the total), scarlet oak (n = 39, 13%), chestnut oak (n = 35, 12%), and white oak (n = 17, 6%). Red maple (n = 26, 9% of all seedlings) and pignut hickory (n = 22, 7%) were also found but in relatively small numbers. In general, the yellow pines were not well-represented in the seedling tally, as we found only 8 Table Mountain pine, 3 pitch pine, and 5 Virginia pine seedlings, comprising only 5% of all seedlings at the Griffith Knob site.

Little Walker Mountain had the lowest number of total seedlings (114 in the three 10 X 20 m plots) found at any of the four sites (Table 4.10). The seedling inventory was dominated by red maple with 50 seedlings (44% of the total) and chestnut oak with 36 seedlings (32%). Other species found in relatively small numbers included northern red oak (n = 8, 7%) and American chestnut (n = 7, 6%). Only 5 Table Mountain pine seedlings were found (4%0, while no other yellow pine seedlings were found.

The overall trend in seedling composition continued at the northernmost site, North Mountain, where red maple dominated the seedling inventory with 73 seedlings (40%), followed by scarlet oak (n = 51, 28%) and black gum (n = 36, 20%). Together,

Table 4.10. The number and species of seedlings documented at each site. Seedlings were recorded in one randomly-selected 10 x 20 m plot within each of the three macroplots at all sites.

Species	Brush Mountain	Griffith Knob	Little Walker Mountain	North Mountain	Total	Percent
Acer rubrum	44	26	50	73	193	23.74
Carya glabra	0	22	0	0	22	2.71
Castanea dentata	0	1	7	2	10	1.23
Fagus grandifolia	0	1	0	0	1	0.12
Nyssa sylvatica	7	0	4	36	47	5.78
Pinus pungens	0	8	5	0	13	1.60
Pinus rigida	0	3	0	0	3	0.40
Pinus strobus	0	1	1	0	2	0.25
Pinus virginiana	0	5	0	0	5	0.62
Quercus alba	0	17	0	1	18	2.21
Quercus coccinea	8	39	0	51	98	12.05
Quercus montana	150	35	36	10	231	28.41
Quercus rubra	7	94	8	8	117	14.39
Quercus velutina	5	45	0	0	50	6.15
Robinia pseudoacacia	0	0	3	0	3	0.37
Tsuga canadensis	0	0	0	0	0	0.00
Total	**221**	**297**	**114**	**181**	**813**	

these three species make up 88% of all seedlings found at the North Mountain study site. Minor species included chestnut oak (n = 10, 5% of the total) and northern red oak (n = 8, 4%). We found no Table Mountain pine, Virginia pine, or pitch pine seedlings, similar to our findings for the other northern site, Brush Mountain.

Together, the future forests of the Jefferson National Forest could look very different from today's forests if the seedling inventory is any clue. The seedlings are currently dominated by the oak group (63%) followed by red maple (24%), a shade tolerant and fire intolerant canopy tree species. Black gum and hickory will also likely be found in this future forest, but the yellow pines appear to be declining in numbers based on trends seen in their importance values (Table 4.8), the sapling inventory (Table 4.9), and the seedling inventory, where they only comprise 2.5% of all seedlings at all four sites.

4.5.4.4 Mountain Laurel

The number and density of mountain laurel are normally kept in check by frequent fires, but the forest stands at all four sites had profuse growth of these stems, often forming thickets that were impenetrable and occasionally relatively tall (ca. 6 to 7 m). We found logs and snags of yellow pines (most likely Table Mountain pine) in the middle of these thickets that contained numerous fire scars, indicating that these locations had once experienced frequent fires and that the mountain laurel was a relatively minor component of the understory then. The current mountain laurel condition is such that any fire that does occur in these thickets could potentially cause moderate to high severity fires that could use the mountain laurels as ladder fuels to reach the crowns of the current canopy trees.

Although I could not crossdate the shrub rings from mountain laurels, I feel strongly that the ring counts are accurate depictions of the true ages of these stems. The trends in stem establishment, or resprouts, at all four sites were similar. Stem establishment began as early as the 1915 to 1935 period (Table 4.11). The stands at the two southern sites, Little Walker Mountain and Griffith Knob, indicated earlier establishment than the two northern sites, peaking in the 1950 to 1964 period. The mountain laurels sampled at Brush Mountain and North Mountain had later peak establishment between 1960 and 1974. Together, the four sites showed major establishment during the period 1945 to 1979, most likely related to the changes in fire frequency we found at all four sites beginning in the period 1925 to 1935.

4.5.5 Duff Depth

For Table Mountain pine seedlings to be able to establish, a duff layer less than 3 cm is needed (Rob Klein, *personal communication*), although other studies seem to indicate that Table Mountain pine seedlings can penetrate duff up to between 7.5 and 10.0 cm in thickness. On average, the duff depth at the four sample sites was consistent, ranging between 7.4 and 8.2 cm (Table 4.12), although we found considerable variability in the depths. At many locations within each site, duff and litter did not occur, likely because of the rather lithic and nutrient-poor soils found on the xeric sites where Table Mountain pines are generally found. However, we also found more than a few locations

Table 4.11. Periods and numbers of mountain laurels that established at sampling sites.

5-Year Period	Brush Mountain	Griffith Knob	Little Walker Mountain	North Mountain	Total
1915–1919	0	0	1	0	1
1920–1924	0	0	0	0	0
1925–1029	0	0	1	0	1
1930–1934	0	1	0	0	1
1935–1939	0	1	3	0	4
1940–1944	0	2	6	0	8
1945–1949	1	7	5	2	15
1950–1954	4	9	11	2	26
1955–1959	3	15	10	6	34
1960–1964	11	13	9	11	44
1965–1969	16	7	7	16	46
1970–1974	16	2	6	11	35
1975–1979	7	3	1	9	20
1980–1984	1	0	0	3	4

Table 4.12. Depth of duff layer at each sampling site.

Sampling Site	Duff Depth (cm) Range	Duff Depth (cm) Average
Brush Mountain	0–15	7.4
Griffith Knob	0–18	7.5
Little Walker Mountain	0–18	8.2
North Mountain	0–19	7.7

where duff was exceptionally deep, up to between 15 and 19 cm in thickness.

4.6 Discussion

4.6.1 Natural Range of Variability of Past Fire Events

The minimum fire interval at all sites was one year, and such fire events commonly scarred only one or two trees at each site. Short fire return intervals highlight the importance of fuels in the Appalachian Mountains. In the past, fires would have burned available fuels during drought years. If the amount of available fuel was low, then the fire event would have been spatially small and would only have burned a small number of trees. If all fuels are not consumed in any one fire event, because of weather or topography, it is likely that the site will burn again within a short time (Swetnam and Dieterich 1985; Grissino-Mayer 1995).

Hazard intervals are useful in the era of rehabilitation because they help determine the critical upper threshold lengths for fire-free periods (Grissino-Mayer 1995). Although these have proven useful at sites in the western U.S., the maximum hazard intervals found in this study for the Brush Mountain and North Mountain sites are ecologically unreasonable (479 and 73 years, respectively, for the all-scarred class). For the 10%-scarred class, only the Little Walker Mountain site had a realistic MHI value of 22 years. These values likely occur due to the unusual shape of the distributions of fire-free intervals for each site, which tend to be dominated by the shorter intervals, creating a distribution that is more shaped like a negative exponential curve rather than a unimodal, though positively skewed, distribution.

In this case, the UEI is a better indicator of the maximum fire-free interval that can be sustained by these ecosystems because it is less affected by the skewness apparent in these fire interval distributions (Grissino-Mayer 1999). Inspection of the UEI values for all four sites shows that fire can be expected after only relatively short fire-free periods. For example, the UEI for all four sites for the all-scarred class ranged from 4 years at Griffith Knob to 8 years at Brush Mountain, indicating that fire is highly likely after fire-free periods of these lengths have been reached. The values for the 10%-scarred class show that more widespread fires are likely to occur after only 8 fire-free years have passed at Little Walker Mountain and up to 19 years have passed at Brush Mountain. The maximum fire intervals for all four sites for both scarred classes surpass the UEI values, indicating that conditions have occurred in the past that allowed extended fire-free periods, highlighting the variability that exists in these fire regimes.

Particularly noticeable is the long fire-free period at all four sites since the last fire year. At Brush Mountain, the last fire event that scarred at least two trees in our study occurred in 1957. The very last fire, recorded on only one tree, occurred in 1972. These fire-free intervals (51 years and 36 years) far exceed the UEI for Brush Mountain of 8 years, as well as the maximum fire-free interval recorded during the period of reliability of 13 years, highlighting the degree of fire hazard that currently exists on Brush Mountain. Curiously, our sites sampled for fire history here were immediately adjacent to expensive mountain-side houses.

Similar situations exist at the other three sites. At Griffith Knob, the very last fire of any type occurred in 1980, creating a current fire-free intervals of 28 years, which again far exceeds the UEI for this site of 4 years and the maximum interval of 9 years found during the period of reliability. At Little Walker Mountain, the last fire recorded on at least two trees occurred in 1954, although three later fires occurred that scarred only one tree each in 1962, 1976, and 1994. The fire-free interval since 1954 of 54 years is much longer than the UEI value of 5 years and the maximum interval actually sustained during the period of reliability of 10 years. Finally, the fire hazard situation on North Mountain is particularly dire because the last fire that scarred two trees in our study occurred in 1963, creating a long fire-free interval for major fires of 45 years (although single-tree fires were found in 1968, 1970, 1972, and 1998) which far exceeds the UEI of 7 years and maximum interval of 17 years found for this site. This results suggest that the maximum threshold fire-free interval has been reached and exceeded at all of our study sites, and that the probability of fire at all sites is dangerously high.

The standard deviation values were high, mainly because of the significant skewness that was apparent in all fire interval distributions. The SD values for the all-scarred class ranged from 2 to 3 years, indicating little variability about the mean, but this arises because the measures of central tendency in all distributions were quite low. Based on this finding, I would recommend that fire managers use more variety in fire-return intervals inside the boundaries of the LEI and UEI for each site. Not surprisingly, we found that the range of values of the coefficient of variation were similar for all four sites, indicating the variability of fire-free intervals was similar.

4.6.2 Fire Seasonality

Occasionally, the arrival of Native Americans to an area is heralded by a change in the seasonality of fire events (Lewis 2003). However, this was not the case for the

Table Mountain pine sites sampled for this research. The seasonality of the fires was, for the most part, constant and unchanging. At Brush Mountain and North Mountain, the majority of fire events took place during the dormant season, with the occasional fire taking place during a different season. At Griffith Knob and Little Walker Mountain, there was more of an even mix between dormant, early-early, and middle-early season fire events, with few late-early or late season fire events.

During the early spring before hardwoods flush, fires are common because of increased temperatures and wind speeds and low humidity, which work together to dry surface fuels. These fuels remain exposed to the sun and wind until hardwoods flush in mid- to late April in low to middle elevations. During the late spring and into the summer, new vegetation growth increases, humidity rises, and wind speeds decline, all of which reduces the likelihood of fires relative to the number of lightning flashes (Lafon *et al*. 2005). However, summer fires are beneficial in pine stands because they cause greater hardwood mortality than dormant season burns (Sutherland *et al*. 1995), fewer hardwood sprouts (Lafon *et al*. 2005), and are also followed by pine recruitment (Sutherland *et al*. 1995). Such burns occurring after hardwoods have flushed are the best control of hardwoods because burning soon after flush depletes root reserves of food (Farrar 1998).

4.6.3 Age Structure

The age-structure analysis at all sites indicates that fire-tolerant pines and hardwoods, as well as fire-intolerant hardwoods, establish after fire events. However, the last major cohort establishment initiated by a fire event in the 20th century was then succeeded by fire exclusion practices, such as active fire suppression, road building, and development in the wildland-urban interface. This resulted in an increase in the numbers of fire-intolerant hardwoods because the last cohort was never thinned by fire and has been allowed to expand. All sites are multicohort stands, in which two or more disturbance events create stands of component trees and because subsequent disturbances do not entirely remove the existing tree cover. This type of stand occurs where disturbances occur at regular intervals (Oliver and Larson 1996).

Stand ages are a good approximation for the date of the last higher-severity fire, because such fires can occur without producing fire scars (Kulakowski and Veblen 2002). Age-class data can provide evidence of additional fires not recorded as fire scars (Arno and Petersen 1983). Such events are recorded by obvious cohort establishments that do not coincide with a known fire event. Such events occurred at both Griffith Knob in 1926 and Little Walker Mountain around 1900. The 1900 cohort establishment at Little Walker Mountain is likely the result of an unrecorded fire event. However, the cohort establishment in 1926 at Griffith Knob could be the result of the chestnut blight. Chestnut blight reached southwestern Virginia by the 1920s (Gravatt and Marshal 1926; Agrawal and Stephenson 1995) and uses scarlet oak as a secondary host (Fralish and Franklin 2002). The demise of the tree would have opened up the canopy for competing hardwoods and pines. However, this does not explain the cohort establishment of Table Mountain pine, which would have still required fire for regeneration. For this reason, there must have been a 1926 fire event at Griffith Knob that was not recorded by any of the sampled trees. The lack of post-fire cohorts indicates that those fires were low severity or spatially small (Kulakowski and Veblen 2002).

In general, the age structure of overstory trees in stands at all four sites indicate to some degree past disturbances (likely wildfires) that prepared the stands for new establishment by both pines and hardwoods. At Brush Mountain, oaks clearly established en masse in the late 1920s while the yellow pines established beginning in the early 1930s. The fire chart for Brush Mountain also shows a dramatic establishment of yellow pines following the 1853 wildfire. At Griffith Knob, the age structure shows that yellow pines established in three pulses: beginning ca. 1890, again ca. 1925, and again beginning soon after 1950. The oaks appear to establish ca. 1920, perhaps following the widespread fire of 1916. The fire chart for Griffith Knob also shows a major cohort of pines established ca. 1890, corroborating the evidence shown in the age structure graph.

At Little Walker Mountain, the yellow pine show continuous establishment beginning in the early 1900s, while the oaks show continuous establishment beginning in the early 1800s. This result is slow shown by the fire history chart, as no clear cohort was evident in the establishment dates of the yellow pines used for the fire history analyses. At North Mountain, the oaks and other hardwoods established en masse beginning ca. 1900, similar to the stands at Brush Mountain and Griffith Knob. The yellow pines, however, do not show a major pulse of establishment in the age structure graph, although a small cohort is evident in the fire history chart beginning ca. 1930, again similar to brush Mountain and Griffith Knob.

For these fires to initiate pulses of establishment of both pines and hardwoods, the fires must have been of moderate intensity and severity, removing much of the duff and litter to prepare a bare mineral soil seedbed. In addition, it is likely these fires removed competing vegetation in both the understory (e.g., mountain laurel) and overstory (e.g., young and/or overmature pines) to ensure adequate nutrients and sunlight were available for seedlings that established soon after. These results suggest that the fire regime of our pine/mixed hardwood stands were mixed-severity, dominated by low-severity wildfires but punctuated occasionally by the moderate severity fire. In none of stands did we find evidence of a high severity fire, which would have been revealed by all trees establishing within a short time frame, as is typically found in portions of the western U.S. (e.g., ponderosa pine stands)

4.6.4 Future Stand Composition

Certain stand characteristics, such as the age structure, the amount of pine reproduction, type of understory, and duff depth, give an indication of the permanence of the stand (Zobel 1969). We were able to investigate these stand characteristics at each site using increment cores obtained from canopy dominants, calculating importance values, tallying seedlings and saplings by species, and examining the ages in mountain laurel cross-sections.

Table Mountain pine currently dominates the canopy at three of our four study sites: Brush Mountain IV = 48, Griffith Knob IV = 70.03, and Little Walker Mountain IV = 41.79. However, at North Mountain, Table Mountain pine (IV = 16.28) is third in dominance behind chestnut oak (IV = 35.36) and black gum (IV = 31.92). Table Mountain pine has the highest basal area of any canopy tree at Brush Mountain, Griffith Knob, and Little Walker Mountain, and the second highest at North Mountain. When considering all sites, Table Mountain pine has the highest frequency, dominance, density, basal area, and importance values of all tree species, indicating that the species is the overall canopy dominant. This indicates that a large seed source should be available to reestablish dominance of the species in the understory once a regular fire return interval is maintained. However, we found no Table Mountain pine saplings in the macroplots at North Mountain and only five saplings (roughly 4%) at Brush Mountain. In contrast, at the two more southerly sites, Griffith Knob had 131 (41%) Table Mountain pine saplings and Little Walker Mountain had 92 (39%) saplings. Sapling tallies at Brush and North Mountains were both dominated by black gum.

Inspection of the current seedling population can provide some indication of what the forest of the far future could look like. We found no Table Mountain pine seedlings in the macroplots at North Mountain and Brush Mountain. Chestnut oak (n = 150 seedlings) dominated the seedling tally at Brush Mountain, while red maple dominated the seedling tally at North Mountain (n = 73 seedlings) and Little Walker Mountain (n = 50 seedlings). Northern red oak dominated the seedling tally at Griffith Knob (n = 94). There were very few Table Mountain pine seedlings at Griffith Knob (n = 8) and Little Walker Mountain (n = 5). Taken together, the future of Table Mountain pine, if the seedling and sapling inventories are any indication, is rather bleak. Table Mountain pine is likely not establishing in large numbers as would be expected given the dominance of this specie sin the current overstory. We suspect changes in the fire regimes beginning in the early 1900s and continuing into the late 20th century may have altered stand conditions (increased duff and litter accumulation, crowded understory dominated by mountain laurel) so that Table Mountain pines can no longer successfully establish.

Out of the thousands of seedlings produced by a mature tree, only a few survive. Most seedlings die because of a lack of light, water, and/or nutrients, and because of strong competition that prevents their reaching the canopy (Bonan 2002). Chestnut oak, a long-lived, fire-dependent species, can compete with fire-intolerant species because infrequent fires burn within their lifespan (Barnes *et al*. 1998). Even though there are high numbers of red maple and black gum at Brush Mountain, if fires continue to be suppressed the canopy will become dominated by chestnut oak with red maple and black gum as codominants.

Griffith Knob has a high number of Table Mountain pine saplings, indicating that a future canopy could remain dominated by the species. However, the seedling tally indicates a future canopy dominated by oaks and hickories. A similar situation exists on Little Walker Mountain where Table Mountain pine dominates the sapling tally, but red maple and chestnut oak dominate the seedling tally. The canopy at North Mountain is not currently dominated by Table Mountain pine and cannot be considered a true yellow pine stand. The lack of Table Mountain pine and dominance of oaks, black gum, and red maple in the understory suggest that North Mountain will be a hardwood site in the future.

Rates of Table Mountain pine establishment are higher at Little Walker Mountain and Griffith Knob than they are at North and Brush Mountains. This is likely related to two factors: seasonality of fire events and age of the Table Mountain pine canopy. Little Walker Mountain and Griffith Knob both have high occurrence of fire events during the dormant and early-early season, which would better control hardwood competitors and allow for more yellow pine establishment. This is not the case at North and Brush Mountains, where the vast majority of fires occurred in the dormant season. Dormant season fires do little to control hardwood competitors in yellow pine stands. Secondly, Little Walker Mountain and Griffith Knob have a larger population of Table Mountain pines older than 76 years, creating a population of adult trees producing viable seeds (after Gray 2001). The population of Table Mountain pines at North and Brush Mountains in this age class is minimal, so the viability of seeds produced at these sites will be less.

Analyses of mountain laurel establishment dates (more correctly termed “resprout dates” as this species primarily reproduces from basal sprouts) indicated that fire events can initiate cohorts of the shrub. This species benefited from the last fire event at all four sites that allowed it to establish and then the succeeding years of fire suppression ensured its dominance and density in the understory. However, mountain laurel establishment has slowed greatly over the last 30 years, likely because over-crowded stands cannot allow any new establishment, and very few fires have occurred that would have initiated basal sprouting.

Average duff depths were extremely high at all sites, ranging from 7.4 cm at Brush Mountain to 8.2 cm at Little Walker Mountain. This depth would be considered too deep to support adequate pine regeneration at these sites (Rob Klein, personal communication). These depths would likely prevent successful Table Mountain pine seedling establishment and contribute to the declining numbers of Table Mountain pine in general. The greater depths of duff (and the associated litter on top of the duff) likely occur due to changes in fire regimes, beginning in the period between 1925 and 1935, when fire frequency became lower due to fire exclusion. Continued fire exclusion will allow the duff and litter to accumulate over the years, which could contribute to an overall decline in Table Mountain pine. However, Griffith Knob and Little Walker

Mountain have adequate pine regeneration. Therefore, it is more likely that fire seasonality plays a more important role than duff depth.

4.6.5 Anthropogenic Factors

The changes in composition from pre-settlement and early-settlement forests to modern forests were produced by changes in the dominant disturbance regime from fire to gap-phase processes (Cowell 1998). The traditional assumption that forests could return to a pre-settlement state is challenged by modern research and understanding of the role of disturbance in eastern forests and the significance of fire suppression policies (Cowell 1998). More than 60 years of fire suppression in yellow pine stands has led to an increase in hardwood density and the increasing dominance of fire-intolerant species, such as red maple, black gum, white pine, and mountain laurel (Welch and Waldrop 2001). Since the 1950s, fire suppression has increased mountain laurel populations creating understory conditions that prevent pine regeneration (Stanturf *et al*. 2002). Whittaker (1956) reported dense shrub cover of 60 to 90% in the GSMNP, after only 20 years of fire suppression.

The human disturbances that influenced vegetation at these sites was limited to accidental and escaped fires. Other disturbances, such as grazing, agriculture, and logging, were not possible at these rugged, high-elevation sites, or were minimal at best. If grazing had been significant on the landscape, changes in the frequency of fires would have been apparent, as has been shown by numerous studies conducted in the western U.S. This was not the case because these sites are too steep and high to be suitable for widespread and intensive grazing. These sites were also unsuitable for agriculture of any kind because of the steep, rocky soil. Logging was also not significant because Table Mountain pine was not considered a suitable logging species (Walker and Oswald 2000).

The question of who was starting the fires will never be confidently answered for the stands in question. Trees only provide information on the year, seasonality, and certain spatial aspects of the fire. It should be assumed that results presented here illustrate the natural- (i.e., lightning) and human-caused fire history of the sample sites. Fires ignited during the dormant season, early-early season, and late season are likely human caused, but some could be lightning-caused fires as well due to the frontal activity that occurs during the winter-spring transition period. Fires that occurred in the middle-early and late-early seasons are concurrent with the summer lightning season and are likely natural fires.

4.6.6 Spatial Factors

The differences that exist between the fire histories of individual sites can be explained by differences in land-use/settlement history, elevation, and topography. Broken topography is not conducive to the spread of wildfire (Lewis 2003). Natural barriers, such as water sources and rock bluffs, can slow or stop fire spread during a fire event (Sanders 1992). Such is the case at North Mountain where fires are not spatially contiguous. In oak dominated stands, such as North Mountain, fires are lower intensity anyway because oak fuels are less flammable than pine (Stanturf *et al*. 2002). Low-intensity fires tend to favor the recruitment of large-seeded species, such as oaks, which can penetrate a substantial duff layer (Heinselman 1981; Bond and van Wilgren 1996).

A mixed-severity fire regime exists at Brush Mountain, Griffith Knob, and Little Walker Mountain, where spatially large, potentially intense fires are mixed with smaller, potentially less-intense fires. This is possible because the landscape is continuous and undissected. These sites also have pine-dominated canopies, maintaining flammable pine litter on the ground. The spatial arrangement in coniferous forests can be more important in determining whether a fire will occur than biomass and moisture content. Coniferous forests are fire-prone communities with a densely packed crown of low moisture content and litter layers with low decomposition rates (Bond and van Wilgren 1996).

4.6.7 Fire in the Era of Rehabilitation

Table Mountain pines in the 5- to 10-year age class have the lowest seed viability (Gray 2001), which could result in low regeneration if young stands are burned too frequently. Table Mountain pines over 76 years of age have seeds with the highest viability (Gray 2001). Cones collected during the winter, or dormant season, (February) had the most viable seeds, while those collected in the summer (July) had the least viable seeds (Gray 2001). Management plans that include prescribed burning should consider tree age and season to ensure the viability of seeds (Gray 2001).

If trees over 76 years old contain the most viable seeds, this would indicate that regular stand-replacing fires would not be beneficial for regenerating Table Mountain pine stands. Short fire-return intervals suggest that populations may be killed before sufficient seeds have been produced to replace them. However, extremely long intervals suggest that populations are diminished to the extent that they cannot replace themselves (Bond and van Wilgren 1996). Genetic diversity in Table Mountain pine stands is maintained by frequent fire, which also allows for regular population turnover (Gibson 1990; Gray 2001). This suggests that management plans would have to include prescribed burns of mixed severity to encourage genetic diversity but also a viable seed source.

Despite their wet climate, the Appalachian Mountains contain ecosystems prone to regular burning. Appalachian forests experience heavy rainfall; however, droughts coupled with lightning without precipitation can initiate fires (Komarek 1966). When litter and duff are wet, fires do not ignite. However, direct sunlight, higher temperatures, and winds can dry the litter quickly enough to allow a slow, creeping cool fire to start. After several days of such conditions, fuels burn much hotter and after several weeks a significant fire can develop (Komarek 1974). Dead plant material has low moisture content in dry weather and initially carries fire. The combustion of the dry fuels decreases the moisture content of living fuels, making them prone to burning. Live leaves burn more easily if their moisture content is low (Bond and van Wilgren 1996).

A predicted northern retreat of southern pines caused by global climate change (Iverson and Prasad 1998; Barden 2000) has been used to explain the lack of Table Mountain pine regeneration in its southern range. However, the two most southerly sampling sites of this study, Griffith Knob and Little Walker Mountain, have the most significant Table Mountain pine regeneration. The lack of Table Mountain pine regeneration in certain areas is more likely the result of decades of fire suppression.

Griffith Knob and Little Walker Mountain had the most Table Mountain pine regeneration of the four sampling sites. This is likely due to the high percentages of early-early and middle-early season fires, as well as dormant season fires. Hardwood sprouting is more prolific after dormant season burns because of greater carbohydrate reserves (Hodgkins 1958; Van Lear 1990). For this reason, sites dominated by dormant season burns would not see as pronounced an increase in Table Mountain pine regeneration after fire events; such is the case at Brush and North Mountains. Plants with higher moisture contents are killed at lower temperatures, therefore plants in the growing season are more easily killed than when dormant (Bond and van Wilgren 1996). Fires that occur in the early-early and middle-early seasons, after hardwoods have flushed, would be more likely to control hardwood competition and ensure Table Mountain pine regeneration. Management plans should include prescribed burns of dormant through middle-early season.

Thinning may be necessary to prevent catastrophic or escaped prescribed burns in the wildland-urban interface. This would also be necessary to eliminate fire-intolerant hardwoods and shrubs, such as black gum and mountain laurel, which have now reached sizes that make them fire tolerant. Bark thickness typically increases with stem diameter, therefore fire will selectively kill thin-barked species and young individuals and small species (Peterson and Ryan 1986; Uhl and Kauffman 1990; Bond and van Wilgren 1996). Thinning would not be possible at the more inaccessible Table Mountain pine sites; however, such areas would require a higher frequency of prescribed burning until hardwood populations were under control.

Fire chronologies indicate that the current vegetation and fuel conditions in the yellow pine stands of the Central Appalachians are well above their thresholds for maximum fire-free periods. The extremely long fire-free intervals that began after the 1930s have altered the forest composition and fuel loadings, increasing the hazard of fire at these sites. Fire-intolerant shrubs and hardwoods, tree litter, and diseased trees that would have been consumed in the past by frequent, low-intensity fire are beginning to dominate traditional fire-tolerant pine-oak stands. Fire has historically acted as a regenerative force in Appalachian forests (Komarek 1966). Fire suppression has created unhealthy and hazardous conditions in this forest type as any future fires will be of increased intensity because of the increase in fuels. Future fires will also be more destructive because fire-intolerant hardwoods and suppressed fire-tolerant pines will not likely survive such a fire event. This will leave large sections of the Appalachians denuded and sterilized.

CHAPTER 5

RELATIONSHIPS BETWEEN WILDFIRES AND CLIMATE IN THE CENTRAL APPALACHIAN MOUNTAINS

5.1 Introduction

Fire management requires understanding of climatic effects and climate variation in fire occurrence across geographic areas (Schoennagel *et al*. 2005). Statistical, non-linear relationships between fire and climate are identified by comparing fire occurrence to proxy climate indices reconstructed using dendrochronological techniques (Hessl *et al*. 2004). This is accomplished using superposed epoch analysis (SEA) (Swetnam and Betancourt 1992; Swetnam and Baisan 1996), which evaluates climate conditions prior to, during, and after the year of fire (Grissino-Mayer *et al*. 2004). SEA is used to evaluate the responses of biological (such as trees) or physical (such as Earth) systems to external factors (such as changes in solar output or climate variation) (Kelly and Sear 1984; Lough and Fritts 1987; Prager 1992; Cleaveland *et al*. 1992; Taylor 1994; Grissino-Mayer 1995). Such an understanding of the relationship between fire and climate variability would aid forest managers in prescribed burning and fire management planning.

SEA is a form of analysis used to demonstrate periodicity of an effect on some phenomenon (Singh and Badruddin 2006). It was first used to study time variation in geophysical data, in particular periodicity in geomagnetic data. Since then, this method has appeared in testing of relationships between two different phenomena or periodicities (Singh and Badruddin 2006). SEA resolves signal to noise problems when response to a certain signal can be obstructed by another signal on a similar time scale. SEA involves organizing data into categories dependent on dates for synchronization and then comparing the means of these categories. For each date, the typical window analyzed is several years on either side of the date. An underlying response to a forcing event should then emerge in the average while other noise should cancel (Adams *et al*. 2003).

SEA has been used in studies that evaluated the relationship between climate and fire (Swetnam and Betancourt 1992), magnetospheric physics (Lühr *et al*. 1998), the lunar cycle and rainfall (Brier and Bradley, 1964), and the relationship between volcanic activity and climate variations (Mass and Portman 1989; Adams *et al*. 2003). In SEA, epochs (short time span chronologies) are selected depending on the value of each forcing event year. The selected years within the window are then averaged with similarly offset years and an averaged epoch is obtained. This type of analysis is valuable because it identifies persistent trends or relationships through different groupings of data (Chernosky 1960).

5.1.1 History of Superposed Epoch Analysis

The earliest documented uses of SEA were in activity that impacted Earth's physical systems, including weather, and how events in the troposphere impacted other atmospheric layers. One of these early studies evaluated the usefulness of SEA in the study of geomagnetic activity (Chernosky 1960). Chernosky found that solar influences on the Earth depend on previous solar events and solar disturbances are more variable than previously thought. Beynon and Winstanley (1969) used SEA to investigate the possible relationship between local tropospheric winds and the impact of magnetic storms, although this study yielded no concrete results, just possible proof of the relationship. Hines and Halevy (1975) evaluated the influence of solar magnetic activity on the troposphere vorticity area index (VAI), a measure of the strength of cyclonic activity in the Northern Hemisphere. They found that solar influence does have a marked effect on the form, as well as the timing, of weather events. Williams and Gerety (1978) assessed the relationship between the troposphere VAI and daily changes in solar magnetic activity and found that the strength of the VAI determines the strength of solar magnetic activity on weather patterns.

The use of SEA in solar studies eventually evolved into its use in evaluating the relationships between solar activity and weather (Haurwitz and Brier 1981). Joseph *et al*. (1994) investigated the relationship between longwave radiation and the timing of the Asian Monsoon. El Niño events will delay the monsoons the year after an El Niño event. This occurs because a change in sea-surface temperatures associated with El Niño events delays the northwestward movement of the equatorial convective cloudiness maximum, which delays the arrival of the monsoon in Asia.

SEA also began appearing in research of Earth's energy balance. Kelly and Sear (1984) investigated the impact of volcanic activity on the global energy balance and climate using SEA. Later, this involved into the classic study by Sear *et al*. (1987) that sought to prove the role of volcanic eruptions in forcing global temperature change. The level of cooling caused by volcanic eruptions is within the natural range of variability, and noise created by other climatic variables may be masking the volcano signal. Therefore, SEA was used to study the effects of volcanoes on climate to reduce this noise. Sear *et al*. found that Northern Hemisphere surface temperatures are more quickly affected by volcanic activity, while temperatures are slower to respond in the Southern Hemisphere. In fact, Southern Hemisphere surface temperatures did not respond significantly to Northern Hemisphere volcanoes. The influence of Southern Hemisphere volcanoes on Southern Hemisphere surface temperatures was found to be delayed by two years. Later, Adams *et al*. (2003) employed SEA to determine the response of the ENSO ocean-atmospheric system to volcanic activity, and found the probability of having an El Niño event was doubled following a volcanic eruption.

The use of SEA to help establish relationships between tree-ring widths and climatic indices, such as the North Atlantic Oscillation (NAO), also began appearing in climate research. D'Arrigo *et al*. (1993) used SEA to identify below-average ring growth that followed positive NAO anomalies during the winter months when high pressure and cold conditions dominated over Scandinavia. Orwig and Abrams (1997) used SEA to study the impacts of drought on tree rings from mesic and drought-tolerant tree species. Drought-tolerant trees increased growth rates after drought events, whereas mesic species decreased in growth after drought events. Birks (1998) reviewed the use of SEA in paleolimnological studies to discover patterns in paleopopulation data provided by the sedimentary record, thus proving the usefulness of SEA in paleolimnological studies. Ladah *et al*. (2005) documented the influence of the stratification of nearshore water on settlement pulses of *Chthamalus* spp. intertidal barnacles. Stratification of nearshore waters were found to be associated with the occurrence of internal tidal bores, which serve as an important onshore transport of Chthamalus larvae. Licandro *et al*. (2006) investigated the role of temperature oscillations (*i.e*., NAO) on interannual and seasonal fluctuations in populations of zooplankton in the northwestern Mediterranean Sea, and found that positive temperature anomalies increase populations of the zooplankton. Finally, Bradley *et al*. (1987) examined possible relationships between warm and cold phases of ENSO events and continental surface temperatures and precipitation patterns at different latitudes. SEA was carried out for the 36 months preceding each warm and cold phase between 1881 and 1980. During warm phase (El Niño) events, precipitation in the Sahel region of Africa and areas of India normally influenced by the Asian Monsoon was decreased. In the American Southeast, precipitation was found to increase during warm events and decrease during cold (*i.e*., La Niña) events.

Copenheaver *et al*. (2006) used SEA to investigate the occurrence of false rings in jack pines (*Pinus banksiana* Lamb.) growing in Michigan. The trees experienced significantly higher growth rates in the years preceding the false ring and false rings were more common in younger trees than in older ones. Suppressed trees were not likely to produce false rings, while codominant and intermediate trees were. Pohl *et al*. (2006) used SEA to investigate the timing of pandora moth (*Coloradia pandora* Blake) outbreaks with drought, climate variation (ENSO and PDO), and fire events. Outbreaks coincided with below-average moisture but the relationship with fire, which is dependent on climate variation, was unclear. Nola *et al*. (2006) investigated the relationship between outbreaks of larch budworm (*Zeiraphera diniana* Gn.) on the growth of larch (*Larix decidua* Mill.) and Swiss stone pine (*Pinus cembra* L.) in Italy. They analyzed the effects of outbreaks on tree growth in each species. The larch budworm had 19 outbreaks in larch stands between 1760 and 1999 and only three outbreaks in Swiss stone pine. No association was found between outbreaks and succession from larch to mixed stone pine-larch forests.

5.1.2 Superposed Epoch Analyses in Fire-Climate Studies

Fire-climate relationships have been investigated extensively in the ecosystems of the western U.S. (Swetnam and Baisan 1994; Donnegan *et al*. 2001; Floyd *et al*. 2004; Grissino-Mayer *et al*. 2004; Schoennagel *et al*. 2005; Taylor and Beatty 2005). In SEA, the year of the fire event is compared to climate conditions in the years leading up to the fire year, in the fire year itself, and in years following the fire year. The null hypothesis states that no relationship exists between fire occurrence and the climate variable(s) potentially forcing the fire event. SEA identifies average climate conditions by running random Monte Carlo simulations to generate more valid statistical confidence intervals (Mooney and Duval 1993; Grissino-Mayer 1995; Sibold and Veblen 2006), necessary when evaluating which years were significant to fire occurrence.

Heyerdahl *et al*. (2002) used SEA to investigate the influence of drought and ENSO events on fire size and occurrence in ponderosa pine stands of eastern Washington and Oregon between 1687 and 1994. Large fires burned during years of drought and El Niño years while small fires burned seemingly without any influence of major climatic processes. Climate from the previous growing season had no impact on fire occurrence. Stephens *et al*. (2003) found that Jeffrey pines that grow in New Mexico experienced large scale fires one year after significant rainfall. Floyd *et al*. (2004) used SEA and determined that piñon-juniper woodlands of Colorado were experiencing increased fire frequency and severity since 1995 because of natural climate variability, and not local anthropogenic factors. Stephens and Collins (2004) experimented with different spatial scales in fire reconstruction in the Sierra Nevada and investigated the relationship between drought and fire. In their study, the year of drought also tended to be the year of fire. Sibold and Veblen (2006) investigated the relationship between large fire years (1650–1978) recorded in Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and lodgepole pine (*Pinus contorta* Dougl. Ex Loud.) from Rocky Mountain National Park with climate variables, including measures of drought and climate indices (PDO, El Niño, and AMO). Extensive fire events were associated with drought conditions generated by La Niña events, a negative PDO, and a positive AMO. The co-occurrence of these three is more influential on fire occurrence than they are individually. In a related study, Sibold *et al*. (2006) evaluated the relationship between tree-ring-based reconstructions of PDSI and fire and non-fire years in Engelmann spruce, subalpine fir, and lodgepole pine from Rocky Mountain National Park. The authors found a relationship between large, severe fire events and exceptional drought events.

Hessl *et al*. (2004) used SEA to investigate the relationships between fire events and PDSI, PDO, and ENSO in Washington state. Fires were more common during dry summers and positive phases of PDO. There was also a stronger relationship between fire occurrence and ENSO events than found in previous studies. The relationship between drought and fire was strong between 1700 and 1900; however, during the 20th century, this relationship was disrupted due to drastic changes in land use. The authors suggest considering the PDO when developing long-term fire plans in the northwestern U.S. Schoennagel *et al*. (2005) investigated several western national parks to determine the relationship between fire and climate. SEA showed that large fire years in Rocky Mountain National Park coincided with extreme La Niña years. In Rocky Mountain National Park, Yellowstone National Park, and Jasper National Park, the PDO was negative during fire years, but was not statistically significant. Fires in Jasper and Yellowstone tended to occur during an El Niño event with positive PDO years. When considered singly, the warm and cool phases of ENSO and PDO were significant influences on fire occurrence. Combined warm phases (positive PDO and El Niño) increased fire occurrence in the northern Rockies (Yellowstone and Rocky Mountain National Parks) while cool phases (negative PDO and La Niña) increased fire occurrence in the southern Rockies (Jasper National Park).

Taylor and Beaty (2005) evaluated relationships between tree-ring reconstructions of PDSI, the Southern Oscillation Index, the PDO, and pre-EuroAmerican settlement fire regimes to evaluate the influence of drought and Pacific-based teleconnections on fire occurrence and extent. Fire years were associated with drought years, especially when fires were preceded by a wet period (positive PDSI) during the previous three years. A combined negative phase PDO and La Niña was most associated with fire occurrence. In a reconstruction of wildfires in the San Juan National Forest of Colorado, Grissino-Mayer *et al*. (2004) analyzed the impact of climate events around the fire event. Tree-ring indices were used to infer spring/summer rainfall conditions. The two years that preceded a fire event were found to be significantly wet, indicating climatic preconditioning as a factor in fire events. In the drier climates common in the western U.S., fire activity often peaks when drought years follow unusually wet years, which would promote the growth of fine fuels (Knapp 1995; Kitzberger *et al*. 1997; Grissino-Mayer *et al*. 2004; Lafon *et al*. 2005).

5.1.3 Fire-Climate Relationships in the Southeastern U.S.

Drought in the western U.S reduces moisture levels in forest fuels which then increases the probability of wildfire occurrence. The relationship between drought and fire occurrence is less understood, however, in eastern forests. The significance of drought in Table Mountain pine forests was first identified by Sutherland *et al*. (1995) who conducted limited climate analysis on Table Mountain pines in the central Appalachian Mountains. This study is the only research that analyzed the fire history of Table Mountain pines and its relationship with climate. Major and minor fire years were compared to PDSI to determine the role drought played in fire frequency and they found that major fire years did not always coincide with the most intense drought years. However, all fire years were associated with negative PDSI values, indicating a relationship between drought and fire.

Anomalies in global circulation patterns initiate the drought events that lead to fires in the western U.S. (Schoennagel *et al*. 2005). However, humid climates in the eastern U.S. tend to have consistent heavy fuel loadings that are always present, so climate during the year of fire may be the only significant relationship found. Lafon *et al*. (2005), working in the Virginia Blue Ridge Mountains, found a lack of significant correlations between fire occurrence and monthly PDSI values. This indicated that preceding wet years were not necessary to increase fuel loadings, which increases the possibility of high fire activity. There was therefore no evidence of preconditioning.

5.2 Objectives

Knowledge of how wildfires in Table Mountain pine stands respond to different climate variables is considerably lacking. It is important to understand this relationship to better understand how future changes in climate may impact the fire-climate relationship. Will increasing temperatures lead to more intense wildfires? Is temperature even a driver of wildfire activity, or is precipitation largely responsible? Will changes in the seasonality of precipitation alter fire regimes? The specific objective of this research is to evaluate the relationship between drought and wildfire and how excessive dry or wet periods may have influenced past fire occurrence in Table Mountain pine stands. An understanding of this relationship will provide management agencies with critical information concerning when Table Mountain pine stands can have fire introduced during a fire management program designed to rehabilitate deteriorating/declining pine/mixed hardwood stands in the central Appalachian Mountains.

5.3 Study Sites

The four research sites are located in the Ridge and Valley Province in the Appalachian Mountains in the Jefferson National Forest on west-central Virginia. The central Appalachian Mountains are characterized by a humid continental climate (Bailey 1978; Lafon *et al*. 2005). Soils of southern Appalachian pine forests are sandy-loam Ultisols and Inceptisols (Welch 1999), while the underlying geology of all sites is sandstone and shale. Deep, dendritic fissures created by water erosion have formed valleys and spurs on the ancient Appalachian tablelands (Hufford 2002) with distinct vegetation communities that vary with topography and microclimate. Yellow pine stands cover the south-, west-, and southwest-facing sides of these spurs in narrow strips that alternate with hardwood-dominated areas in drainages and on north- and northwest-facing slopes (Lafon and Kutac 2003).

Samples were collected from four adjacent ridges at a total of four study sites. Research sites were located on North Mountain (37º25'N, 80º10'W) in Craig County, adjacent to Craig Creek Valley; Brush Mountain (37º19'N, 80º20'W) in Montgomery County adjacent to the Craig Creek Valley; Griffith Knob (37º1'N, 81º13'W) between Little Walker and Brushy Mountains in Bland County, adjacent to Reed Creek Valley; and, Little Walker Mountain (37°03'N, 80°56'W) located on the north face of the mountain, in Bland County adjacent to Little Walker Creek. Research sites are between 670 and 1150 m (2200 and 3782 ft) in elevation, and receive between 81.5 cm (32 in) and 94 cm (37 in) of precipitation annually (NOAA 2005).

5.4 Methods

Superposed epoch analysis was used to determine whether or not certain climate conditions acted as precursors to fire events in Table Mountain pine stands. SEA is available in the FHX2 (Grissino-Mayer 1995) suite of software designed to analyze fire regimes from tree-ring data. SEA involves stacking, or superposing, fire events and calculating the average climate conditions surrounding that fire event temporally. Average climate conditions were calculated before the fire event (t – 6), the year of the fire event (t = 0), and after the fire event (t + 3). To determine statistical significance, confidence intervals were calculated using bootstrapping techniques on randomly selected fire events from the pool of observations (Grissino-Mayer *et al*. 2004). The null hypothesis states that no relationship (more than 10 years) exists between fire and climate in these stands. I used three different fire event datasets to evaluate climate forcing at three levels: (1) all fire events regardless of the number of trees scarred in any one year, (2) minor fire events, classified as those fire years when 10% of the sampled trees were scarred, with a minimum of two trees scarred per year, and (3) major fire events, classified as those fire events when 25% of the sampled trees were scarred, again with a minimum of two trees scarred in any one year. The more trees that were scarred by a fire event, the spatially larger the fire event is presumed to be.

In addition, SEA was conducted on two periods per site, the longer period of reliability being split into two shorter periods, based on changes in fire events observed visually in the fire charts. If no discernible change in fire frequency was discerned in the fire chart, the longer period was simply divided into two equal lengths. At each site, both fire periods were analyzed using all fire years, minor fire events, and major fire events (both 10%- and 25%-scarred). This type of analysis helps evaluate whether changes in the response by fire to climate has changed over time, thus signaling possible effects of climate change on fire regimes (Grissino-Mayer 1995, Grissino-Mayer and Swetnam 2000).

Fire events were first statistically compared in SEA to the Cook *et al*. (1999) PDSI reconstruction, which is a commonly used reconstruction in studies of fire-climate relationships. For the southeastern U.S., this reconstruction is based largely on eastern oak tree-ring chronologies that span 1700 to 1978 and are organized on a grid so that the point closest to the area of interest can be downloaded from the National Climatic Data Center website (NCDC 2007). I also reconstructed PDSI for each of the four sites using their respective Table Mountain pine tree-ring chronologies. The chronologies were regressed against regional monthly PDSI during the historical period 1940 to 2002 for the September through October fall months, a period deemed the most significant to Table Mountain pine tree growth in earlier analyses (see Chapter 3). Outlier years, usually caused by anomalous weather patterns, were identified using the Cook's D statistic with numbers farthest from zero being identified as probable outliers, and these observations were subsequently eliminated from analyses (Grissino-Mayer 1995). The calibration equation generated by the regression analyses were then used to reconstruct the PDSI values for years preceding 1940 at each site by inserting the tree-ring index for each year into the equation to predict the PDSI value for that year. The resulting PDSI reconstructions for each site were compared to fire events for a second analysis of fire-climate relationships of the region.

5.5 Results

5.5.1 Fire-Climate Relationships based on the Cook et al. (1999) PDSI Reconstruction

No relationships were found between the Cook *et al*. reconstruction of PDSI and fire events at Brush Mountain (Table 5.1). Significant relationships were found at Griffith Knob using the Cook *et al*. reconstruction. Griffith Knob was divided into two periods, 1764–1893 and 1894–1934, based on visible changes in fire occurrence. For all fire events, the early period showed a significant relationship ($p < 0.05$) with negative PDSI values two years after ($t + 2$) the fire event (Table 5.2), but interpretation of this relationship is not possible because climate in later years ca not affect fire in earlier years.

Table 5.1: Comparison of Cook *et al*. (1999) PDSI reconstruction (Cook) and Virginia PDSI reconstructions (VA) for Brush Mountain.

Classification/Epoch	Brush Mountain
All fires	t = 0 (VA)
Major 25% 1750–1860	t – 6 (VA)

Table 5.2: Comparison of Cook *et al*. (1999) PDSI reconstruction (Cook) and Virginia PDSI reconstructions (VA) for Griffith Knob.

Classification/Epoch	Griffith Knob
All fires 1764–1893	t + 2 (Cook)
All fires 1894–1934	t + 1 (Cook), t = 0 (VA)
Minor 10% 1764–1893	t – 5 (Cook)
Major 25% 1894–1934	t – 1, t + 2 (Cook)
Major 25% 1894–1934	t = 0 (VA)

In addition, the later 1894–1972 period showed a statistically significant relationship ($p < 0.05$) with positive PDSI values one year after (t + 1) the fire event (Table 5.2). For minor fire events, the early period showed a significant ($p < 0.05$) relationship with positive PDSI values five years before (t – 5) the fire event. For major fire events, the later period showed a statistically significant ($p < 0.01$) relationship with negative PDSI values one year before (t – 1) the fire event and two years after (t + 2) ($p < 0.05$) with positive PDSI values (Table 5.2).

Significant climate relationships were also found with fire events at Little Walker Mountain using the Cook *et al*. reconstruction of PDSI, which were similar to those relationships found when using the Virginia PDSI reconstruction based on Table Mountain pine (Table 5.3). For example, drought during the year of fire was found to be significant for all fires and for minor fire events (10% scarred) using both the Cook *et al*. reconstruction and the Table Mountain pine reconstruction. The year preceding major fire events was found to be statistically significant using the Cook *et al*. reconstruction. In addition, significant relationships were found for shorter epochs using Cook's data, including the early period (1778 to 1859) for the minor fire events (t – 2), and for the later period (1860 to 1934) for all fires (t – 6 and t = 0), minor fire events (t = 0 and t + 2), and major fire events (t – 1 and t + 3) (Table 5.3).

Lastly, significant climate relationships between fire occurrence at North Mountain and PDSI were found using the Cook *et al*. reconstruction. For all fire events, a significant positive relationship ($p < 0.05$) was found two years before (t – 2) the fire event (Table 5.4). A significant negative relationship was found six years before a minor fire event, while major fire events appear to occur when conditions are wet two years

Table 5.3: Comparison of Cook *et al*. (1999) PDSI reconstruction (Cook) and Virginia PDSI reconstructions (VA) for Little Walker Mountain.

Classification/Epoch	**Little Walker Mountain**
All fires	t = 0 (Cook), t – 6, t – 2, t = 0 (VA)
Minor fires	t = 0 (Cook), t = 0, t – 2, t – 4 (VA)
Major fires	t – 1 (Cook)
All fires 1860–1934	t – 6, t = 0 (Cook), t = 0, t – 4 (VA)
Minor 10% 1778–1859	t – 2 (Cook)
Minor 10% 1860–1934	t = 0, t + 2 (Cook), t – 1 (VA)
Major 25% 1860–1934	t – 1, t + 3 (Cook)
All fires 1778–1859	t – 2 (VA)

Table 5.4: Comparison of Cook *et al*. (1999) PDSI reconstruction (Cook) and Virginia PDSI reconstructions (VA) for North Mountain.

Classification/Epoch	**North Mountain**
All fires	t – 2 (Cook)
Minor 10%-scarred	t – 6 (Cook)
Major 25%-scarred	t – 2 (Cook)
Minor 10% 1858–1963	t – 6 (Cook)

before the fire event. North Mountain was then divided into two periods, 1742–1857 and 1858–1963, based on visible changes in fire occurrence seen in the fire charts for the site. For minor fire events, a significant relationship ($p < 0.05$) was found with negative PDSI values six years before ($t - 6$) the fire event during the second period of analysis.

5.5.2 Reconstructions of PDSI from Virginia Table Mountain Pine

Table Mountain pine tree-ring chronologies were used to reconstruct PDSI to offer a comparison to the fire-climate relationships observed using the Cook *et al*. (1999) PDSI reconstruction using eastern oak chronologies. The month of September through November had the best correlations with PDSI, so these months were combined into an average fall PDSI season that was eventually reconstructed. The reconstruction of PDSI conducted by Cook *et al*. (1999) reconstructed June through August.

For Brush Mountain (Figure 5.1A), I found two observations that could be considered outliers that adversely affected the regression during 1965 and 1980, and these were subsequently not used in the calibration equation. The final model showed a highly significant F-value (18.06, $p < 0.0001$), and indicated that 23% of the variance in the climate data was being captured by the tree-ring data, a value comparable to other pine reconstructions conducted in the southeastern U.S. The equation for reconstructing PDSI from Brush Mountain tree-ring data was:

$$y_t = -3.52 + 3.53(\text{Brush Mountain tree-ring index})_t$$

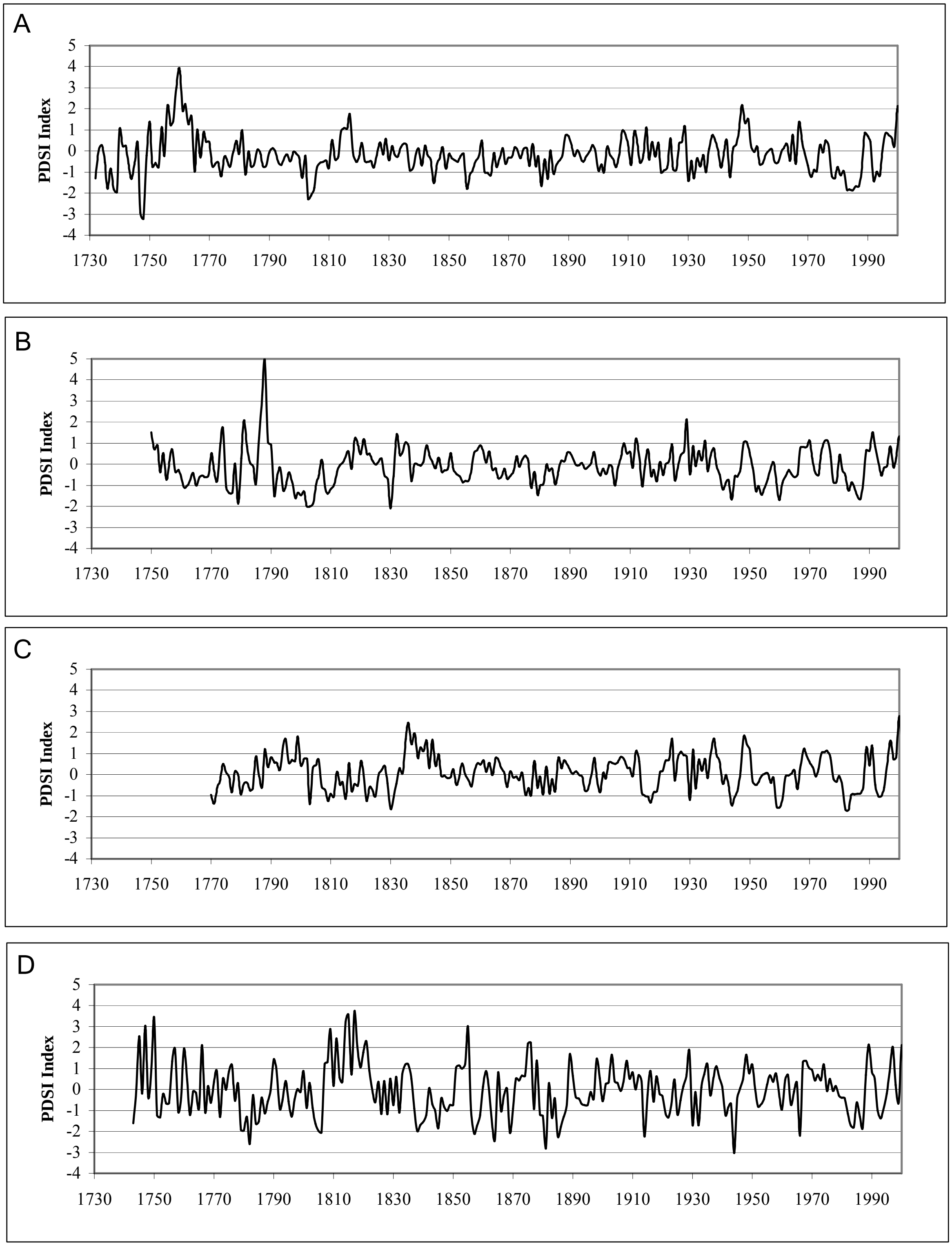

Figure 5.1: PDSI reconstructions based on Virginia Table Mountain pine chronologies for Brush Mountain (A), Griffith Knob (B), Little Walker Mountain (C), and North Mountain (D).

where y is the predicted PDSI during year *t*. A similar equation was developed for the tree-ring data from Griffith Knob (Figure 5.1B), which showed only one possible outlier observation for the year 1943. The final model showed a statistically significant ($p < 0.0002$) F-value of 15.32, while the model r-squared was 0.20. The equation for reconstructing PDSI at Griffith Knob was:

$$y_t = -3.17 + 3.52(\text{Griffith Knob tree-ring index})_t.$$

For Little Walker Mountain (Figure 5.1C), outliers were identified in the years 1943 and 1964 and these were subsequently not used in the calibration process. The final model showed that 20% of the variance in the PDSI data could be captured by the tree-ring data and the F-value (15.16) was statistically significant ($p > 0.0003$). The final equation for reconstructing PDSI from Little Walker Mountain tree-ring data was:

$$y_t = -3.49 + 3.41(\text{Little Walker tree-ring index})_t.$$

Finally, the regression analysis revealed four possible outliers that adversely affected the calibration process in the years 1943, 1964, 1965, and 1989 for North Mountain. The final model has the highest F-value found among the four models of 28.71 ($p < 0.0001$), while the r-squared was also the highest (0.33). The final equation for reconstructing PDSI at North Mountain (Figure 5.1D) was:

$$y_t = -5.13 + 5.11(\text{North Mountain tree-ring index})_t.$$

5.5.3 Fire-Climate Relationships based on PDSI Reconstructions from Table Mountain Pine

The PDSI reconstructions based on the Table Mountain pine tree-ring chronologies (henceforth referred to as the “Virginia PDSI reconstruction”) from each study site were compared to the fire events for that particular site by assessing all fire years, minor fire years (10%-scarred), and major fire years (25%-scarred). I also evaluated whether changes in the fire/climate relationship have occurred over time by comparing the SEA results between an early and late period for each site.

The first analysis concerns evaluating the relationship between climate and all fire events at all four sites, regardless of the number of samples scarred in any given fire year. As can be seen in the fire charts, the number of fires is high because those fires that scarred only one tree were included in this analysis. Significant relationships were found for two of the four sites. At Brush Mountain, the year of the fire event ($t = 0$) was significant ($p < 0.05$) (Figure 5.2A), indicating the occurrence of drought conditions during the year of fire. At Little Walker Mountain, I found a significant ($p < 0.05$) relationship between negative PDSI values and all fire events during the year of the fire event ($t = 0$), as well as two years ($t – 2$) and six years ($t – 6$) prior to the fire event (Figure 5.2C). Furthermore, the consistent near-negative PDSI values for all years from $t – 2$ to $t – 6$ prior to the fire year suggests that persistent drought over several years likely preconditions fuels that eventually lead to a wildfire at Little Walker Mountain. I found no statistically significant relationship between all fire events and drought at Griffith Knob (Figure 5.2B) and North Mountain (Figure 5.2D). However, the SEA results for both sites show similar trends, i.e. the year of the fire event had the lowest PDSI value while conditions preceding the fire year were less dry.

The second analysis concerns using a filter to remove the single scarred trees, using only years in which at least two trees recorded fire, and examine only those fire years where at least 10% of the recorder samples were scarred. Brush Mountain (Figure

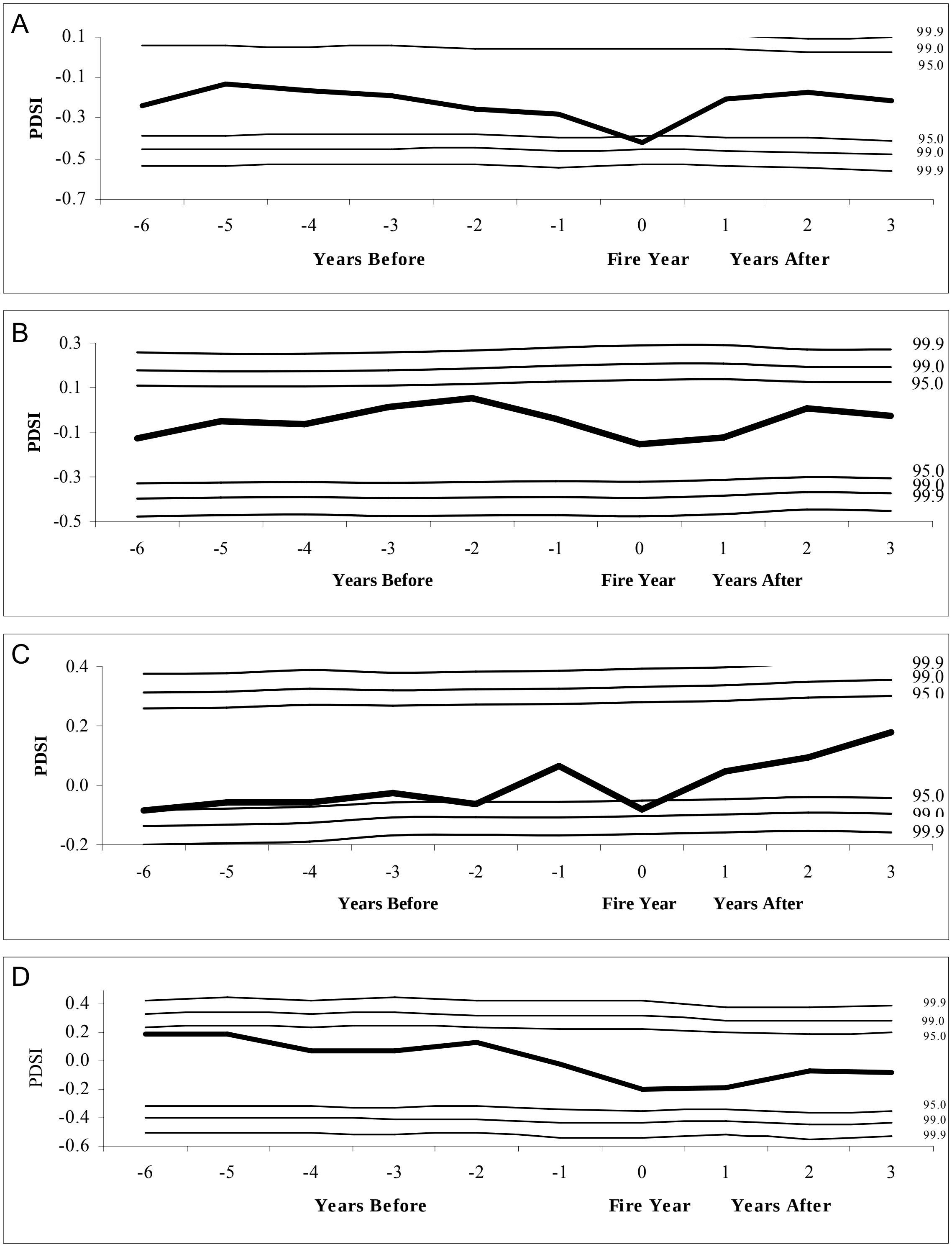

Figure 5.2: Relationships between Virginia reconstructed PDSI and all fire years from Brush Mountain (A), Griffith Knob (B), Little Walker Mountain (C), and North Mountain (D). Positive PDSI values indicate significantly wet periods and negative PDSI values indicate significantly dry periods.

5.3A), Griffith Knob (Figure 5.3B), and North Mountain (Figure 5.3D) showed no statistically significant relationship between drought and wildfire events. However, Little Walker Mountain again displayed statistically significant ($p < 0.05$) relationships between negative PDSI values and fire events for the fire event year ($t = 0$), two years prior to ($t – 2$), and four years prior to ($t – 4$) the fire event (Figure 5.3C). The overall graph of the SEA results for Little Walker Mountain is somewhat similar to the graph using all fire events (Figure 5.2C), suggesting little difference in the fire years used once the filtering process was applied.

The third analysis concerns using an additional, more rigid filter, this time using those fire years in which two trees recorded fire and in which at least 25% of the recorder trees were scarred. This analysis essentially isolates the major fire events, which should be climatically driven. None of the sites showed a statistically significant relationship ($p < 0.05$) between major fire years and PDSI values (wet or dry) during the year of the fire event or years leading up to the fire event (Figures 5.4A–D). At Griffith Knob, the year of the fire event again showed the lowest PDSI value in the 10 years window analyzed (Figure 5.4B).

Finally, I decided to divide up the period of analysis into an early period and a late period at each site, the division occurring at some visually identifiable year where a marked change in the fire regime occurred based on the fire charts. The subset SEA helps evaluate whether changes may have occurred in the climate/wildfire relationship over time, and which may be masking the overall relationship. For example, at Griffith Knob, the early period (1764–1893) showed no relationship between drought and all fire activity (Figure 5.5C), but the later period (1894–1934) did indeed show a statistically significant

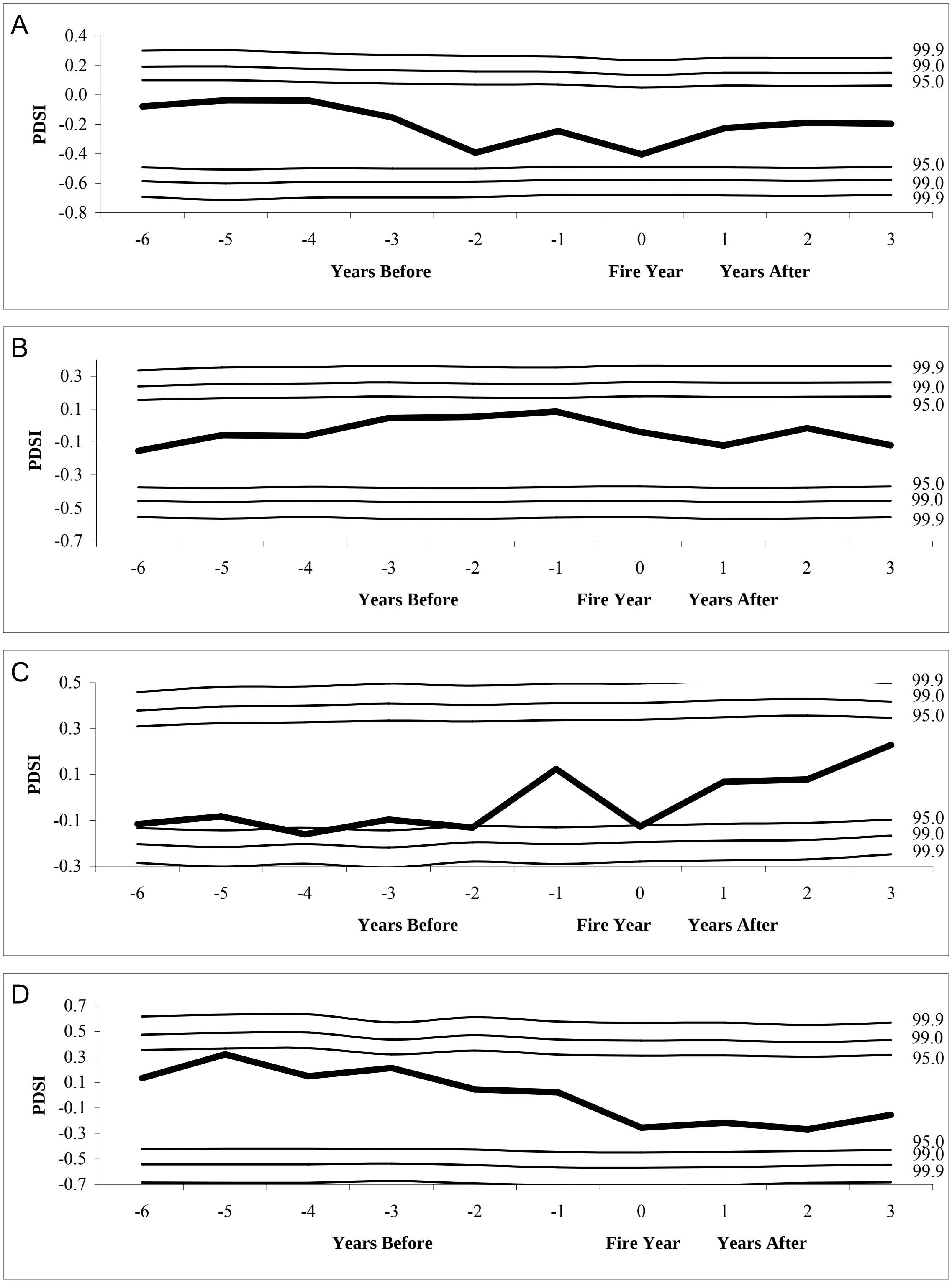

Figure 5.3: The relationship between the Virginia PDSI reconstruction and minor fire events (10%-scarred) at Brush Mountain (A), Griffith Knob (B), Little Walker Mountain (C), and North Mountain (D).

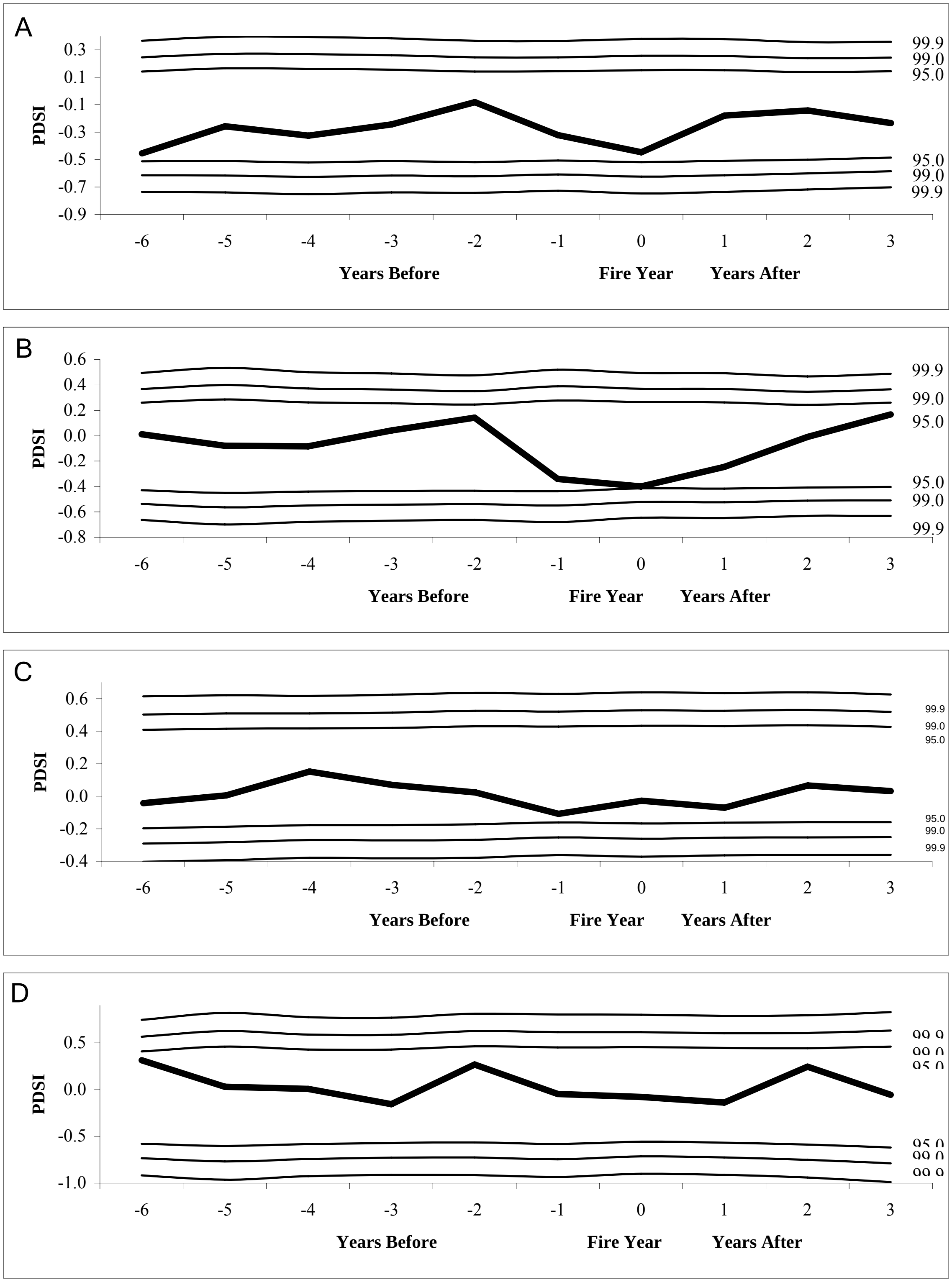

Figure 5.4: The relationship between the Virginia PDSI reconstruction and major fire events (25%-scarred) at Brush Mountain (A), Griffith Knob (B), Little Walker Mountain (C), and North Mountain (D).

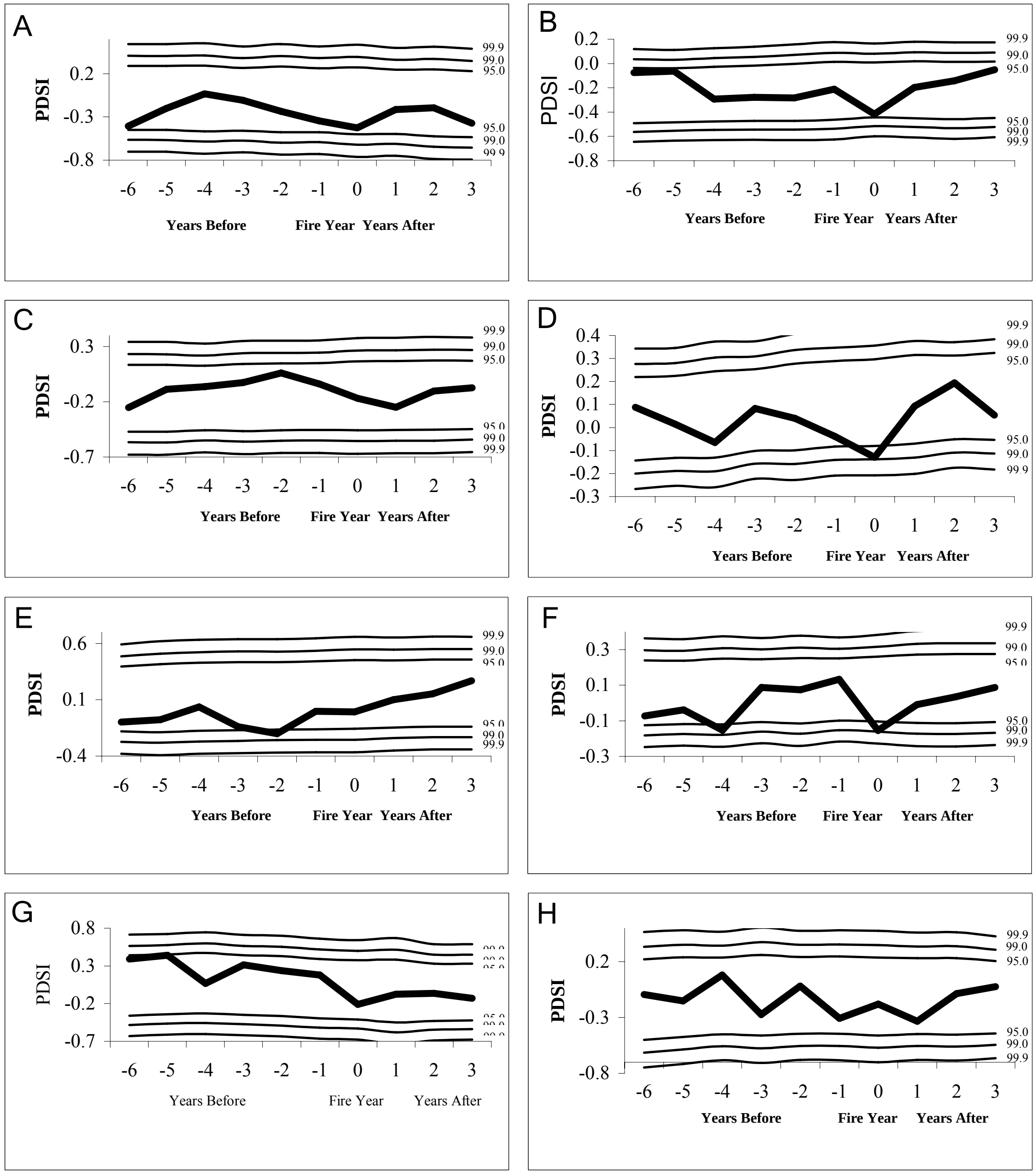

Figure 5.5: Relationships between the Virginia reconstructed PDSI and all fire events for Brush Mountain early period (1750–1860) (A) and late period (1861–1934) (B); Griffith Knob early period (1764–1893) (C) and late period (1894–1934) (D); Little Walker Mountain early period (1778–1859) (E) and late period (1860–1934) (F); and, North Mountain early period (1742–1857) (G) and late period (1858–1934) (H).

($p < 0.05$) relationship during the year of the fire event ($t = 0$) (Figure 5.5D). At Little Walker Mountain, a dramatic change in the relationship was observed when analyzing all fire events. During the early period (1778–1859), fires occurred when dry conditions prevailed two and three years before the fire event (Figure 5.5E). However, in the later period (1860–1934), this relationship changed. Fires now occurred when PDSI values during the year of fire were very low, preceded by dry conditions four years ($t – 4$) prior to the fire event between (Figure 5.5F). No significant relationships were found in this subset SEA for Brush Mountain (Figures 5.5A and B) or North Mountain (Figures 5.5G and H) for all fire events.

Similar relationships were observed when analyzing filtered fire events. For 10%-scarred fire years, Brush Mountain again showed no relationship in the early and late period (Figures 5.6A and B). The formerly significant relationship observed for Griffith Knob disappeared using the filtered data set (Figures 5.6C and D). However, Little Walker Mountain again showed a statistically significant relationship between drought two years ($t – 2$) before the fire event in the early period (1778–1859) (Figure 5.6E), as it did when analyzing all fire events. The later period (1860–1934) revealed that very wet conditions during the year immediately preceding a fire event ($t – 1$) acted as a precursor to fire activity (Figure 5.6F). At North Mountain, no significant relationship was observed in either period (Figures 5.6G and H).

When analyzing only the major fire events (minimum two trees scarred, at least 25% of all recorder trees scarred in any given fire year), the early period for Brush Mountain showed a relationship with drought six years ($t – 6$) prior to the fire event (Figure 5.7A), but no significant relationship was observed in the later period (Figure

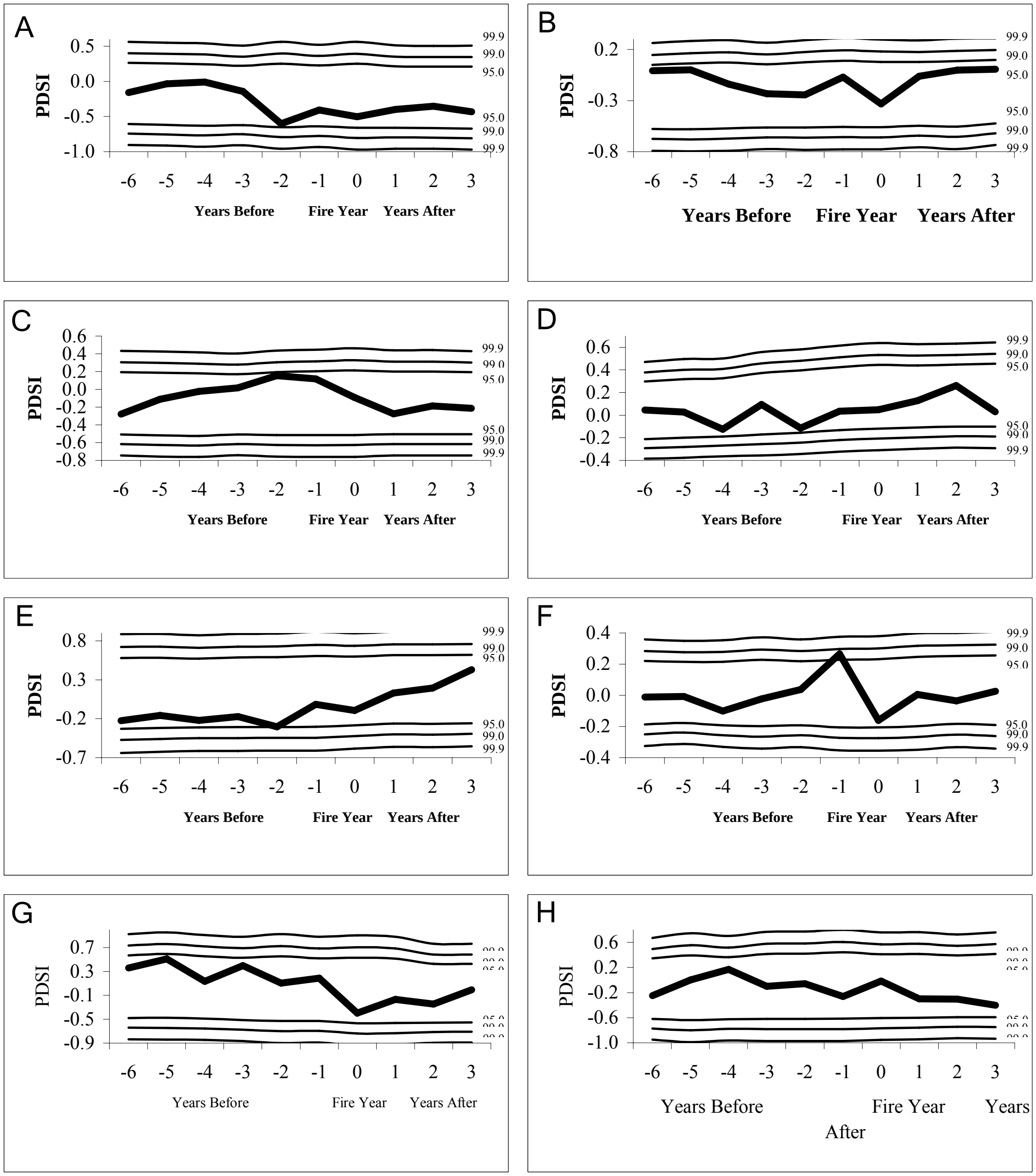

Figure 5.6: Relationships between the Virginia reconstructed PDSI and minor fires (10%-scarred) for Brush Mountain early period (1750–1860) (A) and late period (1861–1934) (B); Griffith Knob early period (1764–1893) (C) and late period (1894–1934) (D); Little Walker Mountain early period (1778–1859) (E) and late period (1860–1934) (F); and, North Mountain early period (1742–1857) (G) and late period (1858–1934) (H).

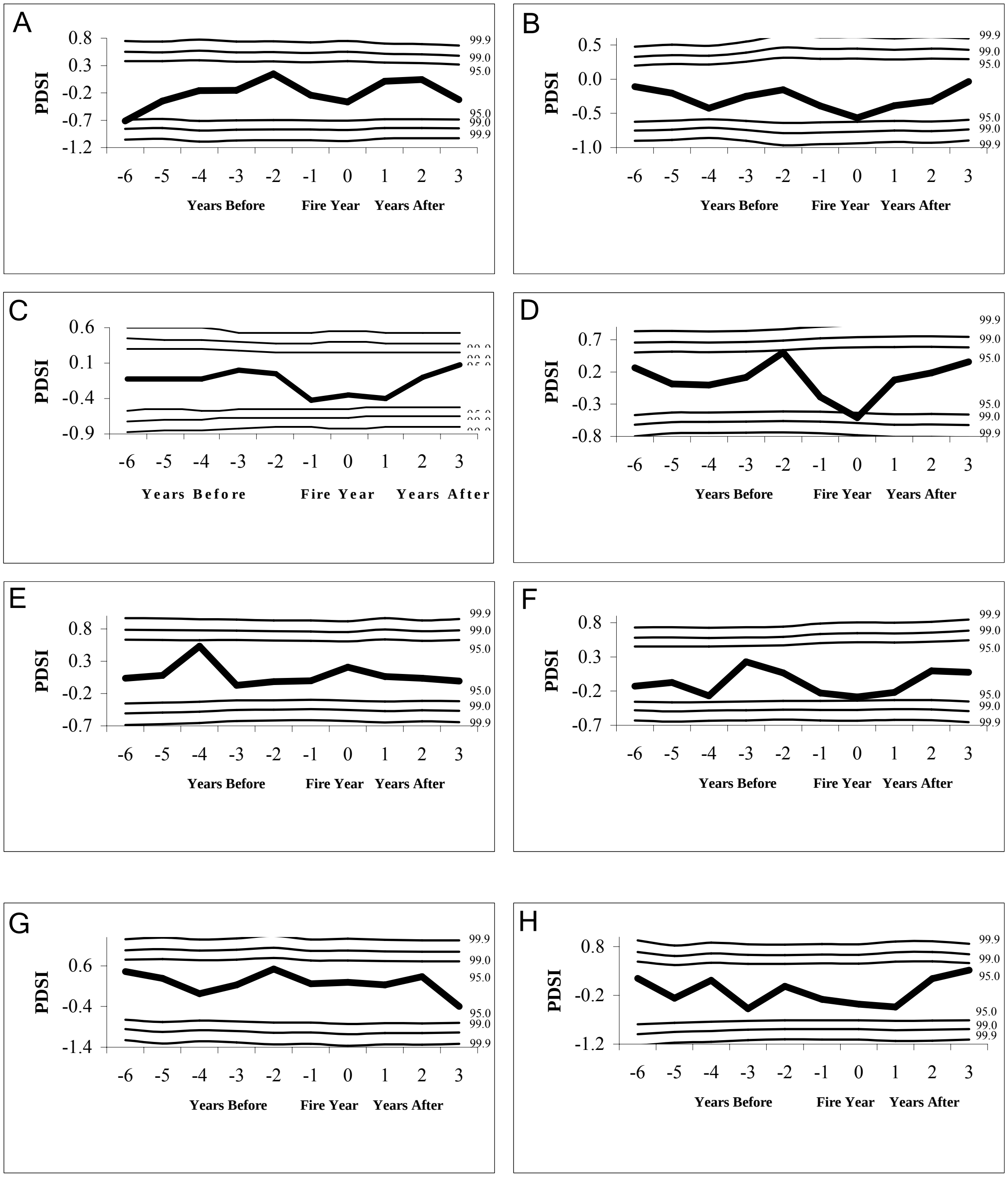

Figure 5.7: Relationship between the Virginia reconstructed PDSI and major fire events (25%-scarred) for Brush Mountain early period (1750–1860) (A) and late period (1861–1934) (B); Griffith Knob fire events early period (1764– 1893) (C) and late period (1894–1934) (D); Little Walker Mountain fire events early period (1778–1859) (E) and late period (1860–1934) (F); North Mountain fire events early period (1742–1857) (G) and late period (1858–1934) (H).

5.7B). At Griffith Knob, the early period (1764–1893) again showed no relationship between fire and drought (Figure 5.7C), but did display a statistically significant ($p < 0.05$) relationship with drought conditions during the year of the fire ($t = 0$) (Figure 5.7D), similar to the all fire event subset SEA for Griffith Knob (Figure 5.5D). In addition, wet conditions generally occurred two years prior to the fire event. At Little Walker Mountain, the significant relationships seen in the all fire year and 10%-scarred fire year analyses (Figures 5.5E and F and Figures 5.6E and F) were no longer seen in the 25%-scarred analysis (Figure 5.7E and F), although the year of year of the fire event and the year preceding the fire event were drier than average in the later period (1860–1934). North Mountain displayed no statistically significant relationships in either period for major fire events (Figures 5.7G and H).

The final type of SEA investigated possible regional climate drivers of fire activity. I combined all the tree-ring data from the four individual sites into one chronology and again reconstructed PDSI from this new composite chronology (Figure 5.8). I also combined the fire events from all four sites and conducted separate analyses on all fire events, those fire years when 10% of the recorder trees were scarred (minimum two trees scarred), and those fire years when 25% of all recorder trees were scarred. No statistically significant relationship was found for all fire events (Figure 5.9), which is to be expected given the large number of fire events found at all four sites when combined. Similarly, no statistically significant relationship was found for the 10%-scarred fire events (Figure 5.10), nor for the 25%-scarred fire events (Figure 5.11), although the year of the fire event in this latter analysis was drier than normal. Dividing up the period of analysis into early and late periods also showed few meaningful relationships. No

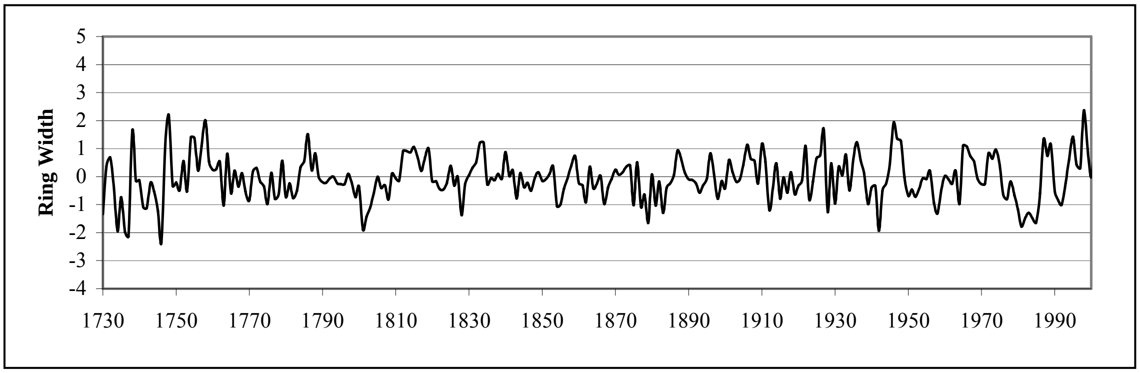

Figure 5.8: PDSI reconstruction based on a composite chronology created from all four Virginia Table Mountain pine chronologies.

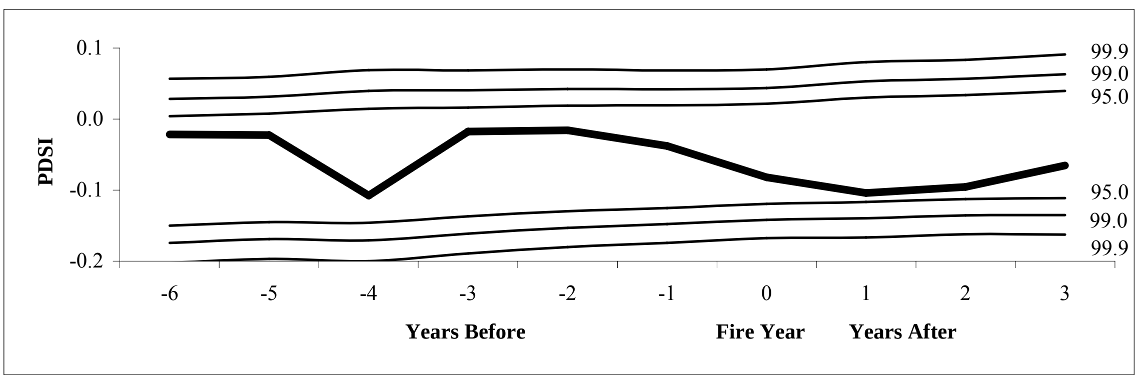

Figure 5.9: Relationships between Virginia reconstructed PDSI and all fire years at all sites.

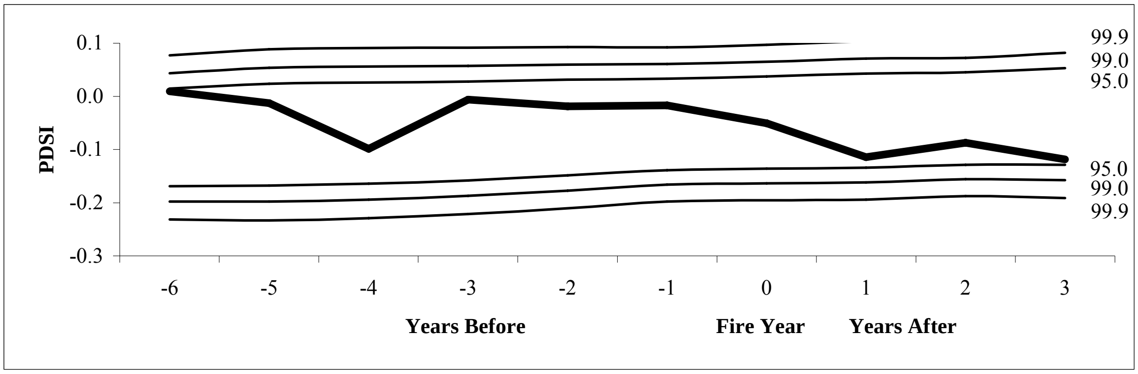

Figure 5.10: Relationships between Virginia reconstructed PDSI and minor fire (10%-scarred) years at all sites.

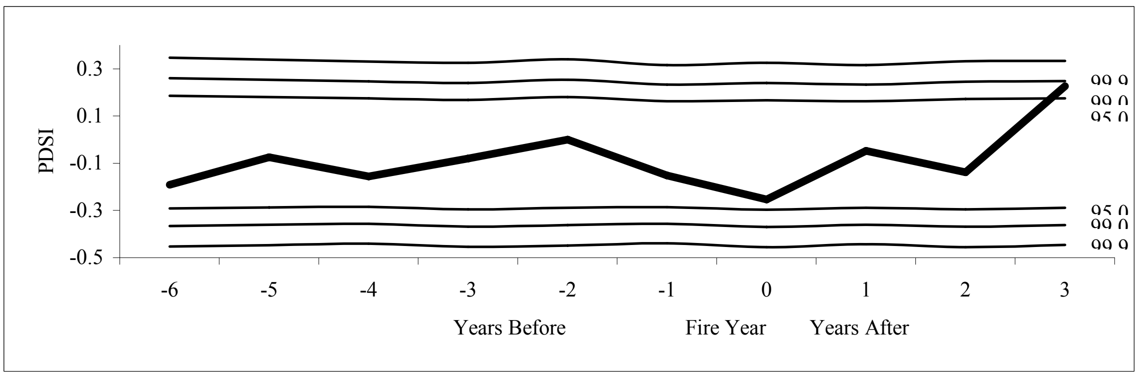

Figure 5.11: Relationships between Virginia reconstructed PDSI and major fire (25%-scarred) years at all sites.

relationship was found for all fire events (Figures 5.12A and B), although six years prior to the fire event was significant in the early period (1732–1850) for 10% scarred events (Figure 5.13A). In the 25% scarred analysis, no statistically significant relationships were observed (Figures 5.14A and B), although the year of the fire event was very dry in the earlier period. The lack of statistically significant and meaningful results in the other analyses may be an artifact of the large number of fire years that exist when combining all four sites, even after applying the 10% and 25% scarred filters.

5.6 Discussion

Using the reconstruction of drought from the Cook *et al*. (1999) gridded network for Virginia appeared a reasonable strategy for two reasons: (1) the reconstruction is known to be robust concerning the strength of species' response to climate, and (2) the oaks that were used would not have been affected by the fires experienced in the four Table Mountain pine study sites. I therefore hypothesized that stronger and more meaningful results would occur using the Cook *et al*. data set. However, the Cook *et al*. drought reconstruction showed only a few, weak relationships with fire events, and only at Little Walker Mountain did the results from the SEA appear similar between the oak reconstructed PDSI and the Table Mountain pine reconstructed PDSI. The Cook study reconstructed the period between June and August of the current growing season because this was the climate period that displayed the strongest and most consistent relationship with the gridded tree-ring data. The Table Mountain pine data sets developed in this study showed a statistically significant relationship with drought during late fall (September through November) of the previous year. However, the different seasonal

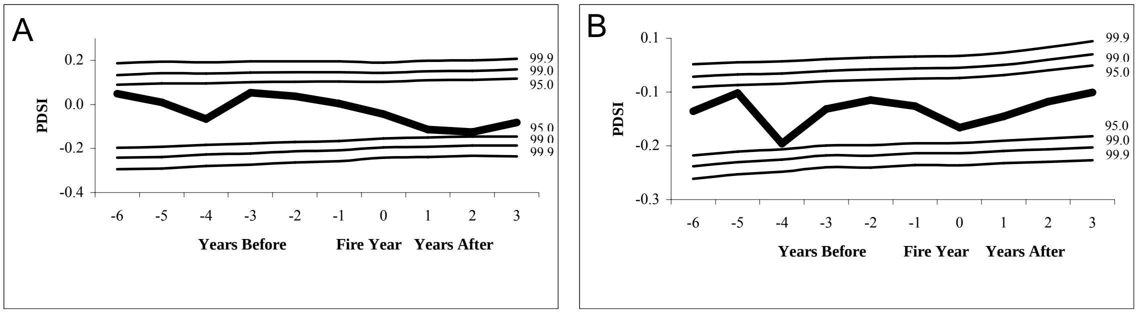

Figure 5.12: Relationships between the Virginia reconstructed PDSI and early period (1732–1850) (A) of all fires and late period (1851–1934) (B) of all fires at all sites.

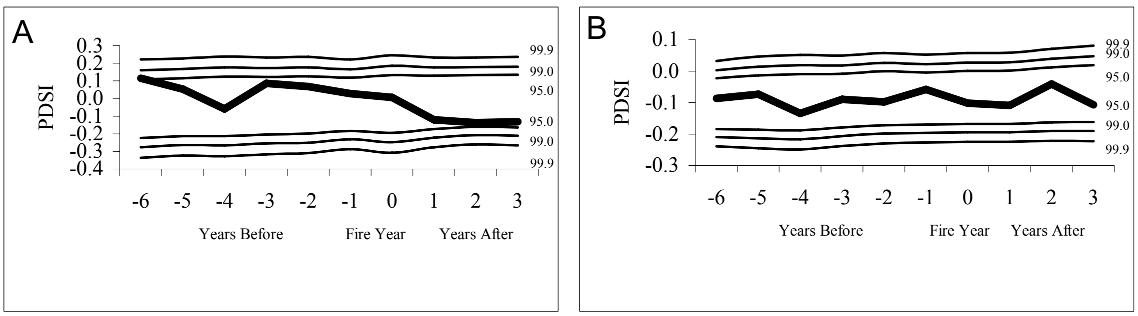

Figure 5.13: Relationships between the Virginia reconstructed PDSI and early period (1732–1850) of minor fires (10%-scarred) (A) and late period (1851–1934) of minor fires (10%-scarred) (B) at all sites.

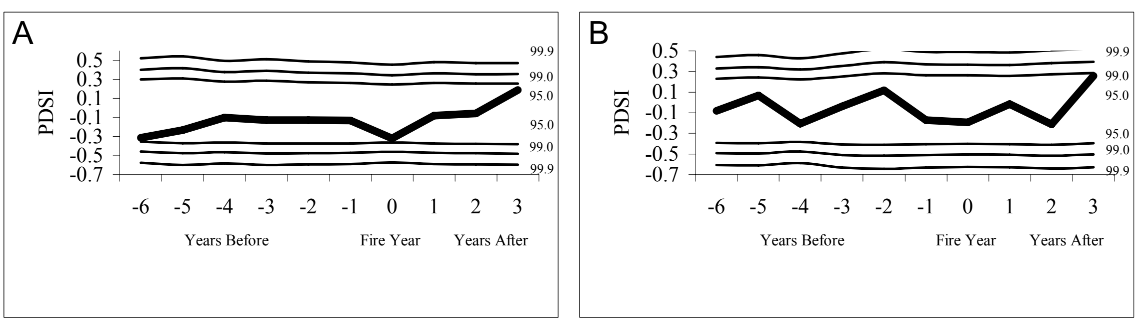

Figure 5.14: Relationship between the Virginia reconstructed PDSI and major fire events at all sites 25%-scarred early period (1732–1850) (A) and major fire events at all sites 25%-scarred late period (1851–1934) (B).

reconstructions should have no bearing or influence on the results of the SEA as both oak and pine are responding to drought (albeit in different seasons).

For the most part, the Cook reconstruction found years following the fire event to be statistically significant. For example, at Griffith Knob, drought during years t + 2 (early period, all fires; late period, major fires) and t + 1 (late period, all fires) were found to be significant. At Little Walker Mountain, the Cook *et al*. reconstruction showed relationships during years t + 2 (late period, minor fires) and t + 3 (late period, major fires). These subsequent years would have no influence on prior fire occurrence, of course, and were analyzed to look for overall temporal trends in climate over the 10-year window analyzed. In general, the results using the Cook *et al*. reconstruction were most ecologically meaningful for the Little Walker Mountain study site, where seven relationships were found in the SEA (Table 5.3).

Little Walker Mountain displayed the highest number of significant relationships between wildfire occurrence and drought (based on either the oak or pine reconstructions) of the four study sites. Griffith Knob showed the second highest number of relationships observed in the SEA results. These two sites are the two most southerly of the four sites, suggesting that some factor was possibly operating at the two northerly sites (Brush and North Mountains) that distorted the climate/fire relationship. One possible factor is the degree of anthropogenic influence on fire regimes at the Brush and North Mountain sites. These two sites today exist directly adjacent to major population centers, Roanoke, Virginia (North Mountain) and Blacksburg, Virginia (Brush Mountain), cities that already had increasing numbers of people in the late 18th and 19th centuries. Human-set fires could be more prominent in the fire chronologies for North and Brush Mountains, which would corrupt any attempts to isolate a relationship between wildfire and climate. Little Walker Mountain and Griffith Knob today exist in sparsely populated locations. Although some settlement occurred in adjacent valleys, the number of human-set fires may have been fewer at these more remote sites, allowing a more accurate assessment of fire/climate relationships at the two more southerly sites.

This hypothesis is also supported by the SEA results using the Cook *et al*. PDSI reconstruction. At North Mountain, no statistically significant nor ecological reasonable (i.e., near significant) results were obtained using the Table Mountain pine based PDSI reconstruction. However, analysis of the PDSI reconstruction developed by Cook *et al*. showed that years leading up to a fire year (t – 2 and t – 6) were especially dry at North Mountain, verifying the preconditioning effects of climate on fire occurrence at that site. The Cook *et al*. reconstruction was developed for locations distant from the sites analyzed in this study, and furthermore were likely located in areas that experienced less human influence.

I had also hypothesized that the fire/climate relationship would become more apparent only after combining the information from all four sites into one larger composite data set, including the tree-ring data to reconstruct PDSI as well as the fire years. However, the analysis of all sites combined did not yield additional information on fire-climate relationships in the region. The fire intervals at all sites are too short and fires so frequent that when fire years were combined among sites, a fire was found for almost every year. For this reason, it was impossible to identify patterns and relationships between drought and fire in the region. In retrospect, a better approach to this type of regional analysis would be to create a composite from the four composite fire chronologies for each site, and analyze only those fire years that occurred at all four sites in all three scarred classes (all fire events, 10%-scarred, and 25%-scarred).

An overall pattern in the fire/climate relationship did emerge when we consider all results obtained for the various superposed epoch analysis trials (Table 5.5). Inspection of the SEA graphs clearly showed that drought during the year of fire ($t = 0$) was necessary for a fire to occur. This relationship occurred more often and was more statistically significant than any other year analyzed in the 10-year window (Figure 5.15). This suggests that despite the possible influence of human-set fires, climate in the form of drought is the overarching factor that preconditions forest fuels for a low- to moderate-severity wildfire. In addition, the years leading up to the fire year also show that dry conditions act as a precursor to dry out the fuels before the fire event occurs in a year of well-below normal rainfall conditions. Unlike studies conducted in the western U.S., I found that wet conditions prior to the fire year had little influence on fire activity in the four study sites. Such wet conditions are thought to increase ground cover and increase fuel amounts overall, so that a fire in a subsequent drought year would be inevitable.

Superposed epoch analysis includes the years following the fire event to identify possible extended dry or wet periods that surround fire events to help evaluate whether an overall trend in climate exists when fire is more likely to occur. No such trends were found by these analyses, except for the Little Walker Mountain site. Here, dry conditions prevailed for nearly all six years prior to the fire event, and the years of the fire event itself was the driest. When all sites were combined, the years following fire event were shown as being significant or nearly significant. I consider these results as spurious and within the allowable statistical tolerances (i.e., at the 95% confidence level, at last one

Table 5.5: Results of Virginia PDSI reconstruction for all sites combined.

Classification/Epoch	All Sites
Major 25%	t + 3
Minor 10% 1732–1850	t – 6
Major 25% 1732–1850	t + 1
Major 25% 1851–1934	t = 0, t – 2

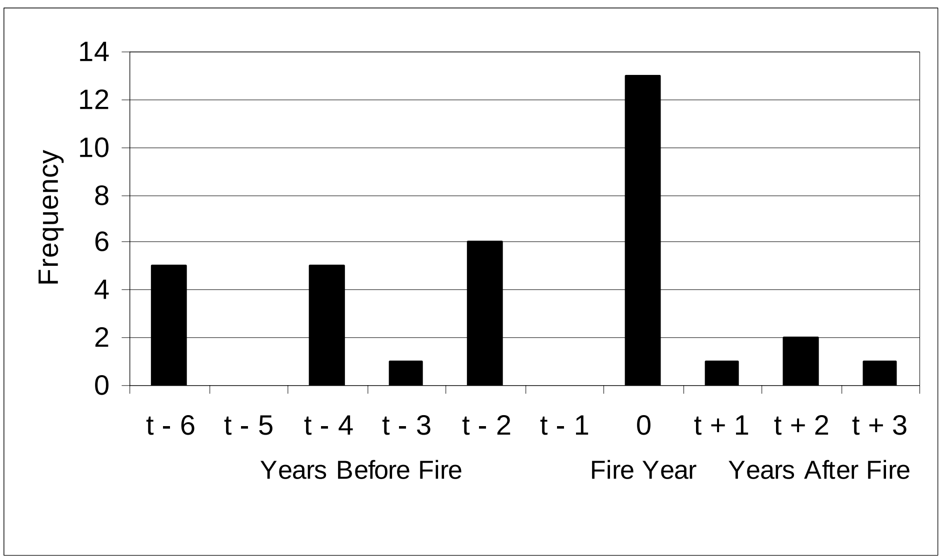

Figure 5.15: Composite results for all superposed epoch analyses conducted in this chapter (all epochs and all fire event classes) using Virginia Table Mountain pine PDSI reconstructions. Only the number of years showing relationships with negative PDSI values (drought years) are shown. Statistically significant and near significant i.e., ecologically meaningful) results are shown.

result in 20 tests will be statistically significant by chance alone) because the individual analyses did not show the years following the fire event to be significant. These analyses represent the first comprehensive set of tests using SEA performed on sites in the eastern U.S., and suggestions for improvement can be offered.

1. Results indicate that sites should be analyzed individually and not combined because sites have varying disturbance histories that will influence their degree of response to climate. Vegetation at sites that have a long history of anthropogenic influence will not have as strong a response to climate as those sites under natural influences.
2. Sites should be targeted that are far removed from large population centers because of the possible historical anthropogenic influence on fire regimes. When choosing sites, anthropogenic disturbance history should be considered a more important factor topographic factors, such as aspect and degree of slope.
3. For a regional analysis, the composite fire data from the composites for each individual site should be used. This will ensure that only fire years that are common to all sites are analyzed, and will lessen the actual number of fire events analyzed so that climatic relationships can be more accurately investigated.
4. Other climate indices should be explored as possible factors that influence fire occurrence, including the El Niño-Southern Oscillation, the North Atlantic Oscillation, and the Pacific Decadal Oscillation. Previous studies conducted in the central and western United States found meaningful

relationships between these climatic teleconnections and wildfire activity, and the influence of these teleconnections could be prominent in the southeastern U.S. as well. The influence of these on fire should be investigated singly and in combinations of positive and negative phases.

5.7 Conclusions

The most important finding of these analyses was that the year of drought is most significantly associated with the year of fire. I also found that there was no overall relationship between positive PDSI values (wet periods) preceding fire events and fire occurrence in Table Mountain pine stands, unlike studies conducted in the western U.S. For fire management in these stands, this suggests that precipitation in preceding years should not be used when trying to predict fire events. This is a logical result in the Appalachian Mountains where vegetation cover is always present regardless of abnormally high precipitation amounts. However, drought years preceding fire events (especially two years prior) could be useful indicators of the potential of future droughts to spark fires. Despite some analyses that showed no relationship between wildfire events and drought, overall we can conclude that fires that occur in Table Mountain pine stands are significantly influenced by climate. However, the degree of this influence is determined by the disturbance history, in particular anthropogenic disturbance, of the sites. These results showcase the importance of drought during the year of the fire event and are similar to those found by previous studies across the U.S.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this research was to investigate the potential of Table Mountain pine as a species acceptable for dendrochronological research, especially for reconstructing both fire history and climate history. Previous research had already established that wildfires had occurred in Table Mountain pine stands prior to pervasive human disturbances, but no study had comprehensively documented fire return intervals, the role of fire in cohort establishment, or the influence of climate variables on fire occurrence in these stands. Furthermore, knowledge of how Table Mountain pines respond to variations in climate is nonexistent; therefore, the ability to understand the role of climate as a driver of fire regimes in Table Mountain pine stands is also nonexistent. This chapter summarizes the major conclusions of this research and offers recommendations on how these conclusions can be implemented into a more ecologically sound land management plan.

6.1 Table Mountain pine as a recorder of fire and climate

1. This research proved that Table Mountain pine is a useful species for dendrochronological research, recording both fire history and regional climate.

Successful crossdating and variability in ring-width patterns is necessary for accurate crossdating of fire scars recorded by the tree. Chronologies developed for all sites had high mean sensitivities by southeastern standards, signifying that necessary variability exists in the tree-ring patterns due to climatic factors to ensure successful crossdating. The commonality of marker rings in the four chronologies across the region further indicates a regional climatic influence and improved accuracy of fire-scar dating. Fire scars recorded by Table Mountain pine cross sections were easily distinguished and crossdated using standard dendrochronological techniques.

Based on the analysis of ring formation and the high quality of crossdating, Table Mountain pine could be a suitable species for climate reconstruction. Table Mountain pines collected for this research showed responses to precipitation, temperature, and drought indices, and their records reflect the influence of certain teleconnections. The importance of the Atlantic Ocean on Appalachian weather systems and Table Mountain pine growth was confirmed from relationships with the NAO and the Kaplan indices found at all sites. This implies that certain large-scale oceanic-atmospheric processes affect regional Table Mountain pine growth. However, small-scale environmental differences, such as effects of topography, competition, and seasonal variations in temperature and precipitation, also affect Table Mountain growth.

2. Fires burned frequently in the past at all four study sites.

Prior to 1934, fire was a frequent disturbance process at all four study sites. For example, the minimum fire interval for all four sites was 1.0 year, while the Weibull median fire return interval was 2–3 years (for the all-scarred class). Larger, perhaps more widespread fires (10%-scarred class) occurred about once every 4 to 8 years. Because these fires were so frequent, fuels could never build up to levels that could support a more moderate-severity or high-severity fire.

3. Fires were usually low-severity/intensity wildfires, although establishment of tree cohorts was evidence of an uncommon moderate-severity fire.

The very fact that the primary evidence of repeated fires in the past relied on fire scars is proof that these fires were almost exclusively low severity/intensity fires. Only a low severity/intensity fire will leave a fire scar. We found some evidence of moderate-severity fires in the cohorts of trees that established soon after these fires, but moderate-severity fires were uncommon. We found no evidence of high-severity fires, whereby all trees within a stand would have established all at once. This research therefore demonstrates that low-severity fires were very common prior to 1934, punctuated occasionally by the uncommon moderate-severity fire. Although the occurrence of a moderate-severity fire would indicate a mixed-severity fire regime, such fires were nonetheless rare, and these stands are better described as having low-severity fire regimes.

4. The statistics of the fire regimes indicate that all sites are beyond the point where they should have burned, i.e. they currently exist outside their range of historical variation.

Since 1934, fires became less frequent, apparent when observing recorded fire events in the fire history chronologies. The years of the last fires that occurred were 1957 at Brush Mountain, 1972 at North Mountain, 1985 at Griffith Knob, and 1994 at Little Walker Mountain. At Griffith Knob, the maximum hazard interval (MHI), upper exceedence interval (UEI), and maximum fire interval (MAX) calculated over the period of reliability were 12, 4, and 9 years respectively (all-scarred class), indicating that a fire event is likely after a fire-free interval of about 10 years. The same is true for Little Walker Mountain where the MHI, UEI, and MAX intervals are 7, 5, and 10 years respectively (all-scarred class). At Brush Mountain and North Mountain, UEI values were 8 and 6 years, respectively, while the MAX values were 13 and 17 years respectively (all-scarred class). That the maximum threshold level has already been reached at all sites indicates the high probability of fire at all sites today. The high values of the coefficients of variation indicate a high variability in fire intervals at all four sites, suggesting that fire managers should try to vary fire-return intervals within the bounds of the LEI and UEI at each site.

5. The majority of fires in these Table Mountain pine stands occurred during the dormant season and early portion of the growing season.

At Brush Mountain and North Mountain, the majority of fire events took place during the dormant season. At Griffith Knob and Little Walker Mountain, I found a more even mix of dormant, early-early, and middle-early season fire events, with few late-early or late season fire events. Fires that occurred during the early-early and middle-early growing seasons are beneficial in pine stands because they cause greater hardwood mortality than dormant season burns (Sutherland *et al*. 1995), produce fewer hardwood sprouts (Lafon *et al*. 2005), and are also followed by pine recruitment (Sutherland *et al*. 1995). In addition, burns that occur after hardwoods have flushed are the best control of hardwoods because burning soon after flush depletes root reserves of food (Farrar 1998).

6. The sites with a higher percentage of early-early season fires had more pine regeneration.

Griffith Knob and Little Walker Mountain had substantial Table Mountain pine regeneration, while Brush Mountain and North Mountain had minimal regeneration. This is probably due to the frequency of fire events that occurred after hardwoods broke dormancy. Hardwood sprouting is more prolific after dormant season burns because they have not depleted their carbohydrate reserves (Hodgkins 1958; Van Lear 1990). For this reason, sites dominated by dormant season burns (such as Brush Mountain and North Mountain) would not see as pronounced an increase in Table Mountain pine regeneration after fire events. However, Little Walker Mountain and Griffith Knob had a larger percentage of early-early season fires that would better control hardwood regeneration and re-sprouting. Management plans should consider conducting prescribed burns that occur in the dormant through middle-early seasons to control hardwoods and facilitate Table Mountain pine regeneration.

7. Fire plays a role in the establishment of cohorts of fire-tolerant and fire-intolerant species.

The age-structure and stand composition analyses at all sites indicate that all tree species (fire-tolerant pines and hardwoods, as well as fire-intolerant hardwoods) can establish after fire events that are more ecologically severe. However, the last major cohort establishment initiated by a fire event in the 20th century was then followed by successful fire suppression that commenced beginning ca. 1934. This caused an increase in the density of fire-intolerant hardwoods because the last cohort was never thinned by fire and has been allowed to grow. All sites are essentially multi-cohort stands, in which at least two fire events are obvious in the fire charts and age-structure/stand composition analyses. These disturbances did not entirely remove pre-existing tree cover. This type of stand occurs where disturbances occur at regular intervals (Oliver and Larson 1996).

8. Understory shrubs, such as mountain laurel, provide supporting information for evaluating the fire regimes of Table Mountain pine stands in the central Appalachians.

Analysis of mountain laurel establishment dates indicated that fire events can initiate cohorts of understory shrubs as well. This species benefited from fire suppression that followed the last fire event that allowed it to establish and literally overtake the understory. The density of mountain laurel today is likely to be unprecedented, and represents a major change in fire regimes likely not captured in fire spread simulation models nor considered in fire management plans. However, mountain laurel establishment had slowed greatly over the last 30 years, likely because over-crowded stands cannot allow any new establishment.

9. Future stands will likely be dominated by xeric oaks and fire-intolerant hardwoods, especially red maple and black gum.

Red maple and black gum exist in high numbers at Brush Mountain, and the future canopy will likely be dominated by chestnut oak with red maple and black gum as co-dominants should fires continue to be suppressed. Griffith Knob has a high number of Table Mountain pine saplings, indicating that a future canopy could remain dominated by the species. However, the seedling inventory for Griffith Knob indicates oaks and hickories could dominate the future canopy. A similar situation exists on Little Walker Mountain where Table Mountain pine dominates the sapling stage, but red maple and chestnut oak dominate the seedling composition. The canopy at North Mountain is not currently dominated by Table Mountain pine and cannot be considered a true yellow pine stand. The lack of Table Mountain pine and the dominance of oaks, black gum, and red maple in the understory suggest that North Mountain will continue to be a hardwood-dominated site in the future.

6.2 Rehabilitation

1. Fire suppression has altered the composition in these Table Mountain pine stands.

More than 60 years of fire suppression in these stands have led to an increase in hardwood tree density and increasing dominance of fire-intolerant species such as red maple, black gum, eastern white pine, and mountain laurel. Brush Mountain, Griffith Knob, and Little Walker Mountain currently have canopies dominated by Table Mountain pine. However, the amount of Table Mountain pine regeneration at these three sites suggests that xeric oaks, with red maple and black gum as co-dominants, will dominate future canopies. Fire suppression at all sites has also allowed mountain laurel populations to increase to unprecedented numbers and ages, but the shrub likely will not gain additional ground in Table Mountain pine stands. The presence of mountain laurel in the stands will be increasingly problematic because prescribed burns will be unable to eliminate the already established shrubs because of their ability to re-sprout quickly, and because burning these shrubs could lead to crown fires.

2. Restoration of Table Mountain pine stands simply may not be possible.

The past is not always the perfect guide to managing the future, because humans have significantly and permanently altered today's landscape. Different climate regimes and a different atmospheric composition exist today, suggesting that no ecosystem can be completely restored to past conditions. Other concerns include the urban-wildland interface, introduced pathogens, and exotic invasive species that now exist in these ecosystems. These ecosystems can be rehabilitated so that they have some historic function and composition, but they can never be completely restored. This would involve a return to historic fire return intervals and possible selective thinning of certain hardwood species and shrubs to promote pine dominance in the understory.

Because trees over 76 years of age contain the most viable seeds, regular stand-replacing fires would not help regenerate Table Mountain pine stands. Short fire-return intervals indicate populations may be killed before sufficient seeds have been produced to replace them. However, extremely long intervals indicate that populations are diminished to the extent that they cannot replace themselves (Bond and van Wilgren 1996). Genetic diversity in Table Mountain pine stands is maintained by frequent fire, which also allows for regular populations turnover (Gibson 1990; Gray 2001)**. My results support the frequent presence of fires, with a wide range in the variability of the fire-free periods, in both low-severity and moderate-severity categories, but dominated by low-severity fires.** This indicates that management plans should include prescribed burns of low to moderate severity to encourage genetic diversity but also to ensure a viable seed source.

3. There can be no blanket fire management plan for Table Mountain pine stands.

The differences that exist between the fire histories of individual sites can be explained by differences in land-use/settlement history, elevation, and topography. For example, the differences in the fire histories and fire/climate response by trees at the two southerly sites (Griffith Knob and Little Walker Mountain) may be attributable to the lack of large human populations, such as those found adjacent to the two more northerly sites (Brush and North Mountains). In addition, a mixed fire regime was obvious at Brush Mountain, Griffith Knob, and Little Walker Mountain, where smaller, potentially less intense fires have occurred together with spatially large, moderate severity fires, though these latter were uncommon. At North Mountain, I found no indication of major cohort establishment that could be attributed to more ecologically severe fires, although future studies may indeed find evidence of moderate severity fires. North Mountain also consists of more dissected topography than do the other three sites, which would affect the ability of fire to spread. Brush Mountain, Griffith Knob, and Little Walker Mountain have vegetated landscapes that are continuous. Even though the drier ridges are separated from each other by more mesic drainages dominated by hardwoods, I speculate that fires could easily spread from ridge to ridge across these drainages provided enough fuels exist to carry fire.

4. Extreme measures are needed to control fire-intolerant hardwoods in current Table Mountain pine stands.

If the removal of fire-intolerant tree species is desired, manual thinning may be necessary to prevent natural or accidental catastrophic or escaped prescribed burns in the wildland-urban interface. Fire-intolerant hardwoods and shrubs, such as black gum and mountain laurel, have now reached sizes that make them fire tolerant. Bark thickness typically increases with stem diameter; therefore, fire will selectively kill thin-barked and small species and young individuals (Peterson and Ryan 1986; Uhl and Kauffman 1990; Bond and van Wilgren 1996). These species also have vigorous re-sprouting capabilities. Thinning will probably not be possible at the more inaccessible Table Mountain pine sites, however. Such areas will require a higher frequency of prescribed burning until hardwood populations come under control.

5. Rehabilitation of yellow pine stands in the Appalachians will further be complicated by the effects of global climate change.

A predicted northern retreat of southern pines (Iverson and Prasad 1998; Barden 2000) due to global warming has been used to explain the lack of Table Mountain pine regeneration in its southern range. However, the two most southerly sites, Griffith Knob and Little Walker Mountain, have the most significant Table Mountain pine regeneration. The lack of Table Mountain pine regeneration in certain areas is more likely the result of decades of fire suppression and changing trends in fire seasonality due to anthropogenic influences.

In reality, increasing air temperatures and fertilization from atmospheric carbon dioxide, in combination with prescribed fire, could potentially increase Table Mountain pine populations in the future. Table Mountain pine is already adapted to warmer ridge tops and increasing CO_2 would ensure a base for fixing carbon for wood production. Prescribed fires would be needed to reduce hardwood competitors, which would also benefit from increasing temperatures and carbon dioxide, and to ensure pine regeneration and reduce competition. An increase in ambient air temperatures may also increase the number of Table Mountain pine cones opening and releasing seeds because of higher temperatures, and not because of fire. However, some seedbed preparation is still needed because seed release during high temperature periods may not result in successful germination unless competition is reduced, the duff layer is removed, and sunlight is increased.

6. Who started the fires?

Although not directly addressed in this research, the cause of fire events is a major concern for fire management and fire historians. In reality, the question of who or what started the fires will never be confidently answered in a scientific manner for these or any stands in the Appalachian Mountains. The year and season and certain spatial aspects of the fire can be determined; however, trees are not able to tell us who or what started the fire. We can safely assume that the results presented here illustrate the combined natural- and human-caused fire history of the sites. Fires that occurred during the dormant season, early-early season, and late season may likely have been caused by humans because lightning is uncommon in these periods. Fires that occurred in the middle-early and late-early seasons are concurrent with the summer lightning season and are likely natural fires.

The results gave no indication that the displacement of Native American populations during the 19th century altered fire regimes in Table Mountain pine stands. In fire history studies in other parts of the U.S., the displacement of native populations is usually accompanied by a shift in fire seasonality. However, no such shift was found in these Table Mountain pine stands. I can therefore say that Native American burning was not significantly affecting these stands after 1732. I found no indication that changes in land use practices that occurred after Native American displacement caused changes in fire regimes or fire seasonality.

6.3 Fire-Climate Relationships in Table Mountain Pine Stands

1. The influence of precipitation and temperature during particular months at the four sites was similar, indicating a regional climate influence.

Correlation analysis and response function analysis conducted on tree growth for all four sites showed similarities that can only be attributed to the influence of a regional climate signal. For example, February precipitation showed an inverse relationship with tree growth at all four sites, while a positive relationship was found for the previous year's September precipitation. Differences between the four sites can be attributed to differences in elevation, topography, and microclimate. At Brush Mountain, Griffith Knob, and Little Walker Mountain, the most significant relationship between climate and Table Mountain pine growth occurs during winter and early spring (i.e. January to April). This period is important for CO_2 uptake, the extension of root length of Table Mountain pine seedlings, twig development and flowering, winter transpiration and photosynthesis, and the mutualistic relationship with ectomycorrhizal fungi. At North Mountain, temperature does not become a significant influence until late spring and summer, which is most likely due to the site's low elevation and different overall fuel type.

2. The most significant relationship found was between tree growth and drought (PDSI) during the fall months.

PHDI and PDSI both showed the most significant relationships during both the previous and current growing seasons at all sites, extending well into the fall months. These relationships illustrate the overriding influence of precipitation on Table Mountain pine growth, augmented by the influence of temperature. Because this species is prolific in areas where it has no access to the water table, growing season precipitation is the most important limiting factor in its growth. Not surprisingly, PDSI (which integrates both monthly precipitation and temperature) was therefore the climate variable chosen to reconstruct for the superposed epoch analyses. This information can be used by forest managers to determine when Table Mountain pine stands are under the least amount of biological stress to plan prescribed burns.

4. Results of the superposed epoch analysis strongly indicate that wildfires occur in years of drought, although some preconditioning by previous years of drought was also noted.

In general, results of the SEA showed that severe drought was occurring during the year of the wildfire, although this was not the case at all sites or in all forms of the superposed epoch analyses. In addition, I found that drought was occurring in some years leading up to the fire year, indicating that some preconditioning of fuels occurs that eventually leads to a wildfire event. I also found that wet years prior to the fire year had little influence on fire occurrence in the Southeastern U.S., unlike the preconditioning in antecedent months found in western U.S. sites. Finally, SEA includes the years following the fire event to identify possible extended dry or wet periods surrounding fire events. No such extended trend periods were found by these analyses. The lack of significant relationships at some sites could be an indication that other site characteristics, such as soil type or site orientation, are more important than short-term climate changes.

6.4 Recommendations for Future Research

In the world of scientific research, the result of a good scientific query often presents as many questions as it answers. Previous research utilizing Table Mountain pine left scientists and forest managers with the understanding that this species could record fire events. However, these studies did not extend far enough back in time to give any indication of pre-19^{th} fire regimes. My research found that remnants of Table Mountains pines can survive on the landscape for over 150 years and still have visible rings and stable wood. Using this wood, I was able to create Table Mountain pine tree-ring chronologies that extended to the early 18^{th} and late 17^{th} centuries. Because such a abundance of old, fire-scarred Table Mountain pines on the landscape was found, it further made regional climate analysis possible. A significant effort should be made to locate and collect these remnants before their destruction by disturbance processes (especially fire, whether prescribed or natural) and weathering.

Research should be continued in the following four areas: (1) further chronology development and extension back in time, (2) reconstructions of climate history using Table Mountain pine chronologies, (3) expanding the number of Table Mountain pine sites to better understand spatial characteristics of past fires in the central Appalachians, and (4) improved analyses to better understand the impacts of climate on fire occurrence in the eastern U.S.

First, now that the usefulness of Table Mountain pine in fire and climate research has been proven, priority should be given to extending these tree-ring chronologies further back in time and expanding the spatial network of table Mountain pine chronologies to better understand regional climate. This research provided the oldest Table Mountain pine chronologies yet developed, extending back to 1694. However, older Table Mountain pine chronologies are entirely possible and would be beneficial in evaluating and comparing fire regimes in the pre- and post-EuroAmerican settlement periods. Many stands of Table Mountain pines currently exist within the Jefferson National Forest that I did not sample because the trees appeared to have limited information on fire history. These sites should be revisited and Table Mountain pine samples collected for future climate research. Additional Table Mountain pine sites east of the Appalachian Mountains, including the Blue Ridge Mountains and outlier populations, should be sampled. The northern range of Table Mountain pine should also be explored for living and remnant wood. Sampling the entire range of Table Mountain pine would provide a large regional climate reconstruction for the interior Atlantic Coast of the eastern U.S.

Second, this research showed that Table Mountain pine growth reflects changes in climate, especially rainfall and temperature, and additional teleconnections and oscillations should now be investigated. These should include the El Niño-Southern Oscillation (ENSO), the Arctic Oscillation (AO), and the Pacific Decadal Oscillation (PDO). Studies have shown that the ENSO is well-known to affect climate in the

Southeastern U.S. (Peters *et al*. 2003; Coley and Waylen 2006), but no study has yet conclusively shown an influence of ENSO on tree growth activity in the states of the Atlantic seaboard, although Henderson (2006) showed a possible influence of ENSO on longleaf pine growth in Texas and South Carolina. The effects of a distant teleconnection such as the PDO on tree growth in the eastern U.S. at first seems redundant, but recent studies have shown a Pacific Ocean influence on fire regimes well into the central U.S. (Cole *et al*. 2002; Schoennagel *et al*. 2005; Brown 2006) and a possible influence on tree growth and climate activity in the southeastern U.S. (Miller 2005; Henderson 2006). Furthermore, the AO and NAO are closely related, and my research has shown a possible influence of climate activity associated with the NAO on Table Mountain pine tree growth in Virginia. Lastly, given the history of climate research, it is likely that additional teleconnections will be discovered; it is therefore important for Table Mountain pine chronologies to be available for analyses when this occurs.

Third, the spatial characteristics of fires in Table Mountain pine stands should also be investigated further. By analyzing the spatial extent of fire events, it is possible to better understand fire spread patterns and the factors that affect fire spread, such as topography, fuel types, and vegetation structure and pattern. For example, was fire more prevalent along ridge tops where we expect lightning activity to be highest, or in the valley bottoms where we expect human ignitions to be dominant? This would provide a supplementary assessment on the anthropogenic influence on fire events in Table Mountain pine stands. Although I speculate that fire can spread from ridge to ridge through the more mesic drainages, this hypothesis needs further testing by analyzing the fire history of oaks that grow in these drainages. Our field sampling located several fire-scarred oaks in this study in drainages, but I was unable to conclusively crossdate the rings on these samples. Lastly, a comprehensive study to analyze the fire regimes of numerous, consecutive ridges along a single mountain (such as Brush Mountain where considerable neighborhood development is encroaching on nearby forests) would provide a detailed history of fire spread patterns over time, and would help investigate the possible role of climate on fire activity in the central Appalachian Mountains. Such a study could give vital information to fire managers who would be able to create more site-specific fire management plans.

Finally, more superposed epoch analyses should be conducted to determine the impacts of teleconnections and oscillations on fire events in Table Mountain pine stands. In this study, I showed the relationship between drought years (using PDSI) and fire events, but the influence of other teleconnections should be investigated, either singly or via interactions with other teleconnections. In particular, the potential influence of ENSO on fire occurrence in Table Mountain pine stands. The effects of ENSO on climate and 20th century fire activity in the lower portions of the southeastern U.S. are well-established (Jones *et al*. 1999; Beckage *et al*. 2003; Smith *et al*. 2007), but few studies have examined the possible effects of ENSO activity on fires in the Piedmont region of the Atlantic states. The use of other teleconnections could demonstrate the synergy of two or more oscillations in driving fire activity in the Southeastern U.S., as has been demonstrated in the Rocky Mountains of Colorado (Schoennagel *et al*. 2005; Sibold *et al*. 2006).

It is important for the scientific community to accept Table Mountain pine as an acceptable species for dendrochronological research involving regional fire and climate reconstruction. The species has proven its usefulness in both cases. This represents a new source of proxy data that could contribute to our knowledge of the impacts of climate change on Appalachian ecosystems and fire regimes. We should therefore make a serious effort to (1) develop longer and more robust (i.e., high sample depth back in time) Table Mountain pine tree-ring chronologies and (2) comprehensively collect remnant Table Mountain pine sections from the forest floor of areas that might soon burn.

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APPENDICES

APPENDIX A1. Statistical descriptions of the series in the Brush Mountain total ring-width chronology.

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
1	BM000	1810	1912	103	0.434	0.269
2	BMA000	1816	1919	104	0.512	0.38
3	BMA100	1783	1855	73	0.59	0.316
4	BMA102	1786	1844	59	0.66	0.321
5	BMA104	1861	1962	102	0.399	0.35
6	BMA105	1885	2002	118	0.421	0.357
7	BMA106	1828	1958	131	0.622	0.311
8	BMA107	1809	2002	194	0.432	0.314
9	BMA108	1766	1853	88	0.409	0.3
10	BMA109	1773	1871	99	0.364	0.426
11	BMD100	1732	1860	129	0.467	0.312
12	BMD102	1857	1966	110	0.63	0.333
13	BMD104	1860	1965	106	0.648	0.342
14	BMD106	1857	1944	88	0.647	0.341
15	BMD108A	1854	1940	87	0.488	0.364
16	BMD108B	1858	1925	68	0.497	0.322
17	BMD109	1857	1946	90	0.524	0.267
18	BMD110	1857	1988	132	0.587	0.321
19	BMD112	1858	1924	67	0.699	0.258
20	BMD113	1768	1912	145	0.486	0.276
21	BMD114	1868	1928	61	0.664	0.315
22	BMA004A	1903	2002	100	0.667	0.251
23	BMA004B	1903	2001	99	0.662	0.309
24	BMC233A	1952	2003	52	0.376	0.26
25	BMC233B	1952	2001	50	0.451	0.3

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
26	BMC016A	1944	2002	59	0.682	0.342
27	BMC016B	1944	2002	59	0.686	0.263
28	BMC017A	1944	2001	58	0.614	0.45
29	BMC017B	1948	2002	55	0.51	0.265
30	BMC022A	1951	2002	52	0.467	0.467
31	BMA030A	1948	2002	55	0.677	0.269
32	BMA030B	1948	2002	55	0.565	0.237
33	BMA031A	1946	2002	57	0.648	0.211
34	BMA031B	1946	2002	57	0.608	0.2
35	BMC032A	1951	2002	52	0.558	0.302
36	BMC034B	1942	2001	60	0.592	0.331
37	BMA043A	1942	2002	61	0.547	0.21
38	BMA043B	1942	2002	61	0.562	0.211
39	BMC052A	1950	2002	53	0.576	0.239
40	BMC052B	1950	2002	53	0.641	0.293
41	BMC053A	1945	2002	58	0.716	0.265
42	BMC053B	1945	2002	58	0.664	0.285
43	BMC055A	1951	2002	52	0.507	0.392
44	BMC056A	1947	2002	56	0.442	0.286
45	BMC057A	1953	2002	50	0.592	0.27
46	BMC057B	1952	2002	51	0.659	0.242
47	BMA062A	1959	2002	44	0.585	0.2
48	BMA062B	1959	2002	44	0.598	0.286
49	BMA064A	1891	2002	112	0.638	0.304
50	BMA064B	1865	2002	138	0.596	0.301
51	BMA065A	1845	2002	158	0.704	0.273
52	BMA065B	1837	2002	166	0.604	0.258
53	BMA067A	1912	2002	91	0.692	0.223
54	BMA067B	1913	2002	90	0.62	0.222
55	BMA068A	1914	2002	89	0.756	0.269

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
56	BMA068B	1899	2002	104	0.651	0.213
57	BR1011	1842	1992	151	0.518	0.365
58	BR101A	1810	1916	107	0.487	0.333
59	BR101B	1803	1916	114	0.494	0.303
60	BR1021	1950	1992	43	0.717	0.185
61	BR1022	1951	1992	42	0.598	0.218
62	BR1031	1871	1992	122	0.692	0.281
63	BR1032	1870	1992	123	0.607	0.268
64	BR1041	1901	1992	92	0.167	0.302
65	BR1042	1881	1992	112	0.468	0.312
66	BR1051	1873	1992	120	0.539	0.32
67	BR1052	1875	1992	118	0.533	0.327
68	BR1061	1872	1992	121	0.657	0.259
69	BR1062	1876	1992	117	0.608	0.255
70	BR1063	1872	1992	121	0.627	0.252
71	BR1071	1841	1991	151	0.5	0.301
72	BR1072	1877	1992	116	0.658	0.331
73	BR1081	1934	1992	59	0.397	0.243
74	BR1082	1931	1992	62	0.244	0.297
75	BR1092	1874	1992	119	0.697	0.272
76	BR1101	1869	1992	124	0.728	0.297
77	BR1102	1873	1992	120	0.668	0.302
78	BR1111	1822	1992	171	0.632	0.353
79	BR1112	1822	1992	171	0.604	0.343
80	BR112B	1749	1847	99	0.601	0.256
81	BR112D	1765	1872	108	0.341	0.279
82	BR3011	1876	1992	117	0.594	0.361
83	BR3012	1876	1992	117	0.623	0.368
84	BR3021	1880	1992	113	0.659	0.279
85	BR3022	1887	1992	106	0.679	0.267

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
86	BR3031	1870	1992	123	0.664	0.262
87	BR3032	1866	1992	127	0.664	0.291
88	BR3041	1869	1992	124	0.69	0.27
89	BR3042	1870	1992	123	0.77	0.265
90	BR3051	1873	1992	120	0.661	0.319
91	BR3052	1874	1992	119	0.785	0.334
92	BR3081	1893	1992	100	0.69	0.294
93	BR3082	1882	1992	111	0.662	0.27
94	BR3111	1885	1992	108	0.629	0.33
95	BR3112	1870	1992	123	0.702	0.355
96	BR3121	1909	1993	85	0.448	0.393
97	BR3122	1867	1992	126	0.648	0.416
98	BR3131	1873	1992	120	0.639	0.311
99	BR3132	1863	1992	130	0.599	0.324
	Total:	**1732–2003**		**9558**	**0.59**	**0.30**

APPENDIX A2. Statistical descriptions of the series in the Griffith Knob total ring-width chronology.

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
1	GKA005A	1935	2003	69	0.493	0.371
2	GKA005B	1901	2003	103	0.729	0.343
3	GKA016	1807	1897	91	0.629	0.234
4	GKA024A	1902	2003	102	0.632	0.384
5	GKA024B	1901	2003	103	0.769	0.312
6	GKA031A	1902	2003	102	0.819	0.348
7	GKA031B	1902	2003	102	0.754	0.371
8	GKA053A	1903	2000	98	0.652	0.364
9	GKA053B	1903	2002	100	0.65	0.372
10	GKA055	1899	1986	88	0.671	0.308
11	GKA057	1899	2002	104	0.795	0.348
12	GKA058	1901	2003	103	0.703	0.314
13	GKA064A	1901	2002	102	0.655	0.318
14	GKA064B	1901	2002	102	0.636	0.321
15	GKA076	1892	2000	109	0.598	0.347
16	GKA101	1811	1913	103	0.602	0.229
17	GKA104	1811	1932	122	0.472	0.259
18	GKA105	1741	1858	118	0.456	0.287
19	GKA109	1892	1961	70	0.453	0.341
20	GKA111	1831	2001	171	0.573	0.411
21	GKA113	1831	1910	80	0.321	0.22
22	GKA114	1809	1940	132	0.453	0.226
23	GKA115	1812	1886	75	0.557	0.3
24	GKA117	1812	1935	124	0.449	0.284

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
25	GKA120A	1789	1871	83	0.632	0.276
26	GKA120B	1795	1871	77	0.619	0.251
27	GKA122	1786	1907	122	0.282	0.287
28	GKA123	1794	1910	117	0.467	0.297
29	GKB016	1895	2002	108	0.697	0.344
30	GKB100	1901	1967	67	0.499	0.38
31	GKB101	1897	1953	57	0.622	0.387
32	GKB102	1897	1953	57	0.556	0.359
33	GKB104	1899	2003	105	0.655	0.287
34	GKB105	1895	1987	93	0.563	0.343
35	GKB106	1905	2003	99	0.669	0.366
36	GKB107	1895	2003	109	0.752	0.342
37	GKB108	1917	1988	72	0.605	0.332
38	GKB109	1805	1894	90	0.415	0.357
39	GKB111	1902	2000	99	0.569	0.377
40	GKB113	1895	1945	51	0.553	0.285
41	GKB114	1912	2003	92	0.52	0.273
42	GKB116	1830	1872	43	0.49	0.219
43	GKB121	1900	2003	104	0.566	0.32
44	GKB122	1936	1980	45	0.393	0.292
45	GKB124	1895	1961	67	0.56	0.377
46	GKB125	1895	1965	71	0.531	0.39
47	GKB128	1862	2002	141	0.516	0.288
48	GKB131	1847	1969	123	0.504	0.333
49	GKB132	1803	1884	82	0.533	0.29
50	GKB134	1896	1932	37	0.643	0.357
51	GKB135A	1943	1974	32	0.538	0.324
52	GKB135B	1820	1864	45	0.577	0.339
53	GKB137	1902	2003	102	0.794	0.389
54	GKB140	1894	1933	40	0.592	0.263

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
55	GKC014A	1946	2003	58	0.457	0.398
56	GKC014B	1944	2003	60	0.483	0.319
57	GKC049A	1899	2003	105	0.588	0.319
58	GKC049B	1899	2003	105	0.484	0.262
59	GKC050	1900	2003	104	0.513	0.319
60	GKC051	1906	2003	98	0.622	0.355
61	GKC098	1894	2002	109	0.493	0.285
62	GKC100A	1902	1947	46	0.654	0.281
63	GKC100A	1902	1947	46	0.654	0.281
64	GKC100B	1908	1942	35	0.697	0.261
65	GKC100B	1908	1942	35	0.697	0.261
66	GKC101A	1900	2003	104	0.604	0.238
67	GKC101B	1897	2000	104	0.521	0.337
68	GKC103	1895	1974	80	0.534	0.319
69	GKC104	1895	2002	108	0.542	0.359
70	GKC105	1895	2001	107	0.556	0.31
71	GKC105A	1897	2002	106	0.671	0.3
72	GKC105B	1897	2002	106	0.553	0.325
73	GKC106	1895	1977	83	0.521	0.308
74	GKC107	1895	1950	56	0.644	0.375
75	GKC108	1911	1939	29	0.659	0.309
76	GKC109	1896	1945	50	0.586	0.375
77	GKC110A	1798	1872	75	0.606	0.311
78	GKC110B	1822	1859	38	0.386	0.262
79	GKC111A	1893	1961	69	0.625	0.337
80	GKC111B	1891	1964	74	0.736	0.319
81	GKC112	1893	1972	80	0.596	0.367
82	GKC114A	1899	1989	91	0.43	0.394
83	GKC114C	1893	1950	58	0.51	0.393
84	GKC115	1893	1954	62	0.596	0.238

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
85	GKC116	1883	1924	42	0.559	0.363
86	GKC117	1896	1947	52	0.558	0.374
87	GKC118	1894	1946	53	0.547	0.25
88	GKC119	1894	1951	58	0.51	0.395
89	GKC120	1889	1934	46	0.258	0.319
90	GKC121	1900	2002	103	0.594	0.332
91	GKC122	1895	1984	90	0.437	0.396
92	GKC123	1895	1989	95	0.346	0.373
93	GKC131	1928	2003	76	0.59	0.309
94	GKC146	1898	2003	106	0.62	0.306
95	GKC149	1902	2003	102	0.694	0.338
96	GKD006	1903	2002	100	0.573	0.317
97	GKD007	1901	2003	103	0.637	0.29
98	GKD021	1902	2003	102	0.604	0.368
99	GKD027	1899	2003	105	0.625	0.365
100	GKD069	1897	2003	107	0.742	0.304
101	GKD072	1882	2003	122	0.597	0.33
102	GKD077	1904	2003	100	0.712	0.325
103	GKD078	1895	2003	109	0.532	0.288
104	GKD102	1848	1978	131	0.509	0.288
105	GKD105	1873	1945	73	0.552	0.372
106	GKD107	1905	1987	83	0.684	0.355
107	GKD110	1862	1925	64	0.525	0.362
108	GKD111	1856	1939	84	0.673	0.279
109	GKD112	1862	1948	87	0.518	0.335
110	GKD113	1859	2003	145	0.635	0.303
111	GKD116	1864	1962	99	0.444	0.31
112	GKD117	1879	1947	69	0.436	0.374
113	GKD118	1781	1860	80	0.514	0.284
114	GKD119	1795	1886	92	0.679	0.248

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
115	GKD120	1855	2003	149	0.565	0.421
116	GKD122	1863	1934	72	0.617	0.295
Total:		**1741–2003**		**10083**	**0.58**	**0.32**

APPENDIX A3. Statistical descriptions of the series in the Little Walker Mountain total ring-width chronology.

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
1	LWA103	1820	1868	49	0.552	0.297
2	LWA105	1800	1864	65	0.32	0.38
3	LWA111	1810	1885	76	0.365	0.394
4	LWA113	1928	2004	77	0.591	0.252
5	LWA115	1933	2004	72	0.686	0.221
6	LWA117	1694	1844	151	0.177	0.33
7	LWA118	1782	1880	99	0.278	0.329
8	LWA119	1790	1860	71	0.473	0.236
9	LWA121	1863	1992	130	0.191	0.376
10	LWA122	1855	2004	150	0.294	0.366
11	LWA123	1895	1936	42	0.421	0.38
12	LWA124A	1772	1899	128	0.418	0.299
13	LWA124B	1769	1860	92	0.338	0.287
14	LWA125	1729	1869	141	0.072	0.411
15	LWA126	1839	2001	163	0.497	0.352
16	LWB011A	1934	2004	71	0.759	0.288
17	LWB011B	1934	2004	71	0.726	0.312
18	LWB017	1904	2004	101	0.514	0.342
19	LWB018	1915	2003	89	0.71	0.381
20	LWB022	1936	2004	69	0.639	0.227
21	LWB023A	1958	1999	42	0.329	0.171
22	LWB023B	1957	1999	43	0.329	0.252
23	LWB025A	1919	2004	86	0.738	0.327
24	LWB025B	1919	2000	82	0.799	0.299
25	LWB025C	1935	2004	70	0.792	0.385

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
26	LWB027A	1927	1978	52	0.696	0.318
27	LWB027B	1926	2000	75	0.686	0.44
28	LWB030	1948	2004	57	0.515	0.319
29	LWB032A	1907	2004	98	0.685	0.303
30	LWB032B	1907	2003	97	0.761	0.367
31	LWB036A	1930	2004	75	0.757	0.267
32	LWB036B	1930	2004	75	0.672	0.262
33	LWB041A	1966	2004	39	0.362	0.278
34	LWB041B	1966	2004	39	0.457	0.322
35	LWB047	1934	2000	67	0.337	0.281
36	LWB050A	1911	2004	94	0.715	0.296
37	LWB050B	1911	2004	94	0.707	0.342
38	LWB053A	1932	2003	72	0.587	0.312
39	LWB053B	1933	2004	72	0.726	0.271
40	LWB059A	1923	2003	81	0.771	0.349
41	LWB059B	1923	2004	82	0.791	0.264
42	LWB063A	1926	2004	79	0.698	0.298
43	LWB063B	1929	2004	76	0.679	0.309
44	LWB064A	1919	2000	82	0.523	0.358
45	LWB064B	1922	1997	76	0.486	0.39
46	LWB065A	1980	2004	25	0.474	0.173
47	LWB065B	1977	2004	28	0.461	0.239
48	LWB067A	1914	1995	82	0.634	0.304
49	LWB067B	1910	1994	85	0.682	0.298
50	LWB069A	1932	2004	73	0.796	0.414
51	LWB069B	1931	2004	74	0.49	0.43
52	LWB070A	1927	1996	70	0.527	0.374
53	LWB070B	1927	1999	73	0.461	0.357
54	LWB071A	1921	2004	84	0.696	0.33
55	LWB072B	1928	2004	77	0.328	0.36

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
56	LWB073A	1915	2004	90	0.502	0.374
57	LWB073B	1930	2004	75	0.522	0.332
58	LWB074A	1923	2004	82	0.624	0.359
59	LWB074B	1922	2004	83	0.565	0.427
60	LWB076A	1929	2004	76	0.753	0.317
61	LWB076B	1931	2004	74	0.743	0.271
62	LWB077A	1915	2004	90	0.555	0.451
63	LWB077B	1942	2004	63	0.608	0.322
64	LWB078	1911	2004	94	0.66	0.323
65	LWB081A	1935	2004	70	0.543	0.246
66	LWB081B	1933	2004	72	0.606	0.252
67	LWB081C	1939	2004	66	0.741	0.285
68	LWB082	1934	2004	71	0.733	0.282
69	LWB083	1958	1996	39	0.474	0.437
70	LWB084A	1923	2004	82	0.635	0.254
71	LWB084B	1925	2004	80	0.644	0.226
72	LWB085	1925	1995	71	0.639	0.401
73	LWB086	1917	2004	88	0.546	0.257
74	LWB087	1920	2004	85	0.562	0.342
75	LWB089A	1975	2004	30	0.624	0.406
76	LWB089B	1975	2004	30	0.549	0.422
77	LWB090	1913	2004	92	0.836	0.343
78	LWB091	1938	2004	67	0.705	0.307
79	LWB092A	1929	2002	74	0.468	0.284
80	LWB092B	1929	2002	74	0.546	0.292
81	LWB093A	1927	2004	78	0.44	0.467
82	LWB093B	1928	2004	77	0.553	0.404
83	LWB101	1804	1885	82	0.501	0.277
84	LWB102	1955	1990	36	0.476	0.263
85	LWB104	1896	1964	69	0.297	0.254

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
86	LWB105	1899	1982	84	0.309	0.273
87	LWB107	1810	1873	64	0.54	0.189
88	LWB108	1895	1951	57	0.445	0.2
89	LWB109	1810	1925	116	0.388	0.225
90	LWB110	1808	1937	130	0.505	0.351
91	LWB111	1781	1864	84	0.35	0.261
92	LWB112	1786	1861	76	0.506	0.232
93	LWB114	1816	1989	174	0.101	0.347
94	LWC001A	1944	2003	60	0.743	0.267
95	LWC001B	1944	2003	60	0.707	0.312
96	LWC002	1990	2004	15	0.539	0.19
97	LWC005A	1912	2004	93	0.767	0.296
98	LWC005B	1912	2004	93	0.681	0.33
99	LWC009A	1910	2004	95	0.722	0.263
100	LWC009B	1909	2004	96	0.788	0.294
101	LWC012A	1949	2000	52	0.51	0.492
102	LWC012B	1949	2002	54	0.389	0.354
103	LWC013	1922	2004	83	0.674	0.344
104	LWC017	1973	2004	32	0.517	0.339
105	LWC023A	1922	2004	83	0.741	0.346
106	LWC023B	1913	2004	92	0.74	0.264
107	LWC030A	1912	2004	93	0.523	0.351
108	LWC030B	1911	2003	93	0.707	0.318
109	LWC033A	1905	2004	100	0.745	0.38
110	LWC033B	1906	2001	96	0.65	0.495
111	LWC034	1974	2004	31	0.693	0.403
112	LWC035A	1970	2004	35	0.426	0.498
113	LWC035B	1973	2004	32	0.488	0.433
114	LWC037	1927	2003	77	0.607	0.318
115	LWC040A	1950	2000	51	0.302	0.431

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
116	LWC040B	1950	2001	52	0.475	0.453
117	LWC043	1927	2003	77	0.611	0.345
118	LWC044A	1921	2004	84	0.769	0.277
119	LWC044B	1921	2004	84	0.767	0.296
120	LWC058A	1939	2004	66	0.78	0.324
121	LWC058B	1948	2004	57	0.524	0.287
122	LWC059	1937	1999	63	0.478	0.328
123	LWC067A	1939	2004	66	0.716	0.283
124	LWC067B	1944	2004	61	0.751	0.285
125	LWC082A	1929	2004	76	0.7	0.332
126	LWC082B	1929	2004	76	0.79	0.268
127	LWC084A	1923	2002	80	0.699	0.306
128	LWC084B	1923	2002	80	0.709	0.323
129	LWC085A	1934	2003	70	0.646	0.33
130	LWC085B	1934	2003	70	0.51	0.325
131	LWC087A	1929	2004	76	0.605	0.353
132	LWC087B	1929	2004	76	0.785	0.287
133	LWC088A	1930	2004	75	0.695	0.268
134	LWC088B	1930	2004	75	0.722	0.324
135	LWC090	1964	2003	40	0.395	0.301
136	LWC091A	1912	2004	93	0.743	0.288
137	LWC091B	1912	2004	93	0.678	0.336
138	LWC092	1931	2003	73	0.638	0.269
140	LWC101A	1791	1922	132	0.307	0.29
139	LWC101B	1851	1934	84	0.428	0.4
141	LWC102	1791	1922	132	0.307	0.29
142	LWC103C	1863	1957	95	0.418	0.307
143	LWC104	1941	2003	63	0.514	0.328
144	LWC106	1924	1988	65	0.669	0.257
145	LWC108	1795	1909	115	0.305	0.281

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
146	LWC110	1929	1991	63	0.601	0.312
147	LWC111	1811	1840	30	0.621	0.267
148	LWC112	1901	1998	98	0.371	0.402
149	LWC114	1747	1879	133	0.257	0.282
150	LWC115	1906	1975	70	0.376	0.343
151	LWC116	1799	1878	80	0.496	0.399
152	LWC119	1812	1931	120	0.132	0.36
153	LWC121	1769	1880	112	0.462	0.412
154	LWD000	1766	1909	144	0.302	0.242
155	LWD101	1870	1977	108	0.682	0.304
156	LWD102	1868	1983	116	0.558	0.345
157	LWD103	1914	1999	86	0.367	0.351
158	LWD104	1888	1945	58	0.558	0.406
159	LWD105	1879	1946	68	0.63	0.457
160	LWD106	1902	2000	99	0.661	0.26
161	LWD107	1912	2004	93	0.679	0.403
162	LWD108	1911	1972	62	0.802	0.391
163	LWD109	1910	2003	94	0.524	0.332
164	LWD110	1907	1953	47	0.531	0.297
165	LWD111	1861	1997	137	0.555	0.301
166	LWD112	1908	2001	94	0.596	0.266
167	LWD113	1909	1995	87	0.601	0.466
168	LWD114	1835	1903	69	0.375	0.389
169	LWD115	1910	1992	83	0.617	0.377
170	LWD116	1908	1964	57	0.749	0.352
171	LWD117	1864	2004	141	0.44	0.24
172	LWD118A	1844	1948	105	0.422	0.297
173	LWD118B	1842	1942	101	0.492	0.289
174	LWD118C	1842	1942	101	0.493	0.288
175	LWD120	1792	1870	79	0.487	0.325

	Interval	No. of Years	Correlation with Master	Mean Sensitivity
Total:	**1694–2004**	**13928**	**0.55**	**0.32**

APPENDIX A4. Statistical descriptions of the series in the North Mountain total ring-width chronology.

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
1	NMA010	1846	2002	157	0.521	0.324
2	NMA022A	1939	2002	64	0.667	0.232
3	NMA022B	1939	2002	64	0.604	0.292
4	NMA025A	1932	2002	71	0.854	0.244
5	NMA025B	1931	2002	72	0.607	0.253
6	NMA026A	1926	1987	62	0.526	0.471
7	NMA026B	1930	2001	72	0.499	0.463
8	NMA028A	1909	2002	94	0.626	0.346
9	NMA028B	1909	2002	94	0.619	0.357
10	NMA037A	1933	2002	70	0.758	0.273
11	NMA037B	1933	1988	56	0.529	0.198
12	NMA039A	1937	2002	66	0.72	0.372
13	NMA039B	1937	2002	66	0.767	0.397
14	NMA041A	1934	2002	69	0.665	0.27
15	NMA041B	1934	2002	69	0.583	0.279
16	NMA045A	1933	1996	64	0.667	0.444
17	NMA045B	1933	1999	67	0.615	0.378
18	NMA046A	1915	2001	87	0.49	0.344
19	NMA046B	1915	2002	88	0.694	0.369
20	NMA047A	1913	2002	90	0.682	0.285
21	NMA047B	1913	2002	90	0.699	0.334
22	NMA048A	1930	2002	73	0.778	0.307
23	NMA048B	1930	2002	73	0.726	0.312
24	NMA050A	1888	1988	101	0.475	0.511
25	NMA050B	1889	2002	114	0.456	0.281

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
26	NMA054A	1936	2001	66	0.799	0.379
27	NMA054B	1936	2002	67	0.739	0.431
28	NMA057A	1930	2002	73	0.775	0.318
29	NMA057B	1930	2002	73	0.751	0.282
30	NMA058A	1921	2002	82	0.742	0.29
31	NMA058B	1921	2002	82	0.695	0.315
32	NMA059A	1908	2002	95	0.776	0.292
33	NMA059B	1908	1987	80	0.613	0.382
34	NMA060A	1930	1987	58	0.394	0.483
35	NMA060B	1921	2002	82	0.638	0.335
36	NMA061A	1892	2002	111	0.762	0.298
37	NMA061B	1891	2002	112	0.741	0.298
38	NMA062A	1904	2002	99	0.714	0.305
39	NMA062B	1893	2002	110	0.574	0.239
40	NMA101	1944	2002	59	0.682	0.277
41	NMA103	1947	2002	56	0.721	0.33
42	NMA105	1760	1848	89	0.587	0.386
43	NMA106	1945	2000	56	0.448	0.367
44	NMA107	1895	2002	108	0.553	0.394
45	NMA108	1948	2002	55	0.64	0.343
46	NMA109A	1940	2002	63	0.527	0.38
47	NMA109B	1940	1999	60	0.359	0.395
48	NMA110	1879	2002	124	0.565	0.331
49	NMA111	1937	1990	54	0.405	0.257
50	NMA113	1753	1833	81	0.513	0.305
51	NMA114	1876	1948	73	0.594	0.415
52	NMA115	1768	1856	89	0.559	0.303
53	NMA116	1754	1817	64	0.642	0.321
54	NMA117	1852	2002	151	0.514	0.27
55	NMA118	1754	1889	136	0.471	0.288

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
56	NMA119	1883	2002	120	0.486	0.349
57	NMB101	1946	2002	57	0.473	0.365
58	NMB102	1944	1973	30	0.65	0.294
59	NMB104	1946	2002	57	0.632	0.258
60	NMB105	1937	2002	66	0.546	0.354
61	NMB106	1958	2002	45	0.386	0.308
62	NMC101A	1800	1881	82	0.468	0.301
63	NMC101B	1800	1880	81	0.653	0.26
64	NMC102A	1888	2001	114	0.472	0.41
65	NMC102B	1890	2001	112	0.505	0.409
66	NMC103	1926	1980	55	0.432	0.467
67	NMC104	1760	1905	146	0.469	0.355
68	NMC161	1897	2003	107	-0.176	0.395
69	NMC161	1907	2003	97	-0.062	0.379
70	NMC163A	1947	2003	57	0.552	0.274
71	NMC163B	1947	1977	31	0.475	0.18
72	NMD007	1743	1865	123	0.527	0.34
73	NMD008	1899	1993	95	0.477	0.327
74	NMD008A	1961	2002	42	0.736	0.199
75	NMD008B	1946	2002	57	0.574	0.329
76	NMD011A	1943	2002	60	0.473	0.372
77	NMD011B	1943	2001	59	0.439	0.32
78	NMD021A	1881	2002	122	0.62	0.3
79	NMD021B	1881	2002	122	0.581	0.321
80	NMD031A	1936	2002	67	0.628	0.357
81	NMD031B	1936	2002	67	0.714	0.336
82	NMD035A	1953	2000	48	0.518	0.258
83	NMD035B	1953	2002	50	0.579	0.298
84	NMD037A	1937	2002	66	0.598	0.242
85	NMD037B	1937	2002	66	0.687	0.196

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
86	NMD048	1891	1975	85	0.647	0.32
87	NMD049	1911	2002	92	0.568	0.588
88	NMD050A	1893	2001	109	0.473	0.536
89	NMD050B	1895	1987	93	0.587	0.345
90	NMD051A	1888	2002	115	0.697	0.304
91	NMD051B	1888	2002	115	0.674	0.306
92	NMD052	1904	2002	99	0.636	0.259
93	NMD053A	1903	2002	100	0.609	0.405
94	NMD053B	1904	1978	75	0.653	0.456
95	NMD054A	1906	2002	97	0.643	0.346
96	NMD054B	1909	2002	94	0.648	0.415
97	NMD056A	1912	2002	91	0.625	0.332
98	NMD056B	1911	2002	92	0.571	0.33
99	NMD058	1934	2001	68	0.591	0.424
100	NMD101	1812	1853	42	0.54	0.279
101	NMD102	1764	1831	68	0.512	0.302
102	NMD103	1913	2002	90	0.541	0.421
103	NMD104	1918	2002	85	0.454	0.338
104	NMD105	1905	1991	87	0.507	0.391
105	NMD109	1893	1977	85	0.651	0.361
106	NMD110	1765	1814	50	0.517	0.304
107	NMD111	1937	1992	56	0.474	0.254
108	NMD112	1751	1902	152	0.536	0.349
109	NMD113A	1850	1898	49	0.61	0.374
110	NMD113B	1841	1903	63	0.718	0.469
111	NMD117	1861	2002	142	0.537	0.275
112	NMD119A	1791	1843	53	0.154	0.388
113	NMD119B	1789	1854	66	0.483	0.412
	Total:	**1743–2003**		**9215**	**0.57**	**0.34**

APPENDIX B1. Standard Index Chronology for Brush Mountain. These values are the tree-ring indices for each year in the chronology. The indices are displayed without decimal points, but the actual value can be obtained by dividing the numbers by 100; therefore, the mean value for all indices is 1.0. Each line represents a decade of indices, and the decades are shown in the lefthand column. The numbers across the top of the table are the last numbers in the year for that particular decade. This format, known as the "Index format," is the internationally accepted format of the World Data Center for Palaeoclimatology.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1730			705	1127	1203	945	544	840	533	492
1740	1410	1155	1154	899	671	887	1187	178	97	876
1750	1301	755	794	764	1304	930	1618	1349	1396	1842
1760	2100	1548	1650	1375	1491	729	1293	942	1305	1156
1770	1138	805	889	881	684	967	891	833	1056	1227
1780	1022	1487	732	1065	855	871	1086	1026	882	855
1790	1077	1120	1080	922	886	981	1045	951	1081	1057
1800	973	702	1022	392	450	577	846	924	933	927
1810	862	1180	896	994	1292	1336	1357	1563	1018	887
1820	950	1173	898	901	923	800	1005	1090	1079	1264
1830	950	1128	1055	930	1093	1185	1130	778	809	1020
1840	1090	867	1166	1015	968	560	889	996	1147	833
1850	1054	981	940	916	1022	1069	550	736	793	923
1860	1002	1194	804	794	735	1040	860	932	1104	918
1870	991	988	1135	1099	984	1118	1132	866	1191	863
1880	1004	574	957	671	1089	733	883	928	1026	1307
1890	1283	1161	999	1073	970	902	993	1042	1136	1065
1900	766	848	749	1100	984	914	806	973	1313	1258
1910	1103	837	1298	1125	863	967	1364	904	1162	962
1920	1148	745	761	799	1192	782	760	1134	1136	1329
1930	604	867	642	899	792	953	709	1045	1223	1186
1940	1039	787	1026	1148	661	1061	1121	1309	1660	1409
1950	1477	1112	1029	1099	859	884	1009	1063	1081	897
1960	898	1046	1110	1172	923	1302	879	1491	1225	1046
1970	876	704	823	814	1189	1085	1274	1172	724	702
1980	878	743	816	537	536	533	601	600	858	1468
1990	1392	1301	691	733	704	1051	1272	1261	1199	1047
2000	1647	1367	1094	1137						

APPENDIX B2. Standard Index Chronology for Griffith Knob.

	0	1	2	3	4	5	6	7	8	9
1740		7600	7704	5941	4996	4004	4187	2890	2566	1564
1750	1331	1097	1152	792	1048	691	950	1100	797	828
1760	733	588	616	699	781	612	725	751	724	751
1770	1052	813	674	1182	1381	596	506	513	911	367
1780	977	1495	1139	917	867	638	1251	1830	2301	1198
1790	1165	480	707	852	547	617	792	661	444	514
1800	482	529	330	334	366	630	745	960	591	505
1810	564	624	795	879	921	1016	1071	836	1245	1158
1820	1034	1240	1038	1045	946	894	946	970	740	696
1830	308	741	1300	1025	1062	1196	1131	674	901	893
1840	880	929	1158	1006	937	846	985	800	821	833
1850	1048	840	771	742	656	674	676	841	1054	1089
1860	1157	1052	920	1070	826	847	709	732	841	705
1870	739	812	1004	869	967	1013	949	581	795	488
1880	616	633	894	812	840	630	809	944	937	1054
1890	1056	969	887	886	915	842	866	909	1065	838
1900	747	837	768	886	865	616	868	1013	1181	1044
1910	1065	854	1245	1020	602	865	1102	738	822	671
1920	931	755	900	935	1160	681	856	1028	1077	1502
1930	770	1149	873	1078	951	1220	811	1023	1113	880
1940	760	559	657	685	424	740	734	847	1195	1198
1950	1055	853	536	607	486	585	707	829	924	618
1960	417	650	739	822	771	724	765	1120	1134	1134
1970	1217	982	780	758	1052	1207	1218	999	661	664
1980	1028	834	751	546	656	592	476	434	644	1088
1990	1080	1332	1142	929	748	856	883	1142	858	980
2000	1273	1098	1031	1255						

Appendix B3. Standard Index Chronology for Little Walker Mountain.

	0	1	2	3	4	5	6	7	8	9
1690					868	1144	1357	983	912	770
1700	706	573	1045	1066	1014	667	497	847	943	1305
1710	1436	819	1272	1349	1252	1580	1129	1190	1473	1448
1720	1644	1194	1252	1039	880	1435	771	192	532	1400
1730	1286	1003	1087	1351	1612	1682	904	782	267	453
1740	460	562	711	853	642	971	863	890	833	661
1750	848	901	842	906	938	726	1141	1203	1287	906
1760	1367	1182	503	545	549	639	1095	957	1101	931
1770	1016	862	765	946	1236	1282	1335	1477	1283	925
1780	819	801	704	890	999	1084	958	1106	1129	1019
1790	1090	1049	886	1026	1341	985	1111	1120	1094	1131
1800	1144	1144	1247	961	1051	987	933	822	872	846
1810	855	755	989	970	1009	967	1109	1002	1072	910
1820	1083	941	1020	862	918	976	1037	1119	1184	1159
1830	491	751	846	836	904	1140	1197	1188	1165	991
1840	1114	1101	1130	939	1166	1120	1156	1100	1010	903
1850	935	933	925	843	860	918	965	896	955	1066
1860	1182	1198	1109	1032	917	973	910	1006	927	852
1870	833	880	960	982	1027	901	909	988	1164	877
1880	906	790	1084	878	960	829	1165	1177	1273	1249
1890	1203	1151	1095	1063	1027	797	772	940	1242	979
1900	807	971	837	1059	1089	1088	1066	1189	1201	1046
1910	1033	907	1330	1194	753	636	676	607	758	756
1920	1015	951	1120	1207	1451	974	1209	1296	1269	1259
1930	671	1320	808	1188	1055	1250	950	1269	1464	1260
1940	1160	862	985	846	580	687	792	1028	1459	1374
1950	1290	878	835	886	963	992	991	868	936	554
1960	557	691	950	959	974	1018	776	1071	1289	1196
1970	1116	1044	938	1024	1229	1229	1243	1154	866	847
1980	932	799	493	495	684	690	691	699	792	1279
1990	1057	1302	803	660	659	790	1093	1359	1119	1181
2000	1666	1214	949	1229	1646					

Appendix B4. Standard Index Chronology for North Mountain.

	0	1	2	3	4	5	6	7	8	9
1740				687	981	1500	965	1599	933	1186
1750	1677	764	743	963	873	879	1266	1378	801	924
1760	1386	1097	766	985	973	831	1418	795	1035	880
1770	1075	1173	747	1105	1003	1170	1231	899	1061	628
1780	619	749	496	950	685	705	930	781	890	992
1790	1283	1178	826	909	1082	892	752	913	1006	982
1800	1174	832	1066	831	683	616	602	1243	1259	1567
1810	1036	1482	1114	1074	1632	1699	1142	1734	1407	1212
1820	1351	1453	1179	991	885	1075	776	1083	774	1103
1830	858	1121	787	1145	1238	1237	1105	827	618	670
1840	700	766	1017	869	806	642	919	843	806	860
1850	862	1210	1228	1200	1242	1585	817	594	665	765
1860	1028	1174	1004	678	540	1162	803	945	1009	597
1870	824	1103	1086	1133	1130	1433	1441	821	1275	771
1880	758	456	1060	739	922	569	655	749	867	1331
1890	1129	933	920	868	858	860	980	916	1288	1108
1900	894	1056	1070	1329	1081	1066	989	1078	1271	1104
1910	1162	1004	1138	1081	563	955	1178	889	1127	962
1920	942	779	744	863	1098	771	902	1033	1138	1362
1930	674	981	669	1025	1145	1241	948	1112	1221	1110
1940	1026	765	837	871	412	906	1016	1102	1327	1155
1950	1239	1011	847	866	915	1050	1135	1075	1154	961
1960	817	1091	1139	861	983	1065	574	1260	1272	1206
1970	1184	1086	1140	1090	1239	990	1101	990	1036	947
1980	926	921	777	669	652	883	748	648	1138	1423
1990	1169	1102	808	734	826	966	1167	1401	1047	886
2000	1416	1046	829	1330						

VITA

Georgina G. DeWeese spent the first 24 years of her life in Baton Rouge, Louisiana. There she earned a B.S. and M.S. in Geography with concentration in GIS from Louisiana State University. After graduating in 2001, Georgina began work at an environmental remote sensing consulting firm. This was unsatisfying work, so she entered the Ph.D. program at the University of Tennessee, Knoxville in 2002. After many glorious years as a graduate student, tromping through the woods, seeing exotic parts of rural Virginia, and going into debt, she found employment as an Assistant Professor at the University of West Georgia, Carrollton. And she lived happily ever after with her cockatiels, Cha and Louie-Phillippe Bourbon.