SPATIAL VARIATION IN CLIMATE-GROWTH RELATIONSHIPS OF EASTERN WHITE PINE (*PINUS STROBUS* L.) IN NORTHERN GEORGIA (U.S.A.), AS REVEALED BY TREE-RINGS

by

SHANNON L. HALL

(Under the Direction of Albert J. Parker)

ABSTRACT

Growth response of eastern white pine (Pinus strobus L.) to climate was studied on four matched pairs of north-facing and south-facing aspects in the North Georgia Mountains. Master chronologies were correlated with temperature and precipitation for a 19-month period encompassing the current and previous growing season. Radial growth is negatively correlated with current year summer temperatures and previous year winter temperatures. Growth is positively correlated with current year spring temperatures and current year summer precipitation. Four of the eight sites did exhibit slight changes in growth in the last 25 years that is not a result of the natural decline in growth with age. These results indicate that climate affects growth in subsequent years, soil moisture us partially limiting to growth on all sites, and that slope aspect does not influence tree growth. These findings also indicate the possibility that climate change may be affecting tree growth response.

INDEX WORDS: dendrochronology, climate change, white pine, tree growth

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Dean of the Graduate School
The University of Georgia
May 2004

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CHAPTER 1

INTRODUCTION

Dendrochronologists have long documented the relationships between climatic variation and radial growth of trees through tree-ring analysis (Cook et al., 2001). Because climate dictates site water and energy balance, it acts as a limiting factor to annual tree growth (Box, 1981). Examining the differences in tree-ring growth responses to climatic variation can be useful for determining differential climatic sensitivity among species or across sites (Fritts, 1976; Graumlich, 1993). Tree-ring data has been used to calibrate climate-growth relationships embedded in forest stand simulation models (Shugart, 1984; Graumlich, 1989). These models have, in turn, been used to project the effects of future climatic change. Knowledge of climate/tree growth relationships has assumed increasing importance in recent decades, with growing concern for the biological impacts of global warming (IPCC, 1992). Analyzing temporal variation in tree ring widths may allow detection of climatic change over the past several decades on local or regional scales.

Dendroclimatological studies have been conducted in various parts of the United States to assess the role of local Site 3Nactors, acting through microclimate, in producing spatial variation in patterns of climate-growth response. Graumlich (1993) examined the importance of regional climate in controlling tree growth in northern hardwood forests of the upper Great Lakes region, which included the species of interest in this proposal: eastern white pine (*Pinus strobus* L.). Using a principal components analysis, Graumlich (1993) discovered that climatic variation is an important factor influencing growth at mesic sites, and that in areas with relatively small climatic contrasts, interspecific differences in growth response to seasonal climate are more important than intersite differences in climate. Cook et al. (2001) looked at dendroclimatic responses across a gradient of increasing aridity in forests of the western Gulf Coastal Plain of Louisiana and eastern Texas. They used tree rings to identify groups of trees that responded similarly to climate. Cook et al. (2001) also tested Graumlich's (1993) conclusion that phylogenetic influences are more important than ecological relationships in determining functional-group composition. They found that there is an underlying organizing principle based on genetics that determines how certain phylogenetic groups of trees respond to climate in a way that is independent of environment. The findings of Graumlich (1993) and Cook et al. (2001) indicate the importance of conducting more studies of regional patterns of tree growth response to climatic factors.

Graumlich (1993) and Cook et al. (2001) emphasize genetic controls of tree growth, but each of their studies was conducted in relatively flat terrain. In regions of greater topographic complexity, site-related variation in tree-growth responses to climate may be accentuated. Ettl and Peterson (1995) examined growth responses of subalpine fir (*Abies lasiocarpa*) to extreme climate in the Olympic Mountains, Washington. They sampled at three elevations on southwest-facing slopes at sites that were located in contrasting precipitation regimes, relatively wet and relatively dry. They concluded that subalpine fir tree growth in high-elevation wet sites was positively correlated with warm summer temperatures, whereas growth in dry, low and middle-elevation sites was negatively correlated with warm summer temperatures. Furthermore, Ettl and Peterson (1995) determined that individual tree growth-climate correlations were of variable strength, with some individuals being relatively unresponsive to climate.

Among the various components of topography, slope aspect exerts an important influence on energy and water balance in temperate mountainous terrain (Cantlon, 1953). South-facing slopes in temperate latitudes of the northern hemisphere generally receive a higher concentration of solar radiation than north-facing slopes, resulting in warmer temperatures, elevated potential evapotranspiration rates, and more xeric conditions. Consequently, trees may experience slower growth rates under these conditions. Furthermore, seasonality of climatic sensitivities may vary between south-facing and north-facing slopes; on south-facing slopes, growth may be more responsive to early season inputs of temperature and precipitation, or more negatively affected by mid-summer dry spells, and may be more sensitive to drought conditions in general.

I propose to examine climatic variation in radial growth of eastern white pine on matched pairs of sites situated on adjacent north and south-facing slopes in the Blue Ridge physiographic province of northern Georgia. My research objective is to determine the importance of climate on tree growth for eastern white pines in the southern portion of the Appalachian Mountains, particularly within the North Georgia Mountains. In addition, I will examine whether growth patterns have been affected by any progressive climatic change that this region of the United States may have experienced in recent decades. Specific research questions I will address include: 1) Do patterns of eastern white pine radial growth differ between north- and south-facing slopes? 2) Are growth chronologies of eastern white pine on north vs. south facing sites responsive to different combinations of climatic variables (temperature vs. precipitation) and seasonal timing of influence (winter vs. spring vs. summer)? 3) Do growth chronologies exhibit any progressive change in radial growth patterns over the past 50 years that provides evidence of local climatic change?

Study Species

Eastern white pine is one of the largest conifers in the uplands of eastern North America, with an average height of 33 m, and an average diameter of about 90-120 cm for mature individuals on optimal sites. It ranges along the eastern seaboard from Newfoundland southward to northern Georgia. It also extends as far west as southeastern Manitoba, northwestern Iowa, northern Illinois and Ohio (Wendel and Smith, 1990). Although its range covers a large area, the species favors cool, humid habitats. The distribution of eastern white pine coincides with the parts of eastern North America where the July temperature averages between 18º and 23º C. In the southern part of its range, white pine grows best on soils along rivers and streams and grows more slowly on well drained sites. In the southern Appalachians, white pine occurs in a band between 370 and 1070m, and exceeded several other species in growth in a comparison of site index and growth (Wendel and Smith, 1990). Annual precipitation ranges from about 500 mm in the northern portion of its range up to 2000 mm in the southern Appalachians. White pine is sensitive to fire (Brown and Jones, 1998), but can regenerate well afterward (Heinselman, 1981).

Study Area

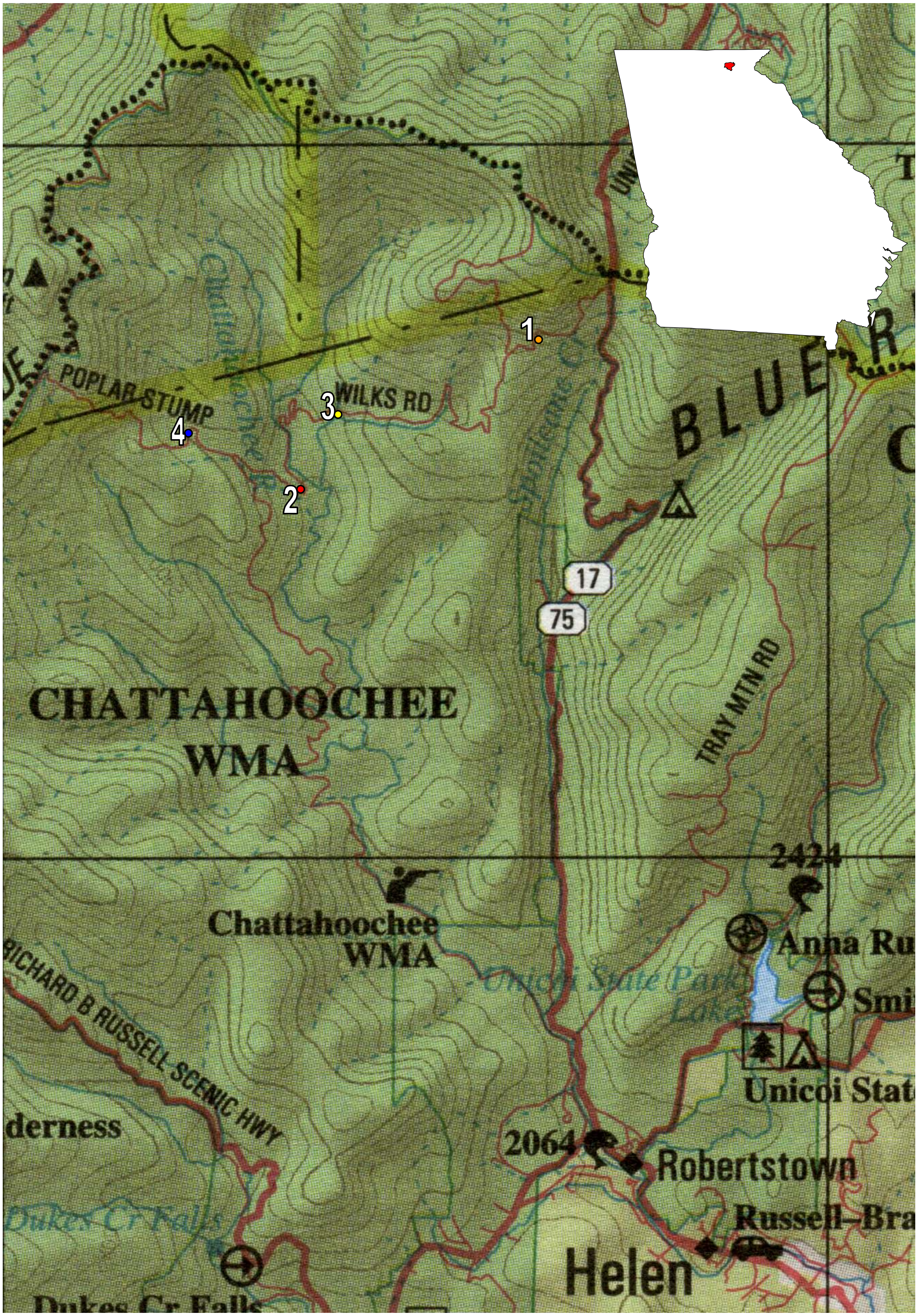
The study area is located in White County in the North Georgia Mountains, on land administered as part of Chattahoochee National Forest, approximately 16 kilometers north of Helen, Georgia. Eight sites were chosen for study, four pairs of adjacent north-facing and south-facing slopes. Elevation of study sites ranged from 715 to 775m, which is considered mid-elevation in the Southern Appalachians. This area is topographically complex, but most of the study sites were situated on moderate to steeply sloping terrain.

Although logging is still conducted in this area, the trees sampled ranged in size from 30 to 70cm dbh, and were estimated to be at least 50 years old. In the North Georgia Mountains, white pine may have been less prevalent prior to clearing, logging and fire suppression in the 20th century. Brown and Jones (1998) suggest that eastern white pine originally grew as scattered trees in fire-protected areas. Today, eastern white pine is one of the dominant tree species, having expanded onto open slopes in the absence of periodic burning.

The average maximum temperature in nearby Helen, in January is 10.1º C, and the average minimum temperature is –2.2º C (Southeast Regional Climate Center). The average maximum temperature in July is 29.8º C, and the minimum temperature is 17.1º C (Southeast Regional Climate Center). The average annual precipitation in Helen is approximately 1800 mm (Southeast Regional Climate Center) with a modest precipitation maximum in spring and minimum in autumn.

Like much of the Southern Appalachian Mountains, the North Georgia Mountains were derived from ancient marine sediments, such as sands and silts, between 200 and 450 million years ago (Brown and Jones, 1998). The mountains originated as a result of continental plate collisions of eastern North America with northern Africa. Pressure and heat from those tectonic forces metamorphosed antecedent igneous rocks into gneiss, schist, and phyllites and antecedent sedimentary material into slate and quartzite. Soils in the Southern Appalachians are generally acidic, thin, and rocky, with weak horizon development (e.g. Dystochrepts). These soils are weathered from acidic bedrock, either in place, deposited on lower slopes, or along stream terraces (Wendel and Smith, 1999).

Figure 1.1 – Study Area



CHAPTER 2

METHODS

Field Methods

Eight sites, or four matched pairs of sites, situated on adjacent north and south slopes, were selected for study in the North Georgia Mountains. Each site included a reasonably dense population of large (>30 cm diameter at breast height [dbh]) eastern white pine trees interspersed with other species, such as white oak (*Quercus alba*), northern red oak (*Quercus rubra*), tulip poplar (*Liriodendron tulipifera*) and eastern hemlock (*Tsuga canadensis*). Sampling was restricted to areas of uniform site conditions, and was conducted between August 2002 and March 2003.

Within each of the sampling sites, elevation, topographic configuration and topographic position were recorded from field observations and topographic maps. Aspect and slope angle were measured with a compass. For each site, 20 of the largest white pine trees were selected within a uniform stand area (50x50m), dbh was measured, and a tree core was extracted from each tree with an increment borer at 30cm height.

Laboratory Methods

Tree cores were dried, mounted, and sanded using standard dendrochronological procedures (Stokes and Smiley, 1968). Next, the tree cores were dated and ring widths were measured to the nearest 0.01 mm with a computer-controlled microscopic stage that employs the

OPTIMAS image analysis system (Parker et al., 2001b.). Each tree-ring series was cross-dated and validated using the COFECHA computer program, which reveals any cross-dating errors by computing cross-correlations between individual series and a master chronology for each stand (Holmes, 1983). At least 75% of the cores in each site were reliably cross-dated.

Statistical Methods

Standard dendrochronological statistical techniques were applied for each site to develop a master chronology based on average growth patterns among the trees sampled. Standardization involves fitting the observed ring-width series to a curve or straight line, and computing an index of the observed ring widths divided by the expected values (Villalba et al., 1994). This helps reduce variances among the cores, and allows computation of average tree-ring chronologies without the average being dominated by the faster-growing trees with large ring widths. Annual variation in ring-width series can arise from several sources (Graumlich, 1993). Non-climatic variation in growth rate is related to aging, biological persistence, and long-term stand dynamics. Master chronology development procedures are designed to identify the source and magnitude of non-climatic variation, and to reduce its expression when compared to climatic influences (Fritts, 1976). Radial growth of trees generally declines as trees age; individual ring series in this study were fit to a negative exponential form to standardize for age-dependent variation in growth.

Low-frequency variance was removed from the series with a cubic smoothing spline (a form of moving average) that was fit to the series with a 50% cutoff. Another source of variation, autoregression, arises from the persistence of climatic effects into subsequent years through variation in food reserves (carbon storage) and preconditioning of growth (Fritts, 1976).

Autogressive modeling was used to diminish interannual carryover in growth from the prior year's carbon storage or depletion.

Correlation coefficients can be computed for ring series covering the same time period to provide a standard for expressing their degree of similarity (Stokes and Smiley, 1968). Master chronologies were correlated to one another to assess the commonality in their growth response across sites (Parker et al., 2001).

To determine if growth chronologies of eastern white pine are responsive to different climatic variables, a series of correlations was conducted to explore climatic controls on tree growth. This involved comparing growth chronologies with records of mean monthly temperature and precipitation. Pearson product-moment correlation coefficients were calculated between the climatic variables and individual standardized tree-ring series at each site. Divisional climate data were gathered for a 19-month period encompassing the previous and current growing seasons. Georgia is divided into nine climatic divisions; all of my sites are located in Division 2. Divisional climate data were used instead of local weather stations because the local stations lacked complete records. In addition, divisional data have been shown to correlate more accurately with tree-rings than data from individual climate stations (Blasing et al., 1981). However, there is a limitation to creating a growth response analysis from tree-ring data. The tree-ring measurements used in this study represent growth responses to local climate, microsite conditions and competition, and regional climatic data provide growth information that varies from the actual conditions affecting growth on each site (Ettl and Peterson, 1995). Nonetheless, a growth response curve based on year-to-year growth variation provides a good approximation of species growth response to summer temperature. This can serve as a starting point for examining the growth equations used to model species response to climate change (Ettl and Peterson, 1995). Climate-growth correlations included lagged correlations with the prior hydrologic year because current-year growth is partially attributable to year-to-year carbohydrate storage and changes in photosynthetic biomass (Fritts, 1976). Bivariate correlations were calculated between annual growth increments and both mean monthly temperature and precipitation, for the 19-month period from March of the previous growing season to October of the current growing season, in order to identify any seasonal sensitivity of radial growth responses of eastern white pine to temperature and precipitation. At least 15 cores from each site were used for these analyses.

To determine differences in growth patterns between north and south-facing slopes, a difference-of-means test was used to compare average raw growth rates on north vs. south-facing slopes. Next, pairwise correlations of master chronologies were produced for years of common record among the eight sites to examine growth differences between north vs. south-facing slopes, and among individual matched pairs.

To determine if growth chronologies exhibit any progressive change in radial growth patterns over the past 50 years, the records were split into 25-year periods. Master chronology z-scores were then compared between the two periods with a difference-of-means test for each of the eight sites.

CHAPTER 3

RESULTS

This chapter provides a quantitative and descriptive summary of climate growth relationships among eastern white pines in the North Georgia Mountains. Temperature and precipitation patterns are explored, and correlations between these climatic variables and annual radial growth of trees are conducted. Radial growth patterns are also examined over the last 50 years to detect progressive change in radial growth that may be linked to regional climatic changes.

Most of the study sites were located on middle to upper slopes, with only one site situated on the lower portion of the slope (Table 3.1). Sites 1S, 1N, 2N, 2S and 4N had a concave configuration, and sites 3S, 3N and 4S had slightly convex configurations. All of the matched pairs except one (sites 4S and 4N) had similar slope angles. Site 4S had a moderate slope of 30º, but its adjacent site (4N) had the steepest slope of all the sites at 48º. Sites 1S and 1N were the most moderately sloping with angles of 19º and 25º, respectively. Sites 3S and 3N were also moderately sloping with angles of 31º and 26º respectively. Sites 2N and 2S had a slightly higher angle with slopes of 39º and 42º. Average steepness was 32.5º. Average age and dbh were similar among matched pairs as well. Sites 1S and 1N contained the youngest trees with average ages of 52 and 57 years, and an average dbh of 37 and 48cm. Sites 4S and 4N held the oldest trees with average ages of 79 and 67 years, and an average dbh of 63 and 74cm.

Eastern white pine was the dominant tree species on all sample sites. Trees ranged in age from 42 to 96 years, with most between 50 and 75 years. Average radial growth ranged from 3.01 ± 1.05 mm/year (Site 1S) to 3.95 ± 0.60 mm/year (Site 2S), indicating similar raw growth rates among all sites (Table 3.2). Collectively, average radial growth was slightly higher on north sites (3.52 ± 0.76 mm/year) than on south sites (3.33 ± 0.70 mm/year), although this difference was not statistically significant. For pairwise comparisons at the site-level, Pair 1 exhibited significantly faster growth on the north-facing slope (Table 3.2). The other three pairs failed to yield significant differences in growth related to slope aspect. Master chronologies were similar among all sites, with series intercorrelation values ranging between 0.452 (Site 3S) and 0.581 (Site 2N). A few years, 1938, 1950, 1955 and 1996 in particular, exhibited extreme growth anomalies (absolute value of z-scores exceeded 3.0) in at least one tree on at least two sites. Site 2S, a south-facing site, experienced growth anomalies in each of the four years.

In general, white pine radial growth was well correlated with warm spring temperatures of the current growth year (Figures 3.1 and 3.2). All but one site (Site 3S) showed significant correlations with March and/or April temperatures. This was to be expected with conifers in particular because their evergreen foliage allows them to take advantage of early growing-season warmth (Graumlich 1993). Site 4S exhibited the strongest correlation (.408) to March temperatures, and Site 1N exhibited the strongest correlation (.424) to April temperatures. Also, most sites exhibited a negative correlation of radial growth increment with May – September temperatures. This was also to be expected, as hotter temperatures induce greater evaporative stress and drier conditions, which will lower photosynthetic rates.

Tree growth correlations with monthly precipitation values were not as strong as those between growth and mean temperature. Nonetheless, most sites showed a positive correlation with June - August precipitation (significantly so in several sites) in the current growth year (Figures 3.3 and 3.4). This suggests the importance of soil moisture as a limiting factor that partially constrains growth in eastern white pines. All of the sites exhibited a negative response to precipitation in March, which is likely linked to cloudier and cooler conditions in early spring of low-growth years along with the tendency for March to be the wettest month of the year (Figure 3.5). Also, interestingly, all of the sites except Site 1S exhibited a slight positive correlation to February precipitation. Collectively, the south-facing sites exhibited stronger correlations to precipitation, which was to be expected as south slopes tend to be drier than north slopes, and thus potentially more sensitive to interannual variability of soil moisture.

For lagged correlations, temperatures from the previous growing season exhibited a positive correlation in June (significantly so in all of the north-facing sites, as well as Site 1S among the south-facing sites), as well as a negative correlation in late summer / early fall. This reinforces the fact that climate affects tree growth in subsequent years. Most of the sites exhibited a negative correlation with precipitation during November – January of the preceding winter. Also, sites 1S and 1N exhibited strong positive correlations to March precipitation of the previous year (.359 and .342 respectively).

Site-to-site correlations revealed strong, statistically significant, associations among matched pairs, as well as strong correlations among the north-facing and south-facing sites (Table 3.4). However, collectively, the north-facing sites showed higher inter-Site correlations than the south-facing sites. This was to be expected as north-facing slopes tend to be more moist than south-facing slopes, and trees that are limited by climatic stress tend to exhibit greater relative variability in ring widths than trees for which growth is less affected by climate (Fritts, 1976). Also, microsite competition or other conditions that could potentially limit growth may be more pronounced in sites that already suffer from moisture stress. With this in mind, it would not be expected that sites experiencing limiting factors, such as moisture stress, would correlate as well as sites that do not experience these conditions.

There was a slight change in growth patterns among four of the sites over the last 25 years (Table 3.5). Statistically, difference-of-means tests comprising growth of the last 25 years (1978-2002) with that of the previous 25 years (1952-1977) yielded t-statistics with p-values of .202, .173, .061 and .100 within sites 1N, 2N, 2S and 3S respectively. Although these differences are not statistically significant, it is important to note that half of the study sites demonstrate this change, which, despite the lack of significance, may suggest a tendency toward reduced growth (after standardization) in recent years.

Table 3.1 – Individual site average age and dbh, and topographic conditions.

Site	Avg. Age	Avg. dbh	Elevation	Steepness	Aspect	Topo. Pos.	Configuration
1S	52	37	863 m	19°	S	mid. to upper	concave
1N	57	48	863 m	25°	N	mid. to upper	concave
2S	59	48	655 m	42°	S	mid. to upper	concave
2N	57	49	655 m	39°	N	mid. to upper	concave
3S	74	59	833 m	31°	S	upper	convex
3N	67	61	833 m	26°	N	upper	convex
4S	79	63	774 m	30°	S	low to mid.	convex
4N	67	74	774 m	48°	N	middle	concave

Table 3.2 – Average radial tree growth for each site.

		Mean	N	Std. Deviation	Std. Error Mean	t	df	p
Pair 1	1S avg.	3.0072	16	1.05402	0.2635	-2.967	15	0.010
	1N avg.	3.7929	16	0.71913	0.17978			
Pair 2	2S avg.	3.9463	16	0.59633	0.14908	-0.784	15	0.445
	2N avg.	3.7635	16	0.7801	0.19503			
Pair 3	3S avg.	3.1151	15	0.63376	0.16364	-0.193	14	0.850
	3N avg.	3.1709	15	0.95371	0.24625			
Pair 4	4S avg.	3.216	16	0.53375	0.13344	-0.816	15	0.428
	4N avg.	3.3595	16	0.60212	0.15053			

Table 3.3 – Inter-site correlations. Each entry includes the correlation coefficient value, the p-value, and the number of years on which the correlation is based. All correlations are significant.

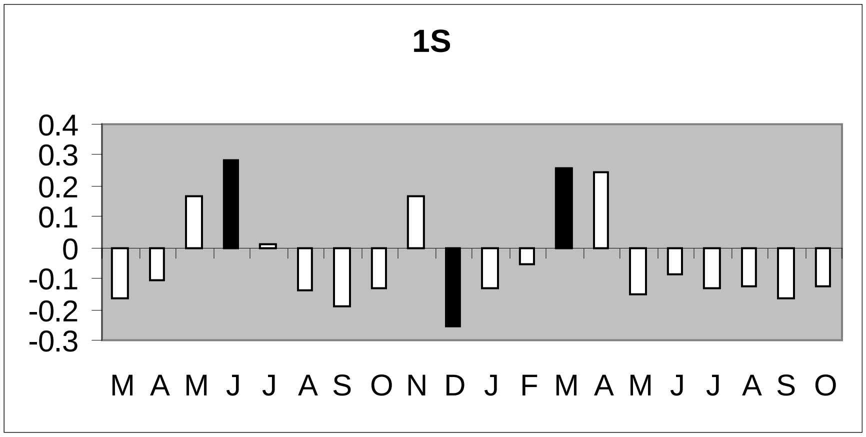
Sites	1S	2S	3S	4S	1N	2N	3N	4N
1S	1	0.387 0.001 66	0.278 0.024 66	0.451 0 66	0.48 0 66	0.536 0 66	0.473 0 66	0.547 0 66
2S		1	0.519 0 86	0.471 0 88	0.617 0 66	0.749 0 66	0.409 0 88	0.487 0 81
3S			1	0.566 0 86	0.525 0 66	0.518 0 66	0.547 0 86	0.409 0 81
4S				1	0.652 0 66	0.613 0 66	0.66 0 91	0.694 0 81
1N					1	0.54 0 66	0.559 0 66	0.542 0 66
2N						1	0.606 0 66	0.648 0 66
3N							1	0.671 0 81
4N								1

Table 3.4 – Site-level differences between 1952-1977 and 1978-2002 for each site.

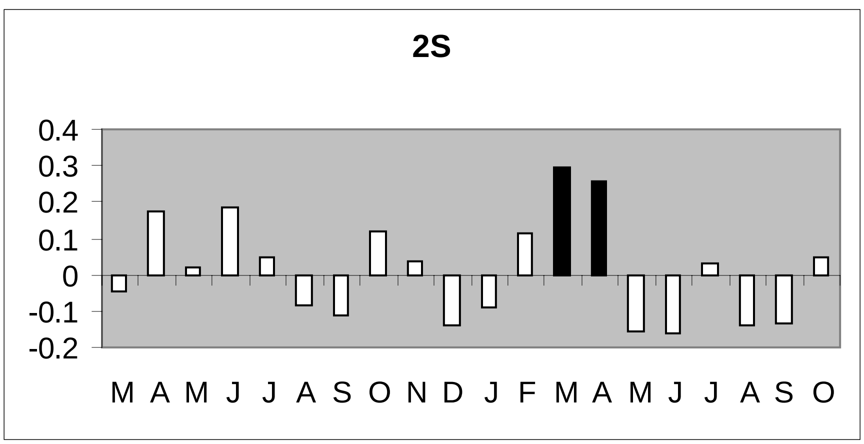
	Mean	Std. Deviation	Std. Error Mean	t	df	p
1S	0.0686	1.0162	0.2032	0.338	24	0.739
1N	0.368	1.402	0.2804	1.312	24	0.202
2S	0.4029	1.0235	0.2047	1.968	24	0.061
2N	0.3236	1.1518	0.2304	1.405	24	0.173
3S	0.4369	1.2786	0.2557	1.709	24	0.1
3N	0.1389	1.2687	0.2537	0.547	24	0.589
4S	0.1531	1.1723	0.2345	0.653	24	0.52
4N	0.1978	1.1966	0.2393	0.826	24	0.417

Figure 3.1 – Temperature Correlations for South-facing Sites, beginning with March of the previous year.

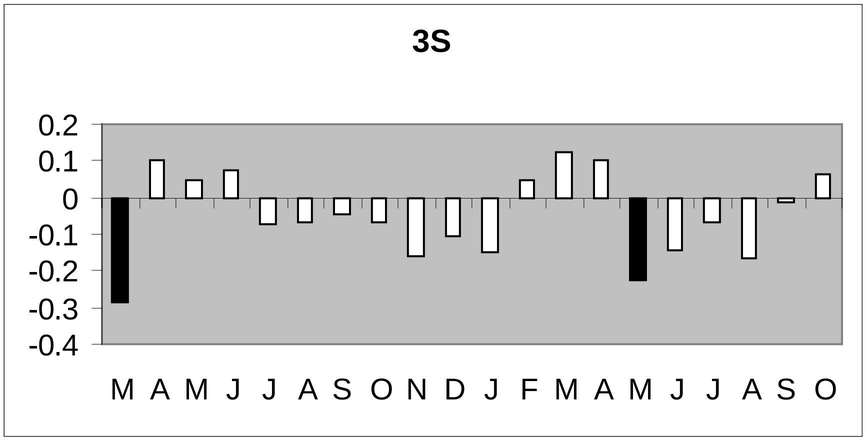
a.



b.



c.


3S
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
M A M J J A S O N D J F M A M J J A S O

d.

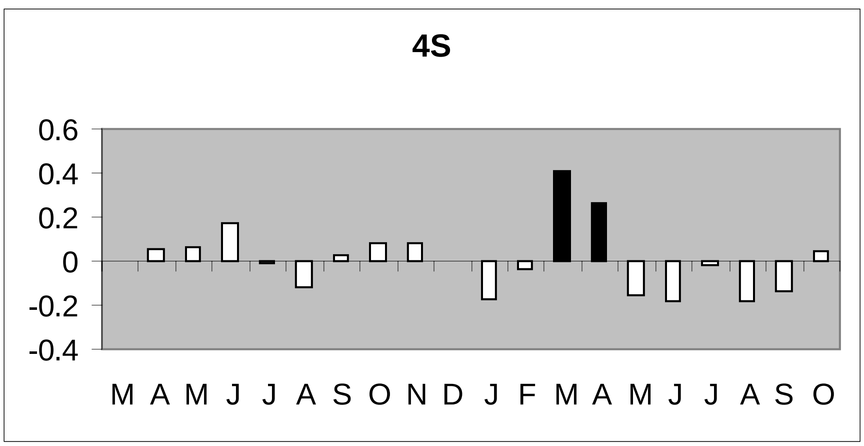
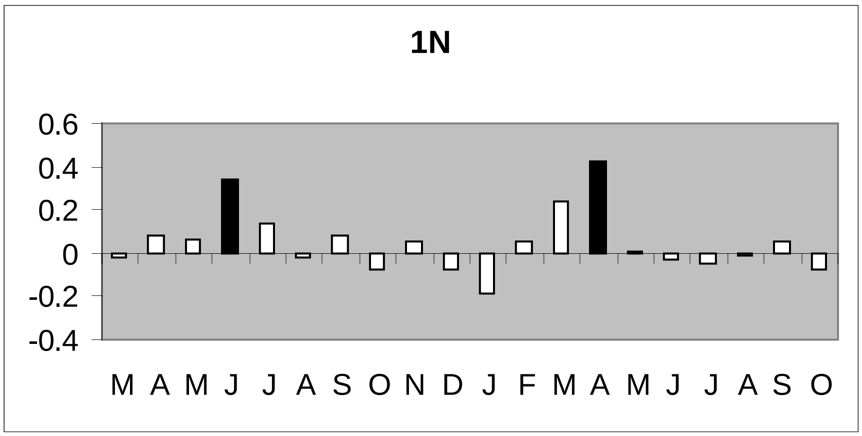
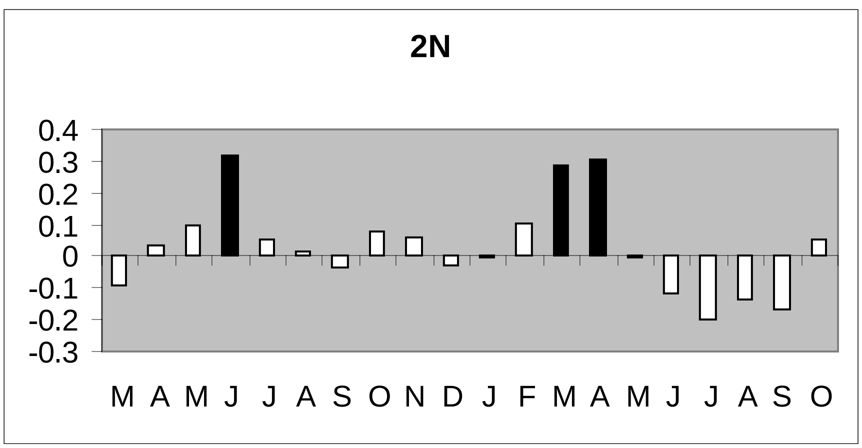

4S
0.6
0.4
0.2
0
-0.2
-0.4
M A M J J A S O N D J F M A M J J A S O

Figure 3.2 – Temperature Correlations for North-facing Sites, beginning with March of the previous year.

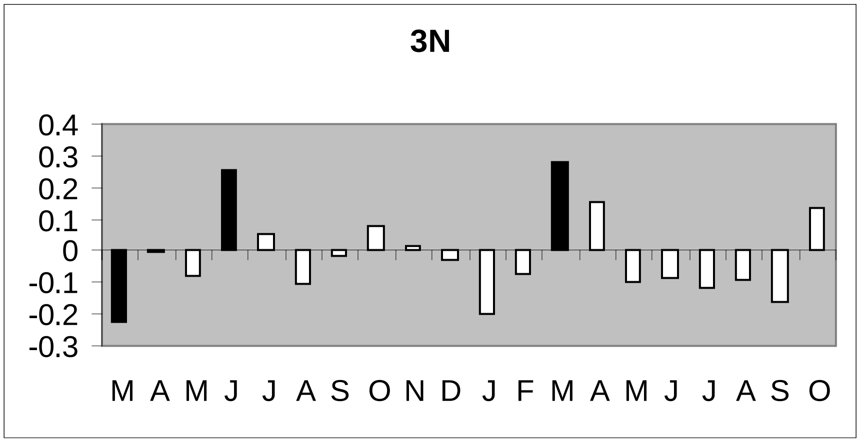
a.



b.



c.


3N
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
M A M J J A S O N D J F M A M J J A S O

d.

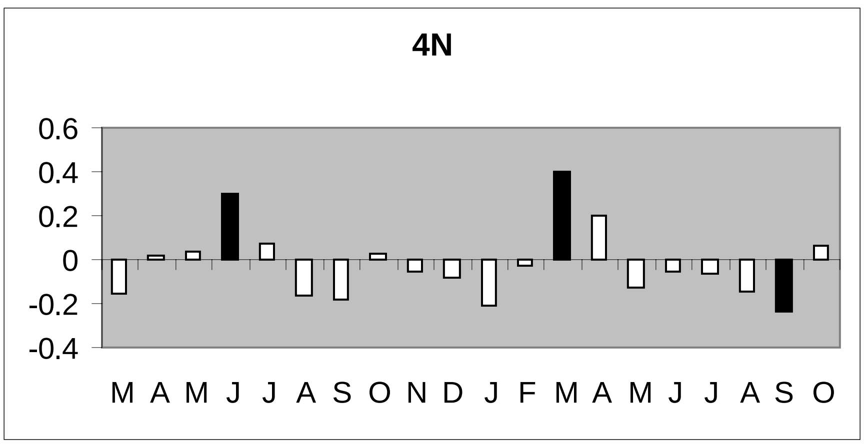
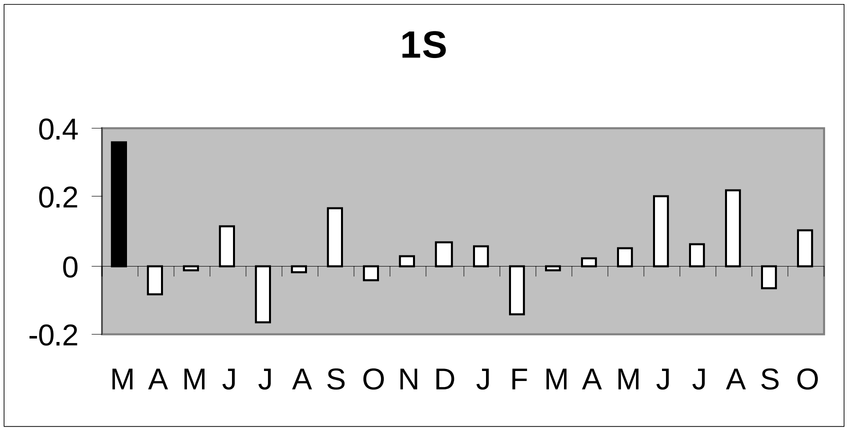

4N
0.6
0.4
0.2
0
-0.2
-0.4
M A M J J A S O N D J F M A M J J A S O

Figure 3.3 – Precipitation Correlations for South-facing Sites, beginning with March of the previous year.

a.



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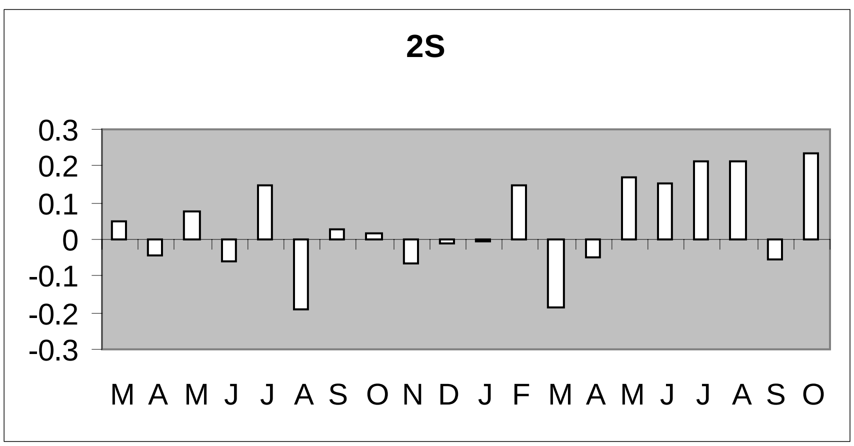
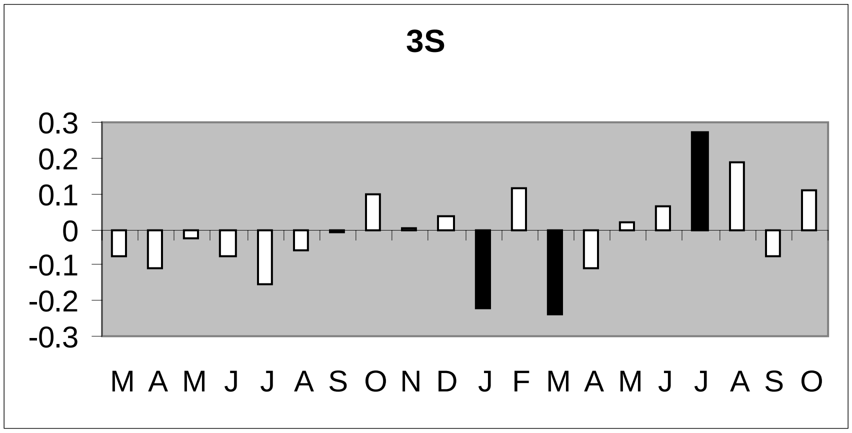


c.


3S
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
M A M J J A S O N D J F M A M J J A S O

d.

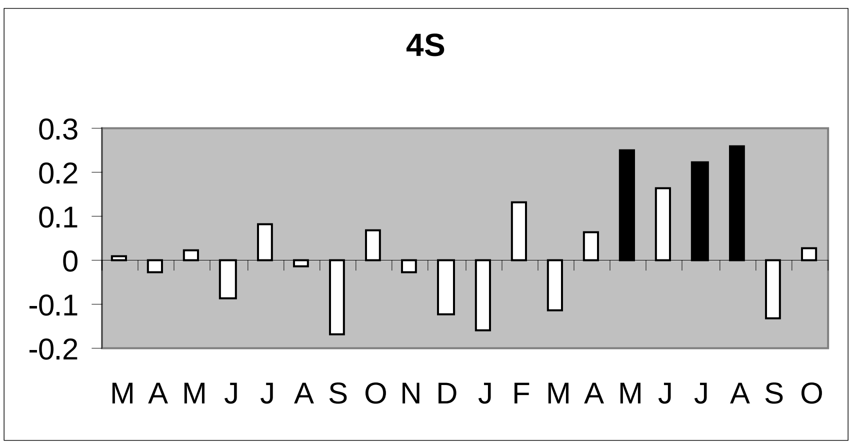
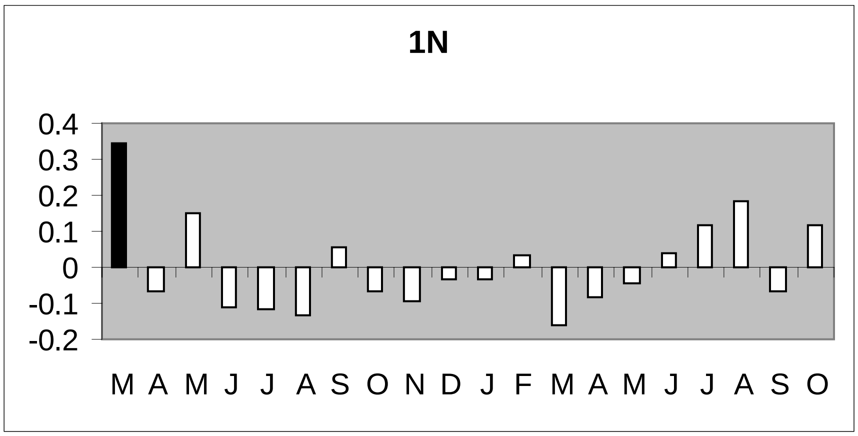
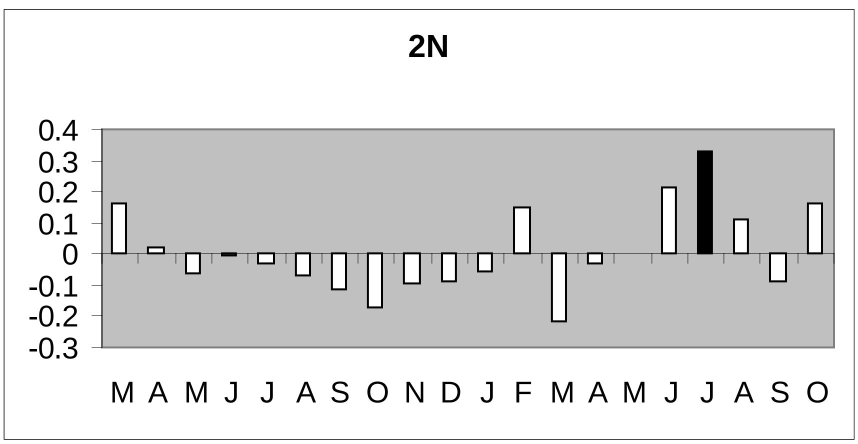

4S
0.3
0.2
0.1
0
-0.1
-0.2
M A M J J A S O N D J F M A M J J A S O

Figure 3.4 – Precipitation Correlations for North-facing Sites, beginning with March of the previous year.

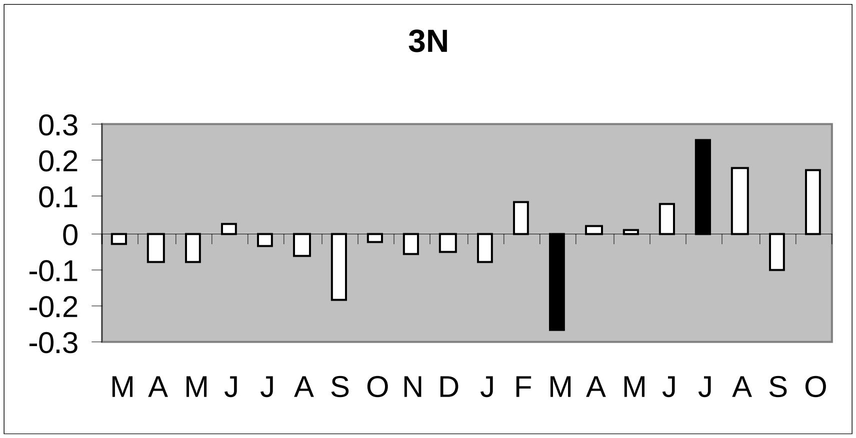
a.



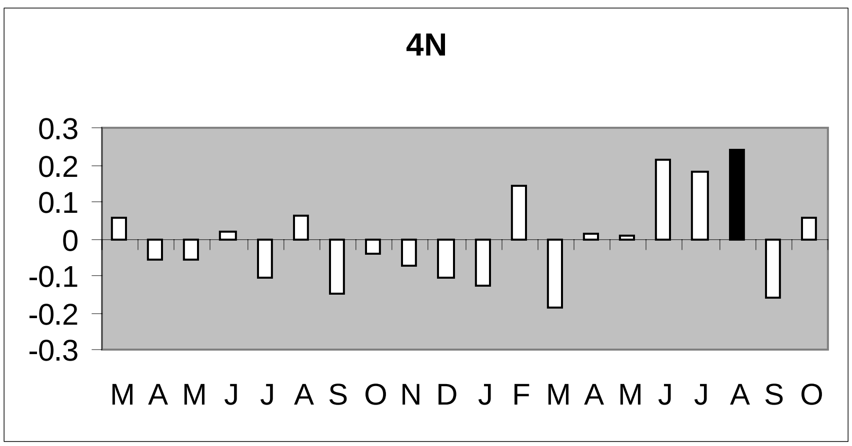
b.



c.


3N
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
M A M J J A S O N D J F M A M J J A S O

d.


4N
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
M A M J J A S O N D J F M A M J J A S O

CHAPTER 4

DISCUSSION

The first section includes a summary of the average radial growth rates on opposing aspects, as well as an interpretation of the effects that slope steepness has on growth. The second section of this chapter includes a discussion of temperature and precipitation correlations as they influence radial growth. The last section begins with an analysis of temperature and precipitation patterns in recent decades, and then concludes with a discussion of some possible effects that climatic changes could have on tree growth and forest structure in the future.

The site-to-site correlations expressed a stronger relationship among the north-facing sites, but the south-facing sites exhibited a positive site-level inter-correlation as well. Average raw growth rates were similar for three of the four matched pairs of north and south-facing sites. One pair did exhibit significantly greater growth on the north-facing aspect, but slope steepness was lowest for this pair, thereby muting the expression of aspect. Overall, evidence for aspect-mediated growth differences was weak, contrary to my expectation that south-facing slopes in the temperate latitudes of the northern hemisphere may experience slower growth rates that result from the moisture stress created by increased insolation. Greater differences in growth rates had been expected between north and south-facing aspects. Instead, there were strong correlations between all of the sites growth patterns. Ziegler (1995) found that white pine reproduced well on south-facing slopes in southwestern Wisconsin, a location where white pine occurs on the dry margin of its range. Neither slope steepness nor configuration influenced tree growth in this study. In fact, the three sites with the steepest slopes (4N, 2S and 2N respectively) had average radial growth rates that were greater than four of the other sites situated at lower slope angles. This is contradictory to the findings of Villalba et al. (1994) in that both steepness and aspect were influential in tree growth response in Colorado. By contrast, Ziegler (1995) found that, despite a great degree of local variability in both steepness and aspect, the presence or absence of white pine was not affected.

The radial growth response of white pine to climatic conditions generally fits ecological expectations. Warm spring temperatures clearly exhibited a strong influence on growth in all of the areas examined. Graumlich (1993) also found that warm April temperatures favored the conifers in her study (white pine included) as the evergreen foliage allows them to take advantage of the early growing season warmth.

Although there were strong correlations to March and April temperatures of the current growth year, all sites exhibited a negative correlation to the previous year's March temperatures. Ettl and Peterson (1995) found similar responses in subalpine fir to July and August temperatures. It seems logical that subalpine fir on the Olympic Mountains of western Washington would experience correlations to later months than the white pines in this study as the elevations in their study were higher (1340m – 1860m), which were approximately double the elevations examined in this study. With cooler temperatures at higher elevations, the growing season will naturally begin later than it would at lower elevations, where warmer temperatures occur earlier. Three possible mechanisms could account for the inverse relationship between growth and spring temperature in successive years.

First, warm spring and summer temperatures may stimulate stem growth during the current growing season by increasing the growth rates of cambial tissue (Kozlowski, 1962). The increase in cambial growth may result in a higher allocation of carbon to stem growth rather than storing carbon for the following year. Conversely, cool spring and summer temperatures reduce stem growth so carbohydrate reserves accumulate due to a decrease in synthesis and maintenance respiration (Kozlowski and Keller, 1966.) Although it has been suggested that cambial growth is primarily attributable to current growing-season conditions rather than carbon stores from previous years (Kozlowski, 1962), other climate-growth relationships and dendroecological studies (particularly of subalpine species) (Fritts, 1974; Graumlich, 1991; Peterson and Peterson, 1994; Ettl and Peterson, 1995) suggest that stored carbon from the previous year can affect growth in the following year.

A second possibility is that warm spring temperatures provide a favorable environment for photosynthesis, which results in the production of larger than average terminal buds (Kozlowski, 1962; Kozlowski, 1979). Shoots would be larger-than-average with the absence of environmental stresses. The increased allocation of resources for stem elongation could reduce carbon stores that would otherwise be available for radial growth later in the season (Ettl and Peterson, 1995). Conversely, cool previous-spring temperatures may decrease the size of terminal buds, reducing height and shoot growth in the following spring, resulting in a larger carbon storage available for cambial growth later in the following growing season.

The third possibility is that higher spring temperature results in faster stem growth, provided adequate moisture is available. Drier conditions may decrease a tree’s ability to store carbon for the subsequent growing season because of stomatal closure resulting in decreased photosynthesis. Additionally, carbon storage may be reduced as available photosynthate is allocated to root growth in an attempt to increase root absorption area (Waring, 1991). An increase in root biomass during previous spring and summer droughts could increase growth in the subsequent year because greater root mass is available for absorption of moisture and nutrients.

Although growth is generally completed by early autumn, fall temperatures can be important in determining the amount of carbohydrate that will be available for the following season. Warm conditions during these months will promote continued photosynthesis, resulting in an increase in carbon storage for the next year. Slight positive correlations to the previous year's October and November temperatures, as well as the current year's October temperature, which occurred at most sites, could indicate continued photosynthesis and root growth in warm autumns, and increased carbon storage for the following growth year. Ettl and Peterson (1995) found positive correlations of November temperatures with growth on low and middle-elevation sites. Villalba et al. (1994) also found positive correlations to the previous year's fall temperatures (September and October) among lodgepole pines (*Pinus contorta*), although that study was conducted at much higher elevations in the Colorado Front Range (2750 –3350m).

Precipitation totals in the warm summer months (June – August) exhibited strong (mostly significant) correlations with tree growth at all sites. Parker et al. (2001) found a similar response among sand pine (*Pinus clausa*) sites in northern and central Florida, as they also found positive correlations to precipitation in the early/middle part of the growing season (March – June). Cook et al. (2001) also found a similar relationship among pines and precipitation, with positive correlations in June – August, particularly among the east-central Texas sites, in their study. This relationship was best expressed on the south-facing sites of this study. Hence, the regionally dry sites in the study of Cook et al. (2001) and the topographically dry sites in this study both yielded strong sensitivity of tree growth to precipitation. Correlations to the previous year's precipitation were mostly negative, with the south-facing sites exhibiting slight positive correlations in September and/or October. This is logical because precipitation is more of a limiting factor on southern aspects in the Northern hemisphere. The pines in the Cook et al. (2001) study exhibited slight positive correlations to the previous year's November and December precipitation. Note, however, that none of the previous-year precipitation correlations in this study were statistically significant.

Although Graumlich's (1993) study found growth of northern pine species to be a function mostly of temperature, this study as well as that of Cook et al. (2001) found growth to be a function of both temperature and precipitation. However, this study and Graumlich (1993) both found growth to be stimulated by warm temperatures early in the growing season, whereas Cook et al. (2001) found growth to be associated with cool temperatures during the growing season. These growth relationships to temperature are logical because spring temperatures in the upper Great Lakes region (Graumlich, 1993) and this study area (southern Appalachians) are much cooler than spring temperatures in Louisiana to east-central Texas (Cook et al., 2001) study area.

Global climate models (GCMs) predict a 2-5ºC increase in mean global temperatures as a response to increased concentrations of greenhouse gases (IPCC, 1992). Changes in raw growth rates over time could be an indicator that trees are responding to climatic change. Decreases in growth rates characterized all eight study sites. Though none of these met the rigorous statistical standard for avoiding a Type I error ($p<.05$), four of the eight sites had p values between 0.202 and 0.061. In essence, the odds of a meaningful growth decline (compared with a random standard) range from 4:1 to 17:1. This outcome could be an early indicator that climate patterns are slowly changing in the southern Appalachian Mountains. Average temperature and precipitation patterns were compared for the periods 1952-1977 and 1978-2002 (Figures 4.1b and 4.2b). Temperature actually decreased slightly in the second 25-year period (1978-2002) during all months except January, October and November. This could be a result of increased cloudiness in recent decades, although this has yet to be documented for the southern Appalachian region. However, it has been documented that the amount of sulphate particles in the atmosphere has increased in several areas, including northern Alabama and northern Georgia (Samab, 1996). An increase in sulphate particles in the atmosphere can stimulate cloud formation.

Interestingly, when comparing average monthly temperatures for the period 1906-1981 with those of 1982-2002, there does appear to be a slight increase in temperature in all months except January and September in the last two decades (Figure 4.1c). However, this increase is minimal, so the effect it may have had on tree growth is debatable. Precipitation differences in the period 1982-2002 compared to 1906-1981 vary, with six months receiving more precipitation in the recent decades and six months receiving less precipitation (Figure 4.2c). However, because divisional data were used in this study, climatic conditions that are specific to the North Georgia Mountains, particularly individual microsites, cannot be ascertained. Thus the on-site change could actually be more or less pronounced.

Warmer summer temperatures could be detrimental to tree growth, with growth already being sensitive to low soil moisture, as indicated by the positive correlations to June – August precipitation and slight negative correlations to previous late-summer temperature. Warmer summer temperatures, which will lead to higher evapotranspiration rates, may result in decreased growth if the warming is not accompanied by increased rainfall. An increase in mean annual temperature could cause the most detrimental changes in growth by increasing the effects of drought stress earlier in the growing season. In this study, the months with the greatest temperature increases in the last two decades are February, March, August and November. Ettl and Peterson (1995) formed similar conclusions for subalpine fir at low and middle elevations. Graumlich (1993) also suggested that climate changes could result in differential growth rates among species, which could ultimately alter the structure and composition of forest stands.

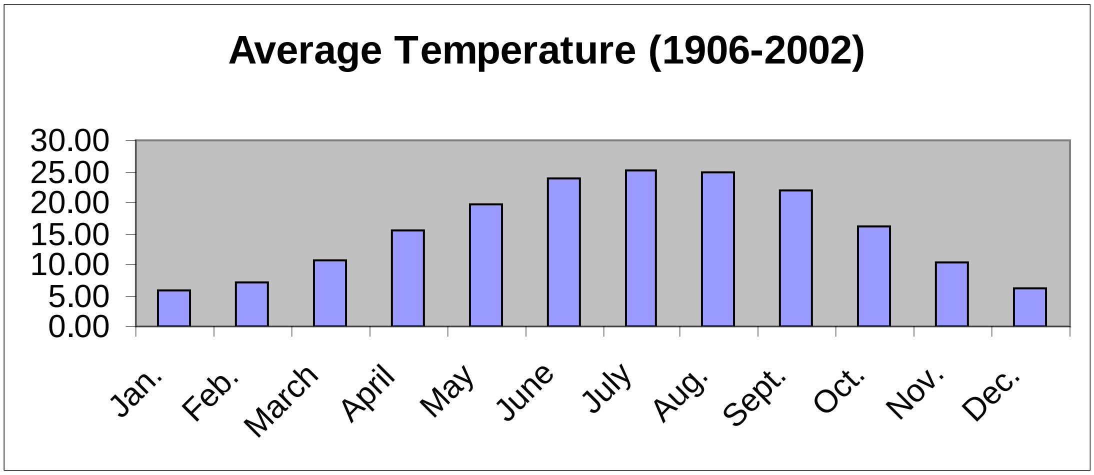
Mountainous landscapes are complex and possess a wide range of topographic features, habitats, and local climates expressed at different geographical scales (Ettl and Peterson, 1995). Therefore, it would be difficult to predict the response of any tree species with a broad distribution in mountainous regions to climate change across its range. Although dendroecological records are available for climate/growth relationships dating back several decades (back to 1906 in this study), predictions of future growth patterns may differ depending on future climatic conditions. Because climate is not the only variable that contributes to tree growth, inferences concerning the effects of climate change on growth should be examined cautiously (Ettl and Peterson, 1995). However, climate change, along with other growth variables, will most certainly affect local stand dynamics, which could potentially lead to dramatic changes in forest structure at a broader scale.

Table 4.1 – Verbal Summary Table for Seasonal Climate Growth Relationships of Eastern White Pine in the North Georgia Mountains. Terms listed indicate direction of climatic influence; for example, early springs (of the current season) that are warmer and drier than normal are associated with increased growth.

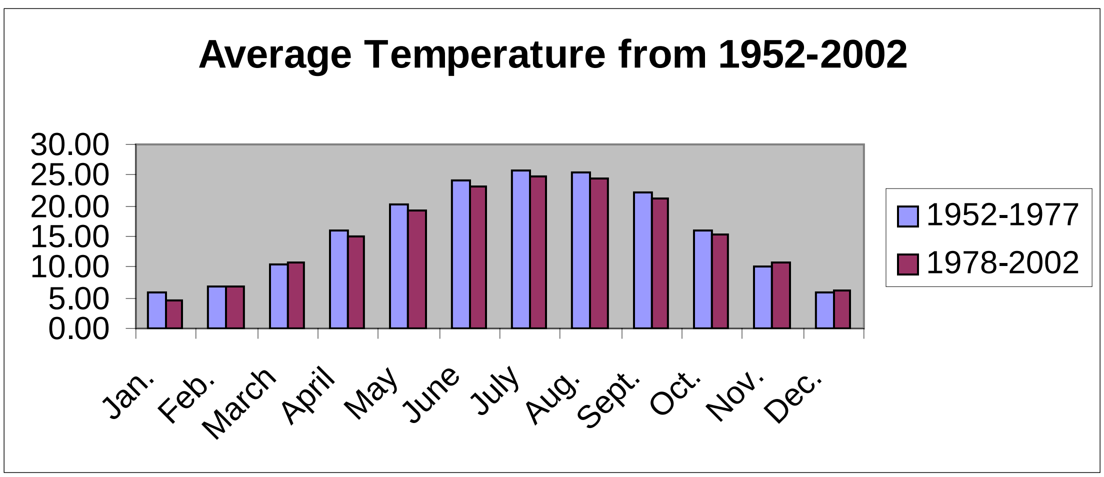
Season	Temperature	Precipitation
Previous Spring	warmer	
Previous Summer	warmer	
Previous Autumn		
Early Winter		
Late Winter		
Early Spring	warmer	drier
Late Spring		
Early Summer	cooler	wetter
Late Summer	cooler	wetter
Early Autumn	warmer	wetter
Late Autumn		

Figure 4.1 – Temperature Data

a.



b.



c.

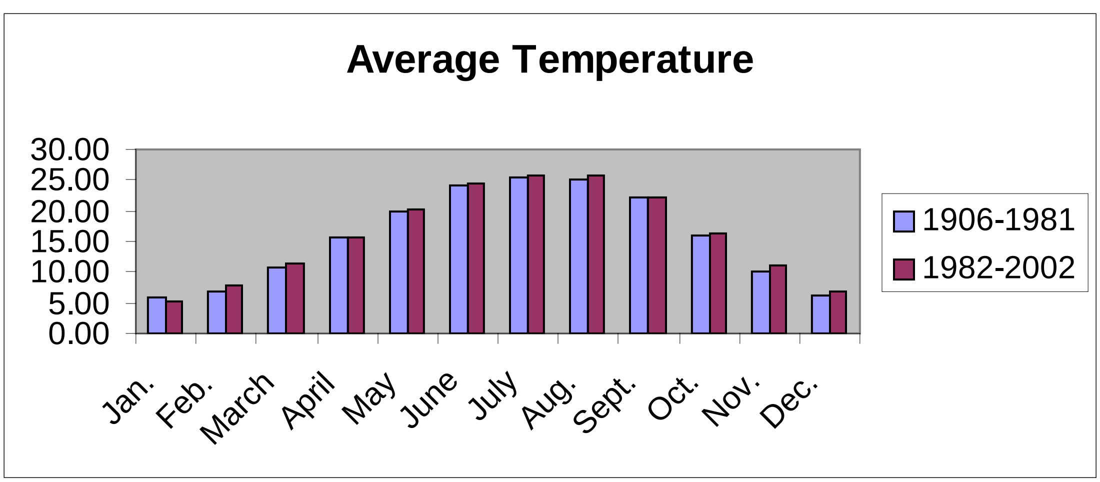
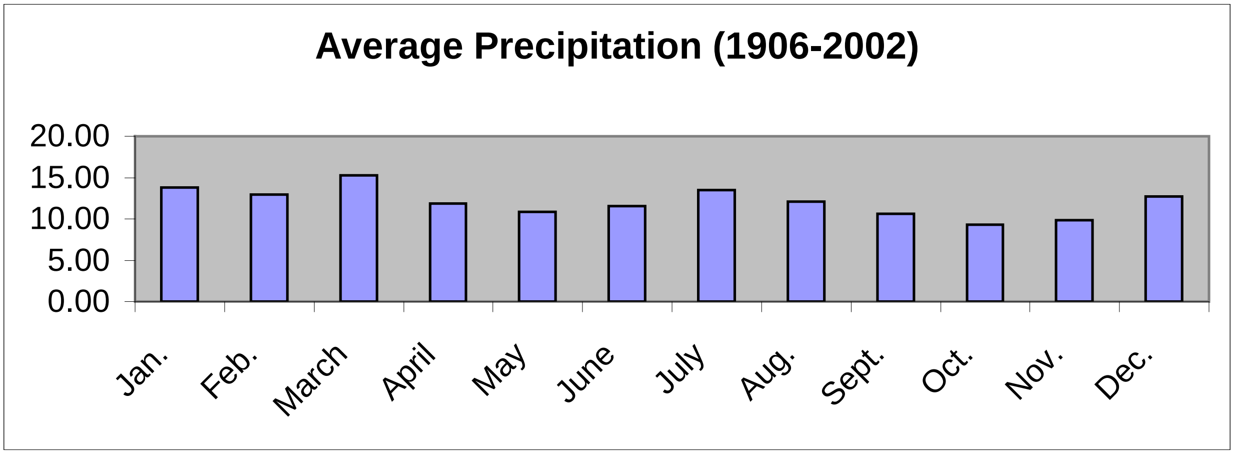
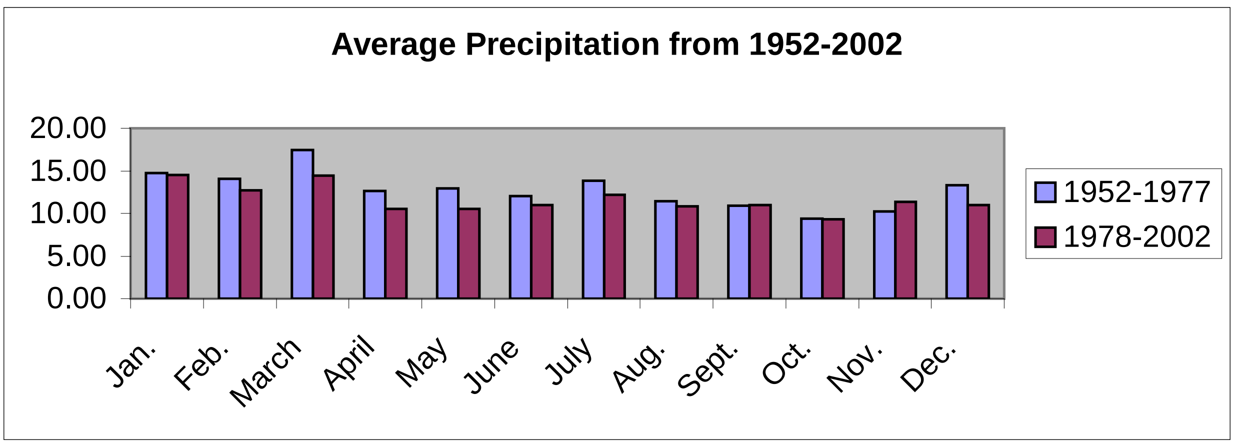


Figure 4.2 – Precipitation Data

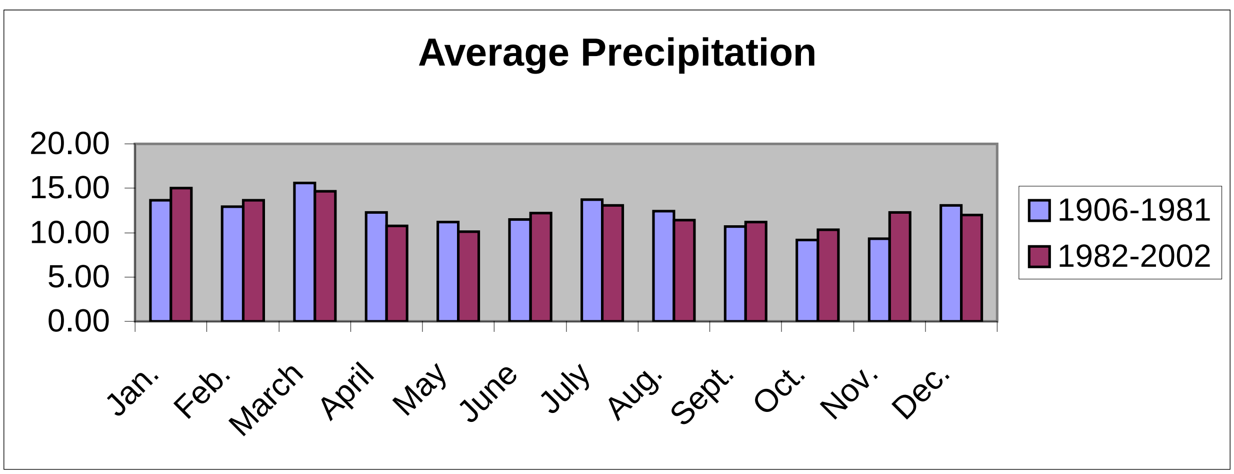
a.



b.



c.



CHAPTER 5

SUMMARY AND CONCLUSIONS

The main goal of this thesis was to determine if the growth rate of eastern white pine differs on north and south-facing aspects. The hypothetical premise behind this research is that south-facing aspects in temperate latitudes of the northern hemisphere receive greater insolation than north-facing slopes, which results in warmer temperatures, higher potential evaporation rates, and drier conditions. These additional stress factors, aside from natural stand dynamics and competition, can hinder tree growth, particularly if ample precipitation is not received.

Through a series of statistical analyses, I determined that slope aspect does not affect tree growth in eastern white pine in the North Georgia Mountains. Average radial growth occurs at approximately the same rate on both north and south-facing aspects. Although average raw growth rates were slightly higher among trees on north-facing slopes, this minor difference is not statistically significant.

Correlations of growth patterns among sites with the same aspect were strong for both north and south-facing slopes. Temperature and precipitation patterns from the current and previous years influenced growth response among trees on both north and south-facing aspects in the same manner, with some months exhibiting stronger correlations than others.

Tree growth in the past 25 years, compared to that of the previous 25 years, has decreased to some extent, particularly at four of the eight study sites. This was determined after the natural decline in growth due to age was assessed. Although the p-values in this analysis were not statistically significant, it does suggest that trees are responding to a change in external stimuli. This growth change underscores the significance of this research, and indicates the need for further study.

If climate change is potentially altering the growth rates of eastern white pine, it could continue until forest structures are altered at a large scale. It would be valuable to conduct similar dendroclimatic reconstructions on other species in the southern Appalachians to examine possible changes in tree growth response in recent decades for other taxa. If other species exhibit recent changes in growth rates similar to those of eastern white pine, it may provide increasing evidence of climatic change in north Georgia. Of course, due to the complexity of mountainous landscapes, climate change may only be one contributor among a series of factors influencing rates and seasonal climatic sensitivity of tree growth in the southern Appalachians.

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