ENVIRONMENTAL EFFECTS ON THE GROWTH OF YOUNG LONGLEAF PINE

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ENVIRONMENTAL EFFECTS ON THE GROWTH OF YOUNG LONGLEAF PINE

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THESIS ABSTRACT

ENVIRONMENTAL EFFECTS ON THE GROWTH OF YOUNG LONGLEAF PINE

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A study to determine the effects of environmental conditions on the growth of young longleaf pine (*Pinus palustris* Mill) was initiated in 1969 on the Escambia Experimental Forest near Brewton, Alabama. Forty young longleaf trees initially ranging from 1 to 1.5 meters in height were measured from 1969 through 1981. The trees were evenly divided between two soil types. From 1969 to 1970, height and diameter measurements were recorded once to four times weekly during the growing seasons and once a month during the dormant seasons. Daily height growth measurements were recorded in the morning and again in the evening during the peaks of these two growing seasons to determine diurnal and nocturnal growth. To test the effects shading on growth, cheesecloth was suspended over ten randomly selected trees from each soil type during the first growing season. Follow up height and diameter measurements were recorded periodically from 1971 through 1981. All environmental conditions were recorded by weather station instruments located on the site.

The shading treatment did not have a significant effect on either height or diameter growth. Soil type did have a significant effect on diameter growth. Dormant season temperature and precipitation explained more of the variability in yearly height and diameter growth than any other environmental conditions measured. Height growth during the peak of the growing season accounted for more than 30% of yearly height growth. Temperature was the most influential environmental variable affecting height growth during the peak of the growing season.

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1. INTRODUCTION

Trees, like all terrestrial plants, are dependent on sunlight, carbon dioxide, oxygen, water, and nutrients to survive and to grow. Growth on the most basic scale can be defined as an irreversible increase in the size or number of cells (Kramer and Boyer 1995). Growth and maintenance are the main purposes of a tree's metabolism and essential to a tree's survival (Kramer and Boyer 1995). However, growth is not achieved without resistance from environmental stresses. Changes in the environment result in changes in a tree's internal physiological processes like photosynthesis, respiration, and absorption of water and minerals, which in turn affect growth (Kozlowski and Pallardy 1997b). The desire to identify and understand the many relationships that exist between the environment and tree growth has influenced numerous research efforts, but often the answers found lead to more questions.

Longleaf pine (*Pinus palustris* Mill.) is a keystone species across the landscape of the southern United States. It is estimated that the longleaf pine ecosystem once covered 92 million acres of Southeast, but this vast acreage has been reduced to about 3% of what it once was (Frost 1993). Longleaf pine was removed for its timber value, to establish cropland, and to plant species more suited to pulpwood production, like loblolly pine (*Pinus taeda* L.).

Researchers in the 1930's began to look at how the growth of longleaf pine was related to variation in the environment. These studies concentrated mostly on relationships between diameter growth and the environment. Precipitation and temperature data were the only long-term environmental data used, and tree cores were examined to determine patterns of past growth (Lodewick 1930). Diameter growth was found to be positively correlated with precipitation and negatively related to temperature (Coile 1936). Lodewick (1930) also found positive correlations between diameter growth and precipitation. Results from these studies raised even more questions about what other environmental variables were affecting tree growth because temperature and precipitation did not explain all the variance in diameter growth. Since the majority of the research at this time had been conducted with tree cores, evaluating relationships between height growth and the environment would require more field measurements over time.

Boyer (1970) reported on the relationships between shoot growth patterns of young loblolly pine and the environment. This research showed that the most important environmental variable affecting height growth was degree-hour heat accumulations above threshold temperature. In this context, threshold temperature is the temperature that must be reached for growth to occur. Solar radiation was also an important variable associated with diurnal growth (Boyer 1970). Boyer (1976), working on the same study, found that threshold temperature and growth rate were the most influential variables affecting seasonal height growth.

In 1969, Boyer initiated a similar study in a young longleaf pine stand in southern Alabama. The main objective of this effort was to try to understand relationships between growth of young longleaf pine and the surrounding environment. The data were recorded at the Escambia Experimental Forest (EEF) near Brewton, Alabama on a middle Coastal Plain site from 1969 through 1981. All of the data were collected, but due to a lack of time and funding the study was not completed. In cooperation with Dr. Boyer, this data set was acquired in May of 2003, and the analysis was started. The advances in computer technology since the initiation of this study were very beneficial in the completion of this research effort.

2. OBJECTIVES

The purpose of this study is to determine the relationships between height and diameter growth of young longleaf pine and natural variations in selected environmental conditions. The following questions will be addressed:

1. What does an examination of seasonal height and diameter growth reveal about young longleaf pine growth patterns?
2. What impact did shading and soil type have on young longleaf pine height and diameter growth? What relationships existed between the selected environmental conditions and young longleaf pine growth?
3. Which environmental condition had the greatest effect on young longleaf pine growth?
4. What interactions occurred among the selected environmental conditions at the site level, and how did these interactions affect the height and diameter growth of young longleaf pine?

3. LITERATURE REVIEW

3.1 Growth and the Environment

Kozlowski and Pallardy (1997b) cite Klebs, a German plant physiologist, as the first person to speculate that plant growth is affected by heredity and the environment. Changes in the environment result in changes of internal processes and conditions in plants, which in turn affects growth (Kozlowski and Pallardy 1997b). However, instead of a cause and effect relationship between tree growth and the environment, there is a complex indirect interaction between the two (Kozlowski and Pallardy 1997b). Environmental stresses can be defined as a combination of both biotic and abiotic factors (Kozlowski and Pallardy 1997a). Examples of abiotic stresses include variations in rainfall, temperature, moisture, light intensity, fire, pollution, wind, soil structure and fertility, while pathogens, insects, and humans are examples of biotic stresses (Kozlowski and Pallardy 1997a, Kozlowski and Pallardy 1997b). To understand more about how trees grow, it is necessary to develop a better understanding of the interactions between the environment and tree growth (Kozlowski and Pallardy 1997b).

A plant's cells continuously swell and shrink depending on changes in water content. This reversible hydration and dehydration of the cells should not be confused with growth (Kramer and Boyer 1995). Height growth or apical growth is the elongation, division, and maturation of cells in the apical meristem (Kozlowski and Pallardy 1997b). Height growth involves a combination of node and internode elongation of one or multiple leaders (Kozlowski and Pallardy 1997b). During the growing season, height growth occurs in waves or flushes of growth and can be classified as fixed and/or free growth depending on species and the climate (Kozlowski and Pallardy 1997b). Diameter growth or cambial growth occurs by the division of fusiform initial cells in the vascular cambium. The dividing fusiform initial cells differentiate into both xylem and phloem cells which collectively make up diameter growth (Kozlowski and Pallardy 1997b). Kozlowski and Ward (1961) state that height growth is inconsistent between species and even among trees of the same species, but diameter growth curves tend to vary more year to year than height growth curves and are more receptive to changes in the environment.

Longleaf pine seedlings are the only southern pines that exhibit a short shoot characteristic. Brown (1964) defines the seedling as a short shoot with a bud that produces a single needle to many needles at the start of the growing season but does not elongate itself. This is commonly referred to as a grass stage seedling (Wahlenberg 1946, Boyer 1990). The seedling will remain in the grass stage until a sufficient root system has developed (Outcalt 2000). Pessin (1935) found an inversely proportional relationship between root growth and height growth while seedlings were still in the grass stage. When the root-collar diameter reaches about 2.5 cm, height growth is usually initiated (Wahlenberg 1946, Boyer 1990). Once height growth is initiated, seedlings tend to have a rapid phase of height growth where they emerge from their ground layer vegetative competitors. At this point the seedlings have developed into saplings and can grow about

30.5 to 100 cm a year, which varies with environmental conditions including degrees of competition and weather conditions (Wahlenberg 1946).

A more intense understanding of what and how environmental conditions are affecting tree growth has the potential to be used to make more effective silvicultural prescriptions (Kozlowski 1955). Manipulating light availability is very important since longleaf pines are considered shade intolerant (Wahlenberg 1946, Boyer 1990). McGuire et al. (2001) found a positive correlation between the amount of light available and longleaf pine seedling growth. Barnett (1989) took a different approach by looking at the effect of shading on container grown seedlings in the nursery. He found significant differences between the shading treatments and a full sunlight control. However, he did not see significant differences between the 30% and 50% shading treatments. Palik et al. (1997) studied the effects of sunlight and nitrogen on longleaf pines planted in forest gaps where light ranged from 40% to 80% of full sunlight. They found an upward curvilinear relationship between the growth rates of the selected trees and the variations in nitrogen and sunlight levels.

Of the natural resources a tree needs to survive, water has been characterized as the most influential (Zahner 1956, Shoulders and Tiarks 1980). Zahner (1956) states that in order for a tree to grow and maintain itself, it needs water more than any other raw material. Shoulders and Tiarks (1980) state that the natural distribution and growth of trees are greatly dominated by water availability. Their study showed that longleaf pine has a lower tolerance to fall and winter rainfall than loblolly and slash pine (*Pinus elliottii* Engelm.). This study also showed the relationship between subsoil moisture and height growth to be a third degree polynomial. At 7% subsoil moisture the curve changes from a positive relationship to a negative one, but at about 18% subsoil moisture the relationship became positive again (Shoulders and Tiarks 1980). They also observed a threshold of height growth response to spring and summer rainfall at about 114 to 144cm. Rayamajhi (1996) found minimum temperature and rainfall to be the most important environmental variables affecting changes in longleaf pine growth. In a study on the Coastal Plain of Georgia, Coile (1936) found a positive correlation between longleaf pine growth and February through April rainfall. Lodewick (1930) explored relationships between longleaf pine diameter growth and precipitation in western Florida. He found no relationship between early growing season precipitation and diameter growth but did see a positive correlation between rainfall and growth later in the growing season. Lodewick (1930) saw a negative relationship between springwood growth and increases in rainfall during the growing season, but springwood growth had a positive relationship with summerwood growth. Rai (1995) also found a negative relationship between rainfall and longleaf pine growth when studying longleaf pine on the Gulf coastal plains of Alabama, Georgia, and Florida for five years. Coile (1936) found a negative correlation between average summer temperature from June through August and diameter growth, but Lodewick (1930) found no relationship between diameter growth and temperature. Coile (1936) saw variation between annual diameter growth and temperature, but stated that when radial growth was linear, good relationships could be found between diameter growth and rainfall and temperature. Coile (1936) stated that the relationship between growth and rainfall was curvilinear, but this was dependent on the portion of the growing season that was being analyzed.

Bengston et al. (1967) looked at 6-year-old slash pines from 14 geographic sources on a study site in Florida and found a proportional relationship between rainfall and height growth in slash pine. Treubig (1960) studied longleaf and loblolly pine in southern Louisiana and also saw a relationship between longleaf pine growth and rainfall. The study showed a significant relationship between longleaf pine growth and the number of weeks with less than 2.54 cm of rainfall but did not see that environmental factors explained much of the variation in longleaf or loblolly pine growth.

Boyer (1970, 1976) measured the height growth of 10 loblolly pine trees during the growing season of 1967. Diurnal and nocturnal growth rate measurements were taken twice daily during the peak of the growth period. This research showed that the most important environmental variable affecting height growth was degree-hour accumulations above threshold temperature, which was 40º F (4.44º C) during the night and 50º F (10.0º C) during the day. Boyer (1976) states that the threshold temperature and the growth rate above the threshold temperature explained 94% of the differences in height growth among the sampled trees. Kramer (1957) also found that temperature was very influential to height growth. He found that the difference between the maximum and minimum temperature for a day was more significant in explaining height growth than either temperature alone.

Solar radiation and vapor pressure deficit also seemed to be important variables associated with growth (Boyer 1970). In this case, there was a direct relationship between the intensity of solar radiation and threshold temperature for diurnal growth while degree-hour accumulation and vapor pressure deficit were significant in explaining diurnal growth. Addington et al. (2004) looked at how vapor pressure deficit affects longleaf pine. They found a negative relationship between stomatal conductance and vapor pressure deficit, which helps explain changes in whole-plant hydraulics. McLaughlin et al. (2003) found growth rates of yellow-poplar (*Liriodendron tulipifera* L.) to be negatively affected by high values of vapor pressure deficit. They performed a study on 10 mature yellow-poplars that were recently released. The study took place in Tennessee and focused on the relationship between diurnal patterns of growth and climatic factors.

Yeh and Wensel (2000) studied the relationship between soil moisture and growth of 6 western coniferous species in northern California. They showed that 67% of the growth variations in the measured pines were explained by variations in temperature and precipitation. Kienholz (1941) looked at hardwoods in Connecticut and found no statistically significant relationships between rainfall and height growth curves. Fritts (1960) studied hardwoods including the following: American beech (*Fagus grandifolia* Ehrh.), white oak (*Quercus alba* L.), red oak (*Quercus rubra* L.), and sugar maple (*Acer saccharum* Marsh.). He found the most influential variable affecting the growth was temperature, but labeled maximum temperature, soil moisture, percent sunshine of the measurement and previous day, relative humidity, and wind speed as important variables when considering how growth is affected by the environment (Fritts 1958, 1960)

Most studies concerning longleaf pine height and diameter growth have been conducted in controlled environments like greenhouses. There has been a lack of studies that concentrate on the environmental effects of height and diameter growth under field conditions or natural conditions (Boyer 1970). Jose et al. (2003) evaluated the effects of light, water, and nitrogen on grass stage longleaf pine seedling growth. The study, performed in a greenhouse, concluded that seedling growth seemed to be more influenced by water and nitrogen than light. Ramsey et al. (2003) studied the effects of fertilization and herbaceous weed control on longleaf pine seedlings. They concluded that herbaceous weed control combined with fertilization would increase seedling height growth and decrease the length of the grass stage. However, fertilization at establishment tended to reduce seedling survival, while herbaceous weed control after the first growing season had little effect.

3.2 Flushes and Seasonal Height Growth Patterns

In contrast to diameter growth, longleaf height growth is somewhat continuous and occurs in flushes (Byram and Doolittle 1950). Allen and Scarbrough (1969) looked at seasonal patterns and flushes in young longleaf pine from 1957 to 1969 on a monthly and weekly basis. They observed the majority of growth between March and October which they classified as the growing season. In examining the patterns of growth, they observed continuous growth of flushes. From about the middle of April until the middle of July there were always at least two flushes elongating at the same time. Tepper (1963) also saw growth of two flushes at one time in pitch pine (*Pinus rigida* Mill.) and shortleaf pine (*Pinus echinata* Mill.). Mudano et al. (1992) and Griffing and Elam (1971) looked at loblolly pine in the Duke Forest near Durham, NC and northern Mississippi, respectively and reported continuous growth of two to three flushes at one time throughout the growing season. However, contrary to the idea of concurrent growth, Eggler (1961) recorded consecutive growth when measuring the 4 southern pines in a study in Louisiana and Mississippi. He reported that after one bud stops, another begins to grow without a “rest” period.

The first flush of loblolly pine contains about 30% of the total year’s growth and is longer than any of the other flushes from the growing season (Mudano et al. 1992, Kozlowski and Pallardy 1997b). The first flush of the growing season resembles a sigmoid curve with a maximum in April. Allen and Scarbrough (1969) found that the curves of the rest of the flushes were not sigmoid in shape for longleaf pine. In loblolly pine, budbreak occurred during mid to late March, 90% of total shoot growth was completed by the middle of August, and growth ceased in early November (Mudano et al. 1992). They found that the third flush tends to start about the time the first flush stops growth while the second flush starts growing as the first flush reaches its peak of growth.

The number of flushes during a growing season is correlated with tree vigor (Allen and Scarbrough 1969). This concept leads to the idea that vigor is dependent on the environment which implies that the number and duration of flushes is dependent on changes in the environment. The study showed evidence that total height was not totally dependent on the number of flushes. However, they did find that that about 47% of the variation in the spring flushes and about 74% of the variation in the summer flushes was accounted for by the number of nodes (Allen and Scarbrough 1970). Bengston et al. (1967) observed significant correlations between the length of the bud set prior to the growing season and total height growth (r=0.91) and early height growth (r=0.97) in slash pine. Boyer (1970) found a significant regression where length of the bud set prior to the growing season explained 78% of the variability in length of the first internode for loblolly saplings. He also found that length of the bud set prior to the growing season and the length of the first internode explained 79% and 87%, respectively, of the variability in the bud set at the end of the growing season for loblolly pine. Allen and Scarbrough (1970) also found that there was a significant correlation between successive flushes which they attribute to the similarities in internode elongation in longleaf pine. However, Griffing and Elam (1971) did not find significant correlations between flushes of the same year or with the previous year. Allen and Scarbrough (1970) reported a negative correlation between the spring growth and summer growth of the next year. Through experimental treatments, Allen and Scarbrough (1969) found that removing foliage did reduce total height growth by half but did not have an effect on the number of flushes.

4. METHODS

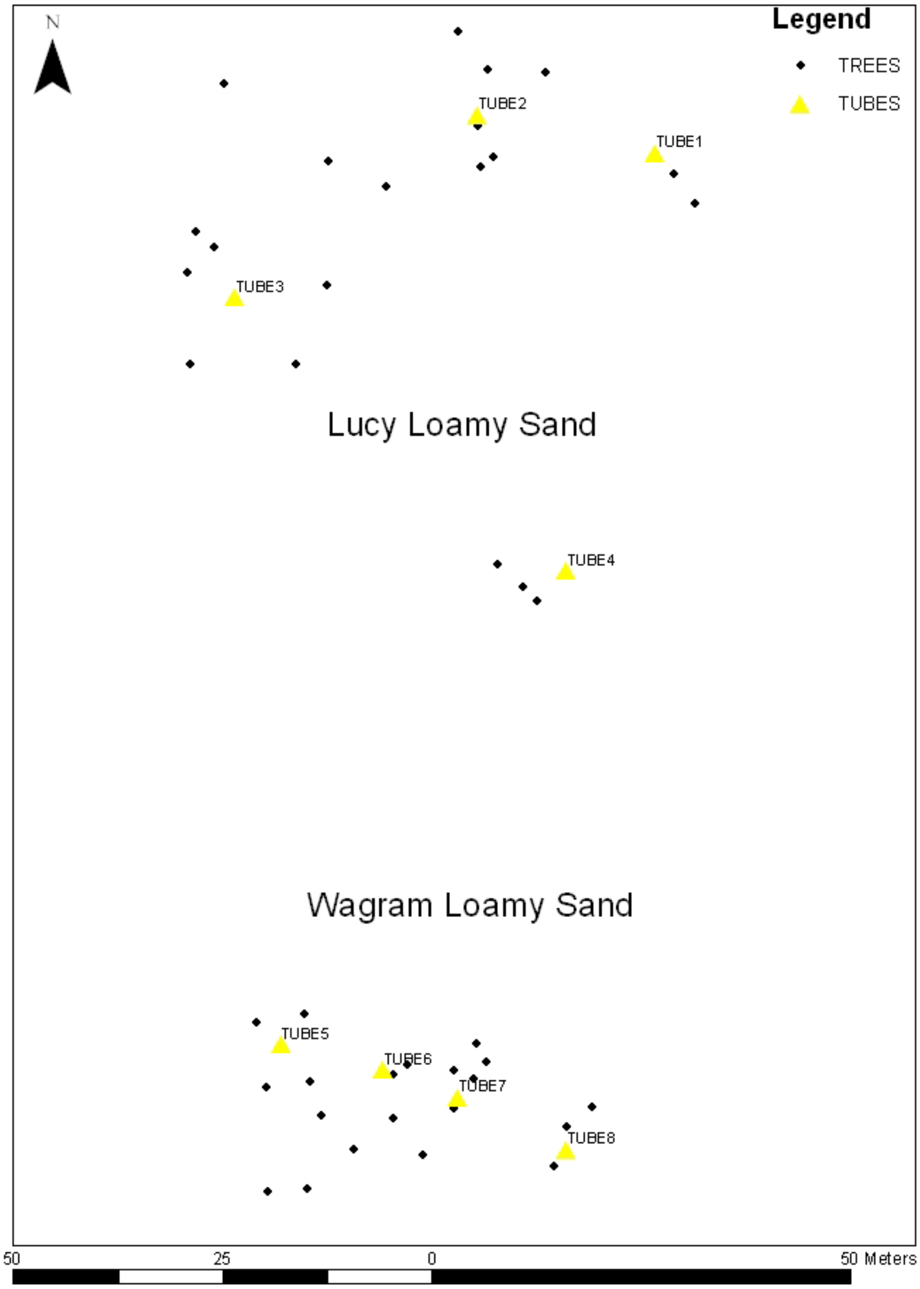
4.1 Location and Layout

This project was installed on the Escambia Experimental Forest (EEF) near Brewton, AL in 1969. The EEF is a 3000-acre forest that was established in 1947, when T.R. Miller Mill Company leased the land to the USDA Forest Service for 99 years at no cost (Boyer et al. 1997). The EEF has been used for extensive longleaf pine research which has resulted in numerous publications (Boyer et al. 1997).

The study sample consisted of young naturally regenerated longleaf pines, which were a product of the 1955 seed crop. Forty longleaf pine trees ranging from 1 to 1.5 m in height were selected for the study. Twenty were selected on each of the 2 distinct soil types that were present in the stand. Figure 4.1.1 shows stem map layout of the study site.

The two soil types that separated the trees were Lucy loamy sand and Wagram loamy sand. The taxonomic class for both soils is: loamy, kaolinitic, thermic Arenic Kandiudults (Soil Survey Division, Natural Resources Conservation Service 2003). The trees on the Lucy loamy sand were located on the crest of a ridge, and the trees on the Wagram loamy sand were located on a slope at the base of the ridge. The soils are very similar with an average site index of 20.4 m. The depth of the A-horizon for the Lucy soil can vary from 55.88 cm to 101.6 cm (Mattox et al. 1975).

Figure 4.1.1 Study site layout of sampled trees and soil moisture tubes



For the Wagram soil, the depth of the A-horizon can vary from 50.8 to 68.58 cm (Mattox et al. 1975). These estimates were developed from a representative sample and will vary depending on the site. Soil samples were taken for this study in coordination with the collection of soil moisture at each neutron probe tube. Appendix 4.1.1 is a table of A-horizon and B-horizon depths for each tube. The average depth of the A-horizon on the site was 121 cm for Lucy soil and 107 cm for Wagram soil. The average depth to the base of the B-horizon was 207 cm for Lucy soil and 226 cm for Wagram soil. A deeper average A-horizon should make the Lucy soil drier than the Wagram soil. However, the sandy clay loam in the shallower B-horizon of the Lucy soil could provide more available moisture for roots than the deeper B-horizon of the Wagram loamy sands (Mattox et al. 1975)

4.2 Shading Treatment

To create artificial shading, half of the trees in each of the two soil types were randomly selected for artificial shading. These trees were shaded with cheesecloth for six months during the growing season of the first year of the study. The shading treatment was installed March 28, 1969 and removed September 24, 1969. The cheesecloth was stretched across a one-meter-square frame that was structured to keep the cheesecloth at least one meter above the growing tip of the tree. The structures were periodically checked, adjusted, and maintained at one meter above the growing tip. The cheesecloth prevented the growing tips of the shaded trees from receiving direct sunlight during the peak of the diurnal cycle. The mean percent difference in solar radiation between non-shaded and shaded was 38.5%.

4.3 Growth Measurements

Initial heights were measured from the ground line to the base of the bud on the terminal growing shoot of each tree on January 27, 1969. The length of the terminal bud was also measured. Separate records were maintained for each new leader. Terminal shoots were measured from 2 to 4 times weekly from March to October of 1969 and 1970. During the dormant season of both years, heights were measured every two weeks or at least once a month.

Monthly growth intervals covered 22 months from March 1969 through December 1970. Each monthly interval was 28 days +/- 1 day. The biweekly intervals included 22 measurements in 1969 ranging from March until December and 24 measurements in 1970 ranging from January to December. Biweekly growth intervals were 14 days +/- 1 day in length. Weekly intervals included 34 measurements in 1969 ranging from March through October and 38 measurements in 1970 ranging from March through November. The weekly intervals were 7 days +/- 1 day in length. From April 28 to October 28 of 1970 needle lengths were recorded for each tree in addition to height measurements.

More intensive measurements were taken during April of both years, which was the peak of the growing season. The trees were measured on 19 days during April, 1969 and 16 days during April, 1970. Measurements were taken in 1969 from April 9 through April 28 and in 1970 from April 6 through April 28. During April of 1970, measurements were not taken on Sunday including April 12th, 19th, and 26th. Each day, leaders were measured in the morning from 8:00 to 10:00 a.m. and again in the late afternoon from 4:00 to 6:00 p.m. Height growth occurring between the morning and afternoon measurements was labeled as diurnal growth, and height growth occurring between the afternoon measurement and the following morning measurement was labeled as nocturnal growth (Boyer 1970). Height growth occurring from the morning to morning was labeled as total growth (Boyer 1970).

Diameters of each tree were measured in centimeters at 10 cm above the ground line with the use of dendrometer bands. The 10 cm height was set because the trees had not reached dbh (diameter at breast height) of 1.37 m. Diameter measurements were taken weekly from March thru October of 1969 and 1970. From the end of October until March, measurements were taken every two weeks to a month during 1969 and 1970. These measurements can again be divided into monthly, biweekly, and weekly growth intervals using the same interval lengths and durations as outlined for height growth.

The sample trees were remeasured yearly during the dormant seasons from 1971 through 1981. Heights and diameters were recorded for each tree. All height measurements were recorded to the base of the bud on the terminal shoot. During the remeasurement period, diameter measurements were recorded at dbh.

4.4 Environmental Measurements

Environmental conditions recorded included: maximum and minimum air temperature, precipitation, soil moisture, relative humidity, wind speed, and solar radiation. An onsite weather station equipped with maximum and minimum thermometers and a rain gauge recorded maximum and minimum air temperatures and precipitation on a daily basis. Air temperatures were recorded in degrees Fahrenheit and converted to degrees Celsius**.** A temperature difference can be calculated from the recorded maximum and minimum recorded temperatures for each day. Precipitation data were recorded in inches and tenths and were to centimeters. Data from the weather station were available on a daily basis from 1964 through 1990.

Soil moisture profiles were also created by using a neutron probe at eight locations with depths of 10, 25, 50, 75, 100, 125, 150, and 175 cm. Four tubes for the neutron probe were installed in each soil type, and the neutron probe was recalibrated at each soil type. Neutron probe measurements were taken at weekly intervals from March to October of 1969 and 1970. From the end of October until March, measurements were taken once every two weeks to a month. Eight soil samples were also taken near the access tubes used for the neutron probes. The samples were taken as 5.08 cm cores and were a depth of 1.9 m and 1 to 1.5 m from the access tubes. The cores were analyzed at the Longleaf Silviculture Laboratory in Brewton, AL. The data obtained from these cores included: moisture retention capacity, texture, organic matter content, and bulk density.

The soil moisture calibration data were not available for this study. To calculate percent soil moisture from the neutron counts, a factory curve for the neutron probe that best fit the data was used. Points from the curve were interpolated and used to find the equation for the line. The actual percent soil moisture values will be misleading, but the change between percent soil moisture values will be more suitable for this analysis and give relative good values. A correlation analysis was computed between the percent soil moisture values and rainfall to see how closely the two sets of data were associated. The correlation matrix can be found in Appendix 4.4.1. The estimated soil moisture values were significantly correlated with lagged precipitation. For analyses used in this study, lagged precipitation will be used instead of the estimated soil moisture values.

During April of 1969 and 1970, more intensive environmental measurements were taken. These measurements included relative humidity, wind speed, and solar radiation measurements. Environmental variables during the month of April of both 1969 and 1970 were taken on days corresponding to the dates that heights were recorded.

A hygrothermograph was used to measure air temperature in degrees Fahrenheit and humidity. Mean temperatures could be calculated for each diurnal, nocturnal, and 24-hour period. Relative humidity was calculated in percent for each period by summing values for each hour and dividing by time (Boyer 1970). Degree-hour heat sums or degree-hour accumulations were calculated by summing degrees above threshold temperatures of 40˚, 45˚, 50˚, and 55˚ F for each period (Boyer 1970). Vapor pressure deficits were calculated in units of millimeters of mercury from mean temperature and relative humidity. An anemometer was positioned at 2.25 meters from the ground to record wind speeds. Winds speeds were recorded in total miles for each diurnal and nocturnal period. A pyrheliograph was used to measure solar radiation in both shaded and unshaded areas. Solar radiation was measured in langleys (cal/cm^3).

4.5 Statistical Procedures

All statistical procedures were executed in SAS (Statistical Analysis System) software version 9.1 (SAS 2003). All analyses were conducted at the 0.05 level of significance. Analyses of variances were conducted to test for the effects of shade treatments and soil type conditions over various growth rates using PROC GLM and PROC MIXED in SAS (SAS 2003). PROC MIXED was used to conduct a repeated measures analysis using tree as the random factor (SAS 2003). The repeated measures analyses were conducted with the measurements from each interval and with consecutive growth from the initial measurement. PROC MIXED was chosen because it allows missing data and an unbalanced data structure (Littell et al. 1996). All date variables used in the repeated measures analysis were converted to Julian days using SAS. SAS converts the date into the number of days since January 1, 1960 (Cody and Smith 1997). Total growth over each interval was also tested using a PROC GLM (SAS 2003). Type III sums of squares were presented for ANOVA effects because unbalanced data were used (SAS 2004). The results of the different tests were compared before final conclusions were determined. Significant interactions were tested further using least significant difference (LSD) multiple comparison procedures and within group t-tests (Ramsey and Schafer 2002, SAS 2003).

Regression and correlation procedures were used to determine the relationships between recorded growth and environmental conditions. Height and diameter growth were the dependent values and the environmental conditions were the independent variables. Correlation procedures were used to evaluate relationships between the independent variables. Regressions between growth and each explanatory variable were evaluated individually before attempting selection searches. Both forward and backward step-wise regression procedures were used, resulting in significant simple and multiple regressions (Neter et al. 1996). Simple linear and multiple regressions were evaluated using the coefficient of multiple determination (R^2) (Neter et al. 1996). Multiple regressions were also evaluated using the adjusted coefficient of multiple determination (adjusted- R^2) because it is not inflated by additional variables in the model (Neter et al. 1996).

All statistical tests were evaluated to confirm any potential violations from assumptions. To evaluate normality of residuals, a normal probability plot or a normal QQ plot was used from PROC UNIVARIATE (Neter et al. 1996, Ramsey and Schafer 2002, SAS 2004). A normal QQ plot is a plot of the ordered residuals of a selected variable against a theoretical normal distribution, where the points should lie on a straight line (SAS 2004). Deviations from normality occur when points do not lie on the line. The distribution can be considered long-tailed when there are large gaps between residuals in the tails where points are off the straight line on both sides (Ramsey and Schafer 2002). The distribution is considered skewed where there are gaps between residuals on one side of the line and shorter on the other side (Ramsey and Schafer 2002). Outliers can also be detected in the QQ plot where one or a few points are far off the straight line and the rest follow the normal distribution (Ramsey and Schafer 2002). The Anderson-Darling test from PROC UNIVARIATE was also used to determine normality of the residuals (SAS 2004). Results from the QQ plot and from PROC UNIVARIATE were compared to determine if normality was suspect. If the assumption of normality was violated, data transformations were applied. If suitable transformations did not correct the violation of normality, the NPAR1WAY procedure in SAS was used to calculate the nonparametric Wilcoxon Rank Sum Test and the Kruskal-Wallis Test, where p-values less than the 0.05 level of significance were considered significant (Cody and Smith 1997, Ramsey and Schafer 2002).

Both Levene's and Bartlett's tests were used to determine homogeneity of variance (Ramsey and Schafer 2002, SAS 2004). A p-value less than the 0.05 level of significance shows deviation from the homogeneity of variance (Ramsey and Schafer 2002). Plotting the residuals against the predicted values is also useful in determining homogeneity of variance, outliers, and if linear models are appropriate for regressions (Neter et al. 1996, Ramsey and Schafer 2002). Plots should show residuals evenly spaced above and below the zero line across the values without systematic deviations. Systematic deviations include increases in spread as one variable increases. To correct outliers and other deviations in the homogeneity of variance, transformations are used (Neter et al. 1996, Ramsey and Schafer 2002).

4.6 Weather and Environmental Conditions

Onsite weather station data were available from 1964 through 1990. Table 4.6.1 includes data on total yearly precipitation, average maximum temperature, and average minimum temperature for each year during the actual years of the study. From 1969 through 1981, the average precipitation for the area was 160 cm. The driest year was 1971 with only 111.53 cm of precipitation, and 1975 was the wettest year with a total of 229.74 cm. The average maximum temperature during this study was 26°C, while the average minimum temperature was 12°C. The highest average maximum temperature was in 1978, while 1976 had the lowest average minimum temperature. A table providing the total yearly precipitation, average maximum temperature, and average minimum temperature for the entire range of the data, 1964 through 1990 can be found in the Appendix 4.6.1.

Table 4.6.1 Total precipitation and mean temperature by year from 1969 through 1981

Year	Precipitation (cm)	Avg. Maximum Temperature (ºC)	Avg. Minimum Temperature (ºC)
1969	176.78	25	11
1970	195.83	25	11
1971	111.53	25	12
1972	145.92	27	13
1973	155.96	26	13
1974	136.14	26	12
1975	229.74	24	11
1976	124.08	25	11
1977	140.84	27	13
1978	144.53	29	15
1979	172.34	25	12
1980	167.89	26	12
1981	126.37	26	11

Table 4.6.2 provides total monthly precipitation, average maximum temperature, and average minimum temperature for each month during 1969 and 1970. Peaks in precipitation occurred during July of 1969 and during June of 1970. Average maximum temperatures were at the highest in June of 1969 and July of 1970. December was the coldest month in 1969, while, February was the coldest in 1970.

Table 4.6.2 Total precipitation and mean temperature by month from 1969 through 1970

Year	Month	Precipitation (cm)	Avg. Maximum Temperature (ºC)	Avg. Minimum Temperature (ºC)
1969	1	5.46	16	4
1969	2	10.16	18	4
1969	3	21.46	18	4
1969	4	13.21	26	12
1969	5	16.13	29	15
1969	6	5.46	34	19
1969	7	33.02	33	21
1969	8	26.16	31	19
1969	9	8.13	30	16
1969	10	7.37	26	13
1969	11	4.45	20	3
1969	12	25.78	16	2
1970	1	8.64	13	1
1970	2	12.57	17	0
1970	3	25.53	20	6
1970	4	2.03	28	13
1970	5	23.75	30	14
1970	6	34.29	30	18
1970	7	11.81	33	20
1970	8	30.99	32	21
1970	9	3.94	33	19
1970	10	22.61	25	13
1970	11	5.33	19	3
1970	12	14.35	19	5

5. RESULTS AND DISCUSSION

5.1 1969 through 1970 Height Growth

Evaluating differences in height growth over the different intervals is necessary to see if the recorded environmental conditions and treatments are affecting height growth. Each interval (monthly, biweekly, and weekly) covers different portions of the growing seasons. Patterns of growth over the growing seasons show that trees do not grow at the same rates during the entire growing season. Growth rate tends to vary over the growing season which could raise questions about how relationships between growth and the environment change over the same period. Table 5.1.1 displays mean height growth for 1969 and 1970 individually, and Table 5.1.2 displays mean height growth over the two year measurement period from March of 1969 through December 1970.

Overall height growth was first tested over the entire monthly interval. Table 5.1.3 shows the effects table from this test. There were no significant differences between shade treatments or soil conditions, but there was a significant interaction between the soil and shade variables. Within group comparisons were then used to evaluate the significant interaction. The normality assumption was checked for each test using a QQ plot and the Anderson-Darling test generated from PROC UNIVARIATE (SAS 2003, SAS 2004). Barlett's and Levene's tests were used to check for violations of constant variance. Unless otherwise stated, the assumptions were not violated. See Appendix 5.1.1 for a detailed description of the statistical tests and results.

Table 5.1.1 Average height growth during 1969 and 1970 intervals

Year	Soil Type	Average Height Growth (m)
1969	Lucy	1.01 a
	Wagram	0.99 a
1970	Lucy	1.09 b
	Wagram	1.12 b

Year	Shade Treatment	Average Height Growth (m)
1969	Not Shaded	0.99 c
	Shaded	1.01 c
1970	Not Shaded	1.09 d
	Shaded	1.12 d

Year	Shade/Soil Combination	Average Height Growth (m)
1969	NW (Not Shaded, Wagram)	1.02 e
	SL (Shaded, Lucy)	1.06 e
	SW (Shaded, Wagram)	0.96 e
	NL (Not Shaded, Lucy)	0.97 e
1970	NW (Not Shaded, Wagram)	1.20 f
	SL (Shaded, Lucy)	1.20 f
	SW (Shaded, Wagram)	1.04 fg
	NL (Not Shaded, Lucy)	0.98 g

Means with the same letter are not significantly different (α=0.05)
NL = no shade, Lucy soil; NW = no shade, Wagram soil;
SL = shade, Lucy soil; SW = shade, Wagram soil

Table 5.1.2 Average height growth during 1969 and 1970 interval from March 1969 to December 1970

Treatment/Condition	Average Height Growth (m)
No Shade	2.10 a
Shade	2.09 a
Lucy	2.10 b
Wagram	2.09 b
Shade/Soil Combination	**Average Height Growth (m)**
NW	2.21 c
SL	2.21 c
NL	1.99 cd
SW	1.95 d

Means with the same letter are not significantly different (α=0.05)
NL = no shade, Lucy soil; NW = no shade, Wagram soil;
SL = shade, Lucy soil; SW = shade, Wagram soil

Table 5.1.3 Testing overall height growth over monthly interval from March 1969 to December 1970 using GLM procedure

Source	Type III SS	Mean Square	F Value	Pr > F
SOIL	38.07	38.07	0.05	0.8164
SHADE	73.33	73.33	0.11	0.7474
SOIL*SHADE	5448.88	5448.88	7.83	0.0084*

*Means significantly different (α=0.05)

Monthly height growth was explored for potential significant differences using the repeated measurements design. Below is the effects table (Table 5.1.4) from the PROC MIXED output. Only time related variables and the shade/soil interaction were significantly different.

Table 5.1.4 Testing 1969 monthly height growth from March 1969 to December 1970 using repeated measures procedure

Effect	DF	F Value	Pr > F
TIME	1069	4755.63	<.0001*
SOIL	1069	0.24	0.6255
SHADE	1069	0.10	0.7558
SOIL*SHADE	1069	12.67	0.0004*
TIME*SHADE	1069	0.10	0.7493
TIME*SOIL	1069	0.01	0.9277
TIME*SOIL*SHADE	1069	16.37	<.0001*

*Means significantly different (α=0.05)

Testing the biweekly interval resulted in no significant differences between shade treatments or soil condition, but the shade/soil interaction was significant (Table 5.1.5). Table 5.1.6 contains the effects table of the repeated measures test looking at biweekly intervals. Again, only time related variables and the shade/soil interaction were significantly different.

Table 5.1.5 Testing overall height growth over biweekly interval from March 1969 to December 1970 using GLM procedure

Source	DF	Type III SS	Mean Square	F Value	Pr > F
SOIL	1	199.04	199.04	0.61	0.4408
SHADE	1	1.03	1.03	0.00	0.9555
SOIL*SHADE	1	2746.06	2746.06	8.39	0.0065*

*Means significantly different (α=0.05)

Table 5.1.6 Testing biweekly height growth over biweekly interval from March 1969 to December 1970 using repeated measures procedure

Effect	Num DF	Den DF	F Value	Pr > F
TIME	1	1802	8410.46	<.0001*
SOIL	1	1802	0.21	0.6470
SHADE	1	1802	0.03	0.8595
SOIL*SHADE	1	1802	19.88	<.0001*
TIME*SHADE	1	1802	0.03	0.8576
TIME*SOIL	1	1802	0.07	0.7857
TIME*SOIL*SHADE	1	1802	25.33	<.0001*

*Means significantly different ($\alpha=0.05$)

Weekly intervals were tested for both 1969 and 1970 because the measurements were not consecutive. Tables 5.1.7 and 5.1.8 contain the output for the GLM and MIXED procedures, respectively. Only the time variable was significantly different. This shows that the soil shade interaction occurred in the 1970 growth.

Table 5.1.7 Testing overall height growth over 1969 weekly interval from March to October using GLM procedure

Source	DF	Type III SS	Mean Square	F Value	Pr > F
SOIL	1	178.99	178.99	0.85	0.3634
SHADE	1	9.24	9.24	0.04	0.8354
SOIL*SHADE	1	176.26	176.26	0.84	0.3670

*Means significantly different ($\alpha=0.05$)

Table 5.1.8 Testing height growth over 1969 weekly interval from March to October using repeated measures procedure

Effect	Num DF	Den DF	F Value	Pr > F
TIME	1	1383	3692.33	<.0001*
SOIL	1	1383	0.77	0.3807
SHADE	1	1383	0.02	0.9020
SOIL*SHADE	1	1383	0.84	0.3608
TIME*SHADE	1	1383	0.01	0.9088
TIME*SOIL	1	1383	1.39	0.2382
TIME*SOIL*SHADE	1	1383	1.17	0.2799

*Means significantly different (α=0.05)

Tables 5.1.9 and 5.1.10 contain the pertinent output for the GLM and MIXED procedures, respectively, for the 1970 weekly height intervals. No significant differences were observed except the shade/soil interaction. Table 5.1.8 shows that only time and the shade/soil interaction were significantly different.

Table 5.1.9 Testing overall height growth over 1970 weekly interval from March to November using GLM procedure

Source	DF	Type III SS	Mean Square	F Value	Pr > F
SOIL	1	204.16	204.16	0.69	0.4136
SHADE	1	5.76	5.76	0.02	0.8902
SOIL*SHADE	1	2572.46	2572.46	8.63	0.0059*

*Means significantly different (α=0.05)

Table 5.1.10 Testing weekly height growth over 1970 weekly interval from March to November using repeated measures procedure

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
TIME	1	1437	2399.64	<.0001*
SOIL	1	1437	0.73	0.3915
SHADE	1	1437	1.54	0.2155
SOIL*SHADE	1	1437	18.45	<.0001*
TIME*SHADE	1	1437	1.52	0.218
TIME*SOIL	1	1437	0.36	0.5492
TIME*SOIL*SHADE	1	1437	20.8	<.0001*

*Means significantly different (α=0.05)

Neither the shade treatment nor soil condition was statistically significant with respect to height growth over the intervals, in overall tests, or in years evaluated. An interaction between the shade treatment and soil condition was significant. The interaction was not significant for the 1969 growth interval, but it was for 1970. The significant interaction for the total growth over the 2 years showed that mean height growth for trees on the Wagram soil with no shade treatment and trees on the Lucy soil with the shade treatment was significantly greater than mean height growth for trees on the Wagram soil with the shading treatment. When isolating 1970 growth, the same general interaction was occurring, but mean height growth for trees on the Lucy soil with no shade treatment was significantly lower instead. From the overall interaction results, it looks like that shade significantly affected mean height growth on the Wagram soils. For the Lucy soil there was an opposite trend for 1970 growth where shaded trees on average grew significantly better than non shaded trees. The lack of an overall significant shading treatment might be due to the percent of shading caused by the cheesecloth or the height it was placed. The cheesecloth was suspended 1 meter above the terminal bud, which allowed the tree to receive lateral rays of sunlight during the early morning and late afternoon. This along with the low percent of sunlight reduced by the cheesecloth did not seem to change the growth rates of the shade trees in comparison to those that were not shaded at all.

5.2 Flushes

In 1969 all trees flushed 5 times with 62.5% starting a sixth bud and 5% having a sixth flush. In 1970, all trees flushed 4 times, 92% had a fifth flush, and 46% had a sixth flush. Figures 5.2.1 and 5.2.2 show the general form of mean flushes by year. It is clear that more than one flush was growing at the same time. Some trees start flushing later than others causing a dip in the curves as seen in Figure 5.2.2 with the fifth flush. As expected, the first flush was consistently the largest for both years and formed an approximate sigmoid curve, but the rest of the flushes varied from a sigmoid shape (Allen and Scarbough 1969). The first flush contained 39% of the total year's growth in 1969 and 35% in 1970, which is consistent with what Mudano et al. (1992) and Kozlowski and Pallary (1997) found in other pines. The peak growth rate of the first flush of both years occurred during April but continued at a slower rate until May. The growth observed in Figures 5.2.1 and 5.2.2 show continuous growth of flushes. Growth of 2 flushes at the same time during the growing season was seen in this study, which has been commonly seen in southern pines (Allen and Scarbough 1969, Byram and Doolittle 1950, Griffing and Elam 1971, Mudano et al. 1992, and Tepper 1963).

Figure 5.2.1 Average flush lengths of the sampled trees during 1969

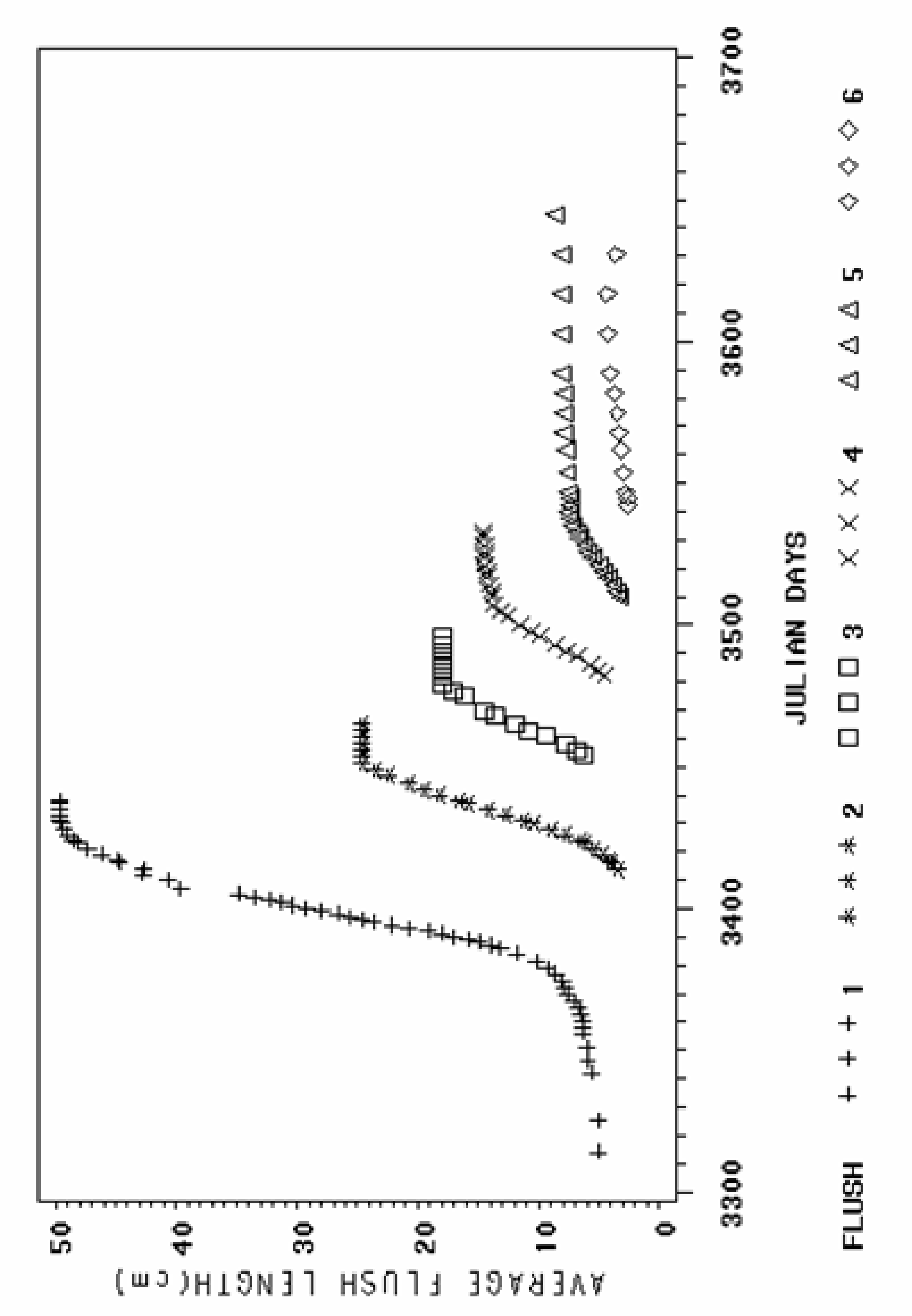
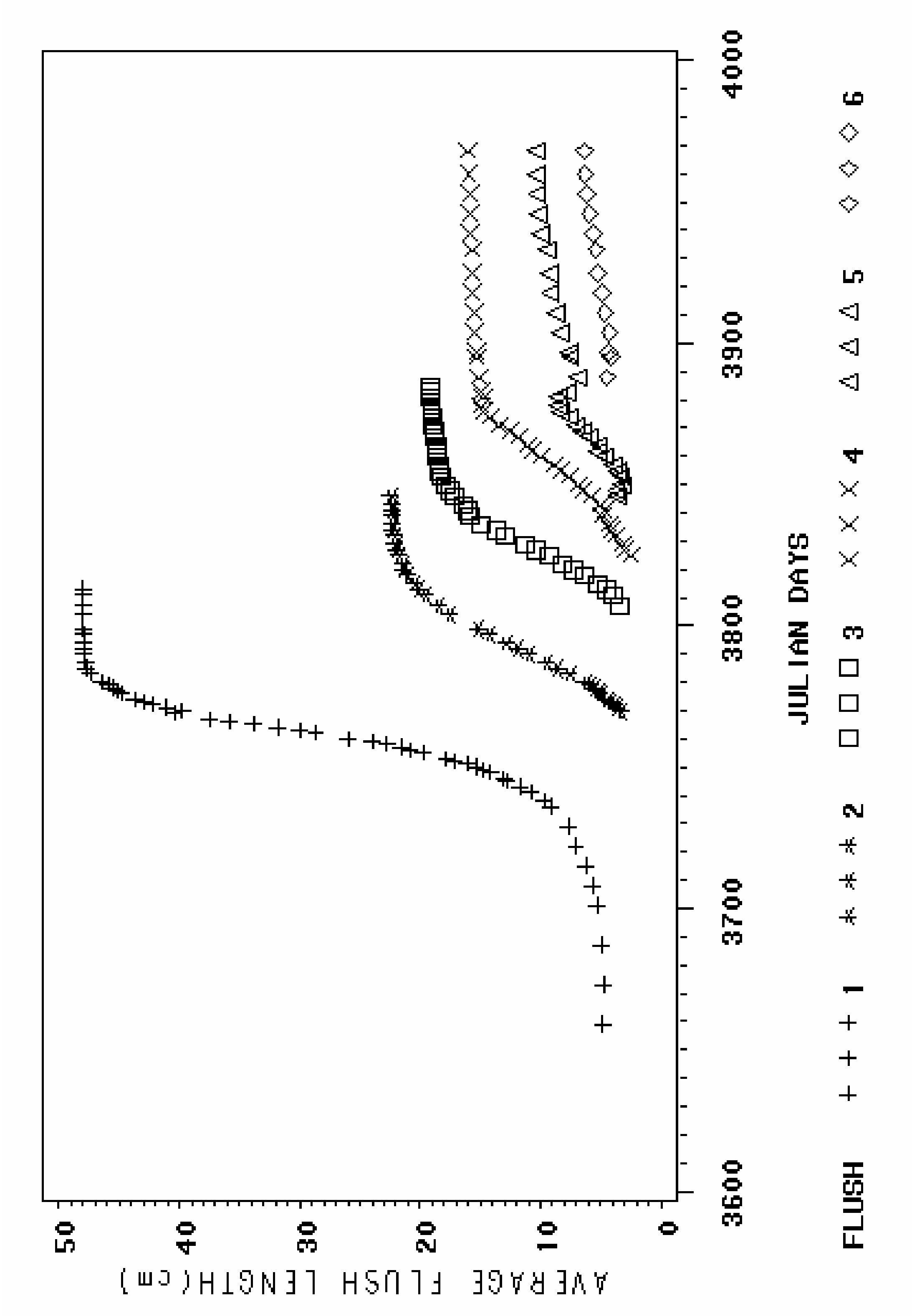


Figure 5.2.2 Average flush lengths of sample trees during 1970



This contrasts the consecutive growth patterns that Eggler (1961) reported. In the case of this study, the next flush did seem to start growing when the previous flush was approaching its peak, but there was overlap between the two. At no time were more than 2 flushes growing at the same time. The amount of growth achieved by each flush was consistently less than the previous flush.

Growth for each flush was tested for significant differences with respect to the shading treatment and soil condition using the same procedures outlined in Chapter 5.1. None of the 1969 flushes were significantly different with respect to the shade treatment or soil condition. Flush 5 in 1970 was significantly different with respect to soil type. Trees on the Wagram soils had significantly larger fifth flushes than those on the Lucy soils. This finding is not supported by any of the other tests with height growth. The shading treatment and soil condition were not significant for any of the other 1970 flushes.

Relationships between the lengths of buds and flush lengths were tested with the 1969 and 1970 data. Table 5.2.1 shows the regression equations for initial bud sets for each year and the length of the first flush during 1969 and 1970. The lengths of buds prior to the growing season have been found to be significantly correlated with the length of the first flush. Bengston et al. (1967) also found a significant correlation with slash pine reporting an r of 0.97. In 1969 and 1970, 21.33% and 30.26%, respectively, of the variability in the first internode of growth was explained by the length of the bud set prior to the growing season. Boyer (1970) found a similar relationship in loblolly pine seedlings and saplings reporting the 76% and 78%, respectively, of the variability in the first internode could be explained by the bud set prior to the growing season. The relationships of the sampled longleaf pine seem to not be as strong as those of work done in slash and loblolly pine. This leads to the idea that the environment during the growing season has more of an effect on the first flush growth than during the bud set of the previous year.

Table 5.2.1 Bud and flush regressions of the sampled trees for 1969 and 1970

Year	Regression Equation	R^2
1969	Flush1 = 2.73Bud69 + 30.96	0.2133
1970	Flush1 = 3.61Bud70 + 25.582	0.3026

Bud(Year) = length of the bud set prior to the growing season for that year,
Flush1 = length of first flush,

Looking further into the relationships between flushes, correlations between flushes were also seen. Flushes 3, 4, and 5 were found to be significantly correlated with each other in 1969 and again in 1970. Flush 5 was also significantly correlated with flush 6 in 1969 only. Allen and Scarbrough (1970) also found successive flushes to be significantly correlated in longleaf pine, which they linked to similarities in internode elongation. The correlation of flushes seems to occur during the middle and toward the end of the growing seasons instead of the beginning and ending. Growth is at its highest during the first flush of the season. This is because the tree is using all of its stored nutrients and soil moisture from the dormant season to grow (Kienholz 1941). As the tree continues to have flushes of growth and reaches these dry summer months, growth rates are continuing to slow down. During this time, separate flushes are growing more concurrently than in the beginning or ending. The final flush of the growing season is setting the bud for the next growing season and is less likely to be correlated with the other flushes in this growing season, but will have a relationship with the first flush of the next growing season.

5.3 Needle Lengths

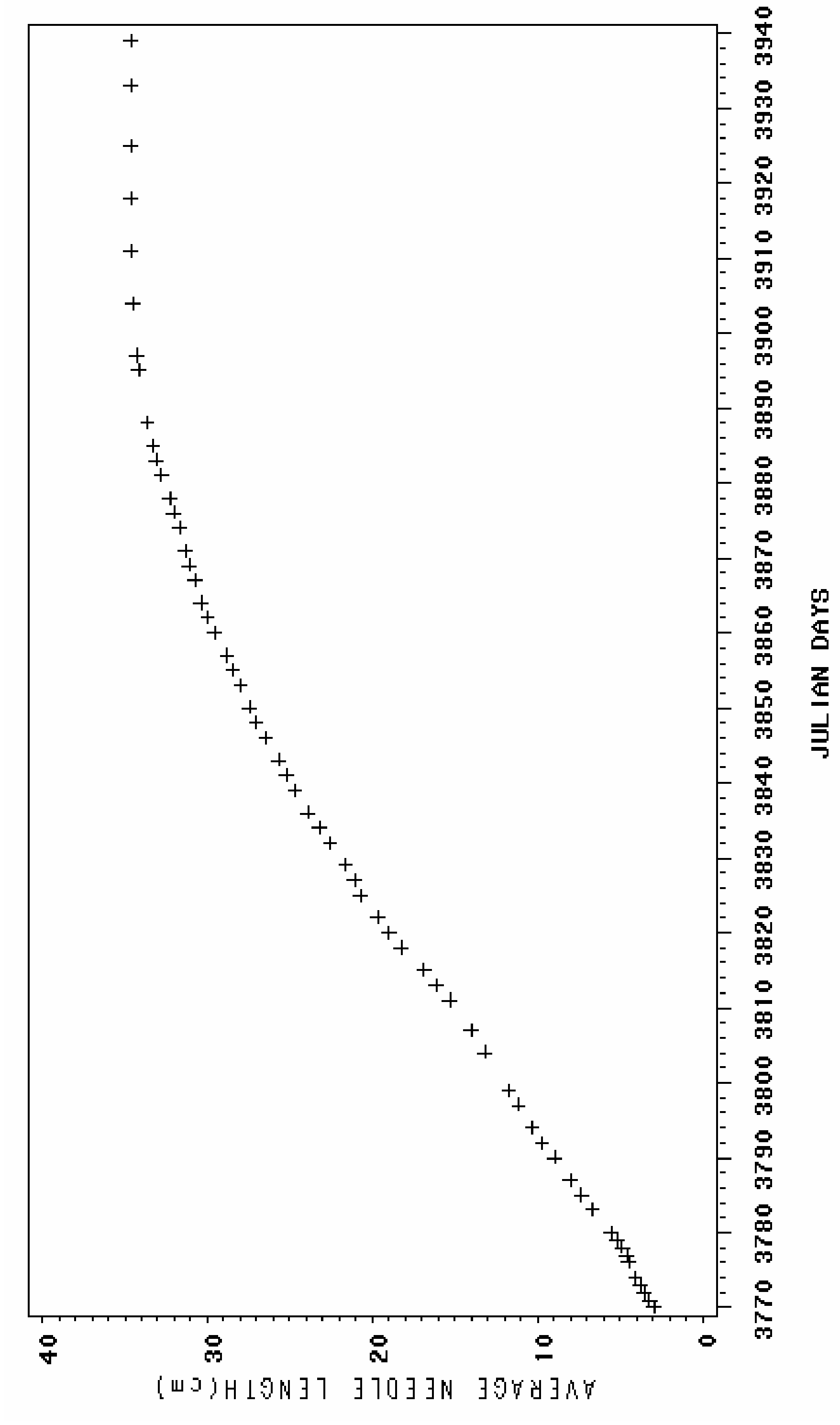
Needle lengths were measured with height growth from April 28 through October 14 of 1970. Needle length measurements were not measured during the 1969 growing season during the shading treatment. Therefore, only residual effects can be tested. The overall average needle growth during this interval was 31.65 cm. Table 5.3.1 shows mean needle growth by soil and shade combinations, and Figure 5.3.1 shows the average needle lengths over the growing season. Needles grew throughout the growing season following similar patterns of height growth. Growth rates were highest at the beginning of the growing season during the April and May and continued to grow until reaching a peak and then leveling off in early August. The following table shows average needle growth by soil, shade, and shade/soil combinations. There seemed to be no significant differences between shading treatments, soil condition or significant interactions at the 0.05 level of significance.

Table 5.3.1 Average needle growth of the sampled trees during 1970

Treatment/Condition	Average Needle Growth (cm)
No Shade	32.45
Shade	30.81
Lucy	29.79
Wagram	32.47
Shade/Soil Combination	**Average Needle Growth (cm)**
NL	31.62
NW	33.27
SL	29.87
SW	31.66

*Means significantly different (α=0.05)
NL = no shade, Lucy soil; NW = no shade, Wagram soil;
SL = shade, Lucy soil; SW = shade, Wagram soil

Figure 5.3.1 Average needle lengths of the sampled trees during 1970



5.4 1969 through 1970 Diameter Growth

Evaluating differences in diameter growth over the different intervals is necessary to see if the recorded environmental conditions and treatments are affecting diameter growth. For diameter growth, each year needs to be individually analyzed because of a calibration issue in January 1970. See Appendix 5.4.1 for a full description of the error and for additional statistical procedures. Tree 27 was in the early stages of mortality and caused a significant problem with the analyses. It was removed where appropriate. Statistical procedures used to evaluate height growth will be followed.

Monthly diameters were measured in 1969 from March 5 through December 24. Table 5.4.1 shows averages of diameter growth by shade treatment and soil type for 1969. A significant difference between trees on the Lucy loamy sand and the Wagram loamy sand was observed from testing overall growth from March of 1969 to December of 1969, shown in Table 5.4.2 All tests were conducted at the 0.05 level of significance.

Table 5.4.1 Average diameter growth during 1969 monthly
from March 1969 to December 1969

Treatment/Condition	Average Diameter Growth (cm)
No Shade	1.37 a
Shade	1.25 a
Lucy	1.57 b
Wagram	1.03 c
Shade/Soil Combination	Average Diameter Growth (cm)
NL	1.50 d
SL	1.36 d e
NW	1.11 f e
SW	1.06 f

Means with the same letter are not significantly different (α=0.05)
NL = no shade, Lucy soil; NW = no shade, Wagram soil;
SL = shade, Lucy soil; SW = shade, Wagram soil

Table 5.4.2 Testing overall diameter growth over monthly interval from March 1969 to December 1969 using GLM procedure

SOURCE	DF	Type III SS	Mean Square	F Value	Pr > F
SOIL	1	1.730625	1.730625	15.35	0.0004*
SHADE	1	0.04866453	0.04866453	0.7	0.2674
SOIL*SHADE	1	0.00038345	0.00038345	0.01	0.5903

*Means significantly different (α=0.05)

Diameters were measured in 1970 from January through December. Table 5.4.3 shows averages of diameter growth during the 1970 monthly interval by shade treatment and soil type for 1970. Testing within group differences, soil type was significant, and mean diameter growth was nonsignficantly larger for the trees with the shade treatment on both soils.

Table 5.4.3 Average diameter growth during 1970 monthly interval from January 1970 to December 1970

Treatment/Condition	Average Diameter Growth (cm)
No Shade	1.49 a
Shade	1.56 a
Lucy	1.71 b
Wagram	1.34 c
Shade/Soil Combination	**Average Diameter Growth (cm)**
SL	1.76 d
NL	1.67 d
SW	1.38 e
NW	1.30 e

*Means with the same letter are not significantly different (α=0.05)
NL = no shade, Lucy soil; NW = no shade, Wagram soil;
SL = shade, Lucy soil; SW = shade, Wagram soil

A significant difference between trees on the Lucy loamy sand and the Wagram loamy sand was observed for overall growth during the 1970 monthly interval (Table 5.4.4).

Table 5.4.4 Testing overall diameter growth over monthly interval from January 1970 to December 1970 using GLM procedure

SOURCE	DF	Type III SS	Mean Square	F Value	Pr > F
SOIL	1	1.19000075	1.19000075	17.18	0.0002*
SHADE	1	0.04866453	0.04866453	0.7	0.4076
SOIL*SHADE	1	0.00038345	0.00038345	0.01	0.9411

*Means significantly different (α=0.05)

Monthly diameter growth was explored for potential significant differences using the repeated measurements design. Initially the data were combined into 22 months ranging from March of 1969 to December of 1970. Tree 27 was also left in the dataset. Table 5.4.5 shows the results of this test.

Table 5.4.5 Testing monthly diameter growth from March 1969 to December 1970 using repeated measures procedure

EFFECT	Num DF	Den DF	F Value	Pr > F
TIME	1	1075	7162.66	<.0001
SOIL	1	1075	107.43	<.0001*
SHADE	1	1075	2.89	0.0893
SOIL*SHADE	1	1075	1.62	0.2028
TIME*SHADE	1	1075	2.38	0.1232
TIME*SOIL	1	1075	161.67	<.0001*
TIME*SOIL*SHADE	1	1075	0.47	0.4921

*Means significantly different (α=0.05)

This test reinforces the above analyses showing that there is a significant difference between trees with regard to soil type. The same analysis was conducted with cumulative growth and with lagging growth by 1 and 2 weeks. The results still only showed a significant difference in relation to soil type. However, removing tree 27 and running the same analysis did change the results. The output is in Table 5.4.6.

Table 5.4.6 Testing monthly diameter growth from March 1969 to December 1970 without tree 27 using repeated measures procedure

EFFECT	Num DF	Den DF	F Value	Pr > F
TIME	1	1048	7066.52	<.0001*
SOIL	1	1048	96.42	<.0001*
SHADE	1	1048	4.85	0.0278*
SOIL*SHADE	1	1048	3.16	0.0757
TIME*SHADE	1	1048	5.07	0.0245*
TIME*SOIL	1	1048	138.91	<.0001*
TIME*SOIL*SHADE	1	1048	1.99	0.1589

*Means significantly different (α=0.05)

After tree 27 was removed, the shade treatment became significant. Dividing the total dataset into a dataset for each year also changed the results. Also, the months of January and February of 1970 were removed from the 1970 dataset due to an error in the original datasheet and to make the 1969 and 1970 datasets over the same span in time. Below are the results of the repeated measures test for each year in Tables 5.4.7 and 5.4.8.

Table 5.4.7 Testing 1969 diameter growth over the monthly interval from March to December without tree 27 using repeated measures procedure

EFFECT	Num DF	Den DF	F Value	Pr > F
TIME	1	464	3557.67	<.0001*
SOIL	1	464	48.72	<.0001*
SHADE	1	464	3.52	0.0612
SOIL*SHADE	1	464	2.47	0.1170
TIME*SHADE	1	464	4.33	0.0380*
TIME*SOIL	1	464	55.84	<.0001*
TIME*SOIL*SHADE	1	464	1.61	0.2045

*Means significantly different (α=0.05)

The results from the 1969 analysis show a significant difference for soil type and a significant interaction between time and shade. The shade treatment is not significant at this level of significance. The results from the 1970 analysis show a significant difference for soil type and the shade treatment.

Table 5.4.8 Testing 1970 diameter growth over the monthly interval from March to December without tree 27 using repeated measures procedure

EFFECT	Num DF	Den DF	F Value	Pr > F
TIME	1	541	8647.28	<.0001*
SOIL	1	541	69.90	<.0001*
SHADE	1	541	15.03	0.0001*
SOIL*SHADE	1	541	0.53	0.4652
TIME*SHADE	1	541	16.46	<.0000*
TIME*SOIL	1	541	97.43	<.0001*
TIME*SOIL*SHADE	1	541	0.20	0.6524

*Means significantly different (α=0.05)

The biweekly intervals from 1969 and 1970 were tested next. The results can be found in Tables 5.4.9 and 5.4.10, respectively. There were no significant differences or interactions in diameter growth with respect to soil condition or shade treatment for the 1969 interval. The 1970 biweekly interval shows a significant soil shade interaction, but neither the shade treatment nor soil condition is statistically significant.

Table 5.4.9 Testing diameter growth over biweekly interval from March 1969 to December 1969 using repeated measures procedure

EFFECT	Num DF	Den DF	F Value	Pr > F
TIME	1	871	1676.82	<.0001*
SOIL	1	871	0.39	0.5302
SHADE	1	871	0.03	0.8733
SOIL*SHADE	1	871	0.26	0.6113
TIME*SHADE	1	871	0.02	0.8774
TIME*SOIL	1	871	0.83	0.3634
TIME*SOIL*SHADE	1	871	0.43	0.511

*Means significantly different (α=0.05)

Table 5.4.10 Testing diameter growth over biweekly interval from March 1970 to December 1970 using repeated measures procedure

EFFECT	Num DF	Den DF	F Value	Pr > F
TIME	1	864	1765.95	<.0001*
SOIL	1	864	0.6	0.4373
SHADE	1	864	0.59	0.4443
SOIL*SHADE	1	864	11.89	0.0006*
TIME*SHADE	1	864	0.57	0.4512
TIME*SOIL	1	864	0.26	0.6078
TIME*SOIL*SHADE	1	864	13.58	0.0002*

*Means significantly different (α=0.05)

Tables 5.4.11 and 5.4.12 contain the results to the repeated measures tests for the 1969 and 1970 weekly intervals, respectively. Both tests show significant differences between soil types and shade treatments. There are also significant interactions between soil conditions and time and also the shade treatment and time, but there was not a significant interaction between the soil condition and shade treatment.

Table 5.4.11 Testing diameter growth over 1969 weekly interval from March to October using repeated measures procedure

EFFECT	Num DF	Den DF	F Value	Pr > F
TIME	1	1356	13699.4	<.0001*
SOIL	1	1356	151.81	<.0001*
SHADE	1	1356	18.79	<.0001*
SOIL*SHADE	1	1356	3.17	0.0754
TIME*SHADE	1	1356	25.33	<.0001*
TIME*SOIL	1	1356	190.23	<.0001*
TIME*SOIL*SHADE	1	1356	1.43	0.2318

*Means significantly different (α=0.05)

Table 5.4.12 Testing weekly diameter growth over 1970 weekly interval from March to November using repeated measures procedure

EFFECT	Num DF	Den DF	F Value	Pr > F
TIME	1	1636	16574.80	<.0001*
SOIL	1	1636	173.13	<.0001*
SHADE	1	1636	17.96	<.0001*
SOIL*SHADE	1	1636	0.01	0.9436
TIME*SHADE	1	1636	20.13	<.0001*
TIME*SOIL	1	1636	267.03	<.0001*
TIME*SOIL*SHADE	1	1636	0.53	0.4667

*Means significantly different ($\alpha=0.05$)

Diameter growth for trees on the Lucy loamy sands was significantly greater than diameter growth for trees on the Wagram loamy sands across all intervals except for the biweekly datasets. The reason for better growth on the Lucy loamy sands could possibly be that longleaf pine grows better on drier soils due to potentially less ground layer competition. If the root systems were deep enough to reach the B-horizon there might be a moisture gradient caused by the higher clay content at shallower depths than the Wagram loamy sands. The significant differences in diameter growth by soil type may also be due to competition of surrounding trees instead of soil differences, but without more detailed data about surrounding tree and vegetation this concept cannot be explored further.

Repeated measures analyses also showed a significant shade treatment for diameter growth for monthly and weekly intervals in 1969 and 1970 when tree 27 was removed. However, adjusting weekly interval tests for autocorrelation did affect the analyses, and the normality assumption was suspect for the weekly 1970 test. Calculating the overall means for these intervals, the shade treatment was not significant, but testing growth within each soil type during 1970 showed that shaded trees grew less than non shaded trees.

5.5 Growing Seasons

Average daily temperature during the 1969 growing season was 28°C. The total amount of precipitation during this time was 131 cm. During the 1970 growing season, there was a total of 155 cm of precipitation with an average daily temperature of 29°C.

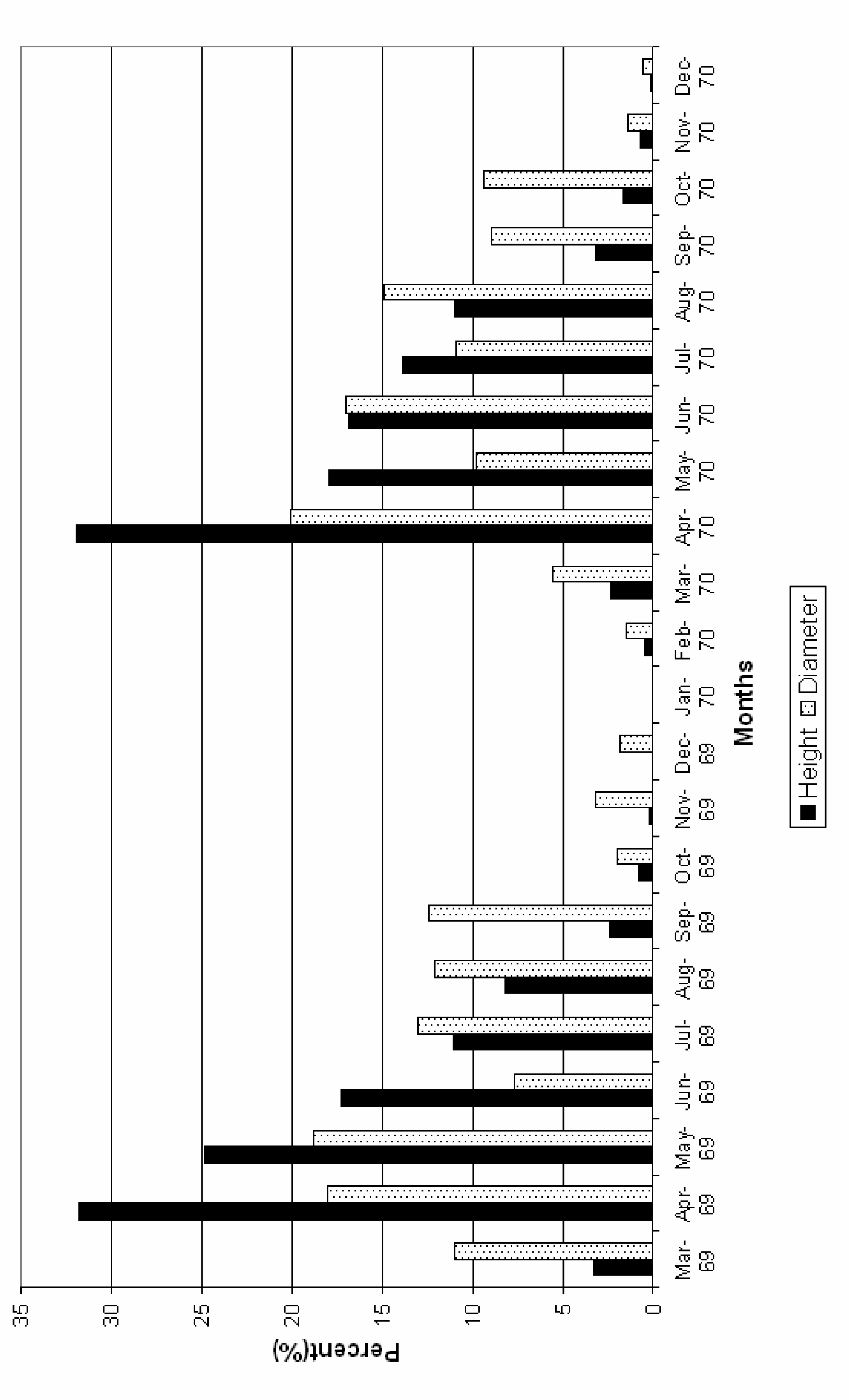
Table 5.5.1 contains the percent of annual average height and diameter growth for each month during the 1969 and 1970 growing seasons. Figure 5.5.1, provides plots of the percent of annual average height and diameter growth by month for both growing seasons. Data recorded during both seasons showed very similar cyclic patterns for height and diameter growth during the two year data. Height growth seems to begin in March, peak in April, and decline until ceasing in October and November. Over 90% of the year's height growth was completed during the month of August of both years. Mudano et al. (1992) reported that 90% of total shoot growth for loblolly pine was completed by the middle of August, and growth ceased in early November. A similar growing season was also reported by Allen and Scarbrough (1969) for longleaf pine. The month of April was the peak of the growing season for height growth, representing over 30% of the total growth each year. Mudano et al. (1992) and Kozlowski and Pallardy (1997b) also saw a peak of about 30% of annual height grow during the month of April.

Diameter growth had similar patterns to height growth starting in March and peaking in April or May. However, diameter growth did not consistently decline until October as height growth did. Diameter growth was somewhat variable from June to October and even persisted into the winter months, which accounted for less than 5% of the average diameter growth between November and December. Over 90% of the years average diameter growth was completed by September or October for both years. This shows that height growth is ceasing about a month before diameter growth for these two growing seasons. Diameter growth is potentially more susceptible to changes in the environment than height growth as seen during the growing season and throughout the year (Kozlowski and Ward 1961). Months following low precipitation seem the greatly affect percent diameter growth. As seen in July 1969 and May 1970, percent diameter following low months of precipitation was reduced by half.

Table 5.5.1 Percent of average annual height and diameter growth by month from 1969 through 1970

Year	Month	Average Height Growth (%)	Average Diameter Growth (%)
1969	March	3.30	11.02
	April	31.77	18.07
	May	24.85	18.80
	June	17.26	7.67
	July	11.10	12.98
	August	8.21	12.09
	September	2.46	12.42
	October	0.80	1.96
	November	0.23	3.17
	December	0.03	1.82
1970	January	0.00	0.00
	February	0.51	1.52
	March	2.31	5.53
	April	31.95	20.04
	May	17.95	9.78
	June	16.82	17.01
	July	13.86	10.94
	August	10.98	14.85
	September	3.17	8.97
	October	1.63	9.37
	November	0.74	1.44
	December	0.09	0.55

Figure 5.5.1 Percent of average monthly height and diameter growth plotted by each month data were collected in 1969 and 1970



5.6 Diurnal and Nocturnal Growth

The diurnal period between the morning and evening measurements was about 8 hours, and the nocturnal period between evening measurements and the following morning measurements was about 16 hours (Boyer 1970). Diurnal growth is the growth that occurred between the initial morning measurement and the initial afternoon measurement. The nocturnal growth refers to the growth occurring between the initial afternoon measurement and the initial morning measurement. The 24-hour growth refers to the growth occurring from the initial morning measurement until the initial morning measurement the following day.

Specimens were measured from the morning of April 8, 1969 until the morning of April 28, 1969. This resulted in 19 diurnal, nocturnal, and 24-hour measurements. During the 19 days the trees were measured in 1969, the average daily temperature was 26°C. The average temperature during the night was 12°C. Average height growth over the 19 days was 21.64 cm. About 35% of the growth occurred during the diurnal period, while about 65% occurred during the nocturnal period.

During the 16 days the trees were measured in April 1970, the average daily temperature was 28°C, while the average nightly temperature was 14°C. The total amounts of precipitation during these measurement periods in 1969 and 1970 were 10.16 cm and 11.43 cm, respectively. During the 16 days the trees were measured in 1970, average height growth was 20.44 cm. About 25% of the growth occurred during the diurnal period, and about 75% of the growth occurred during the nocturnal period. The large percentage of growth occurring during the nocturnal periods is possibly due to the time in which the trees were measured. The trees were also receiving light, but just not from directly above.

There were originally 20 measurement dates in 1970 instead of 16. The reason for the difference is that, on the 17th measurement, a new bud formed. There were four measurements, including diurnal, nocturnal, and 24-hour, that included the new bud. These measurements were removed from the dataset.

There was not a statistically significant difference between the soil types or the shade treatment for average diurnal or nocturnal growth during the measurement periods in April 1969 or 1970. Procedures from Appendix 5.1.1 for analyzing mean differences in growth over numerous intervals were used. To evaluate how the measured environmental variables influenced height growth during the peak of the growing season, a regression analysis was conducted. Since height growth was measured in intervals of diurnal, nocturnal, and total day (24-hour), three sets of regression analyses were conducted on the datasets from each year. Table 5.6.1 is a list of names and brief descriptions of variables used in the regressions. Tables 5.6.2, 5.6.3, and 5.6.4 contain the significant single variable models developed from the regression analyses for 1969 mean diurnal, nocturnal, and 24-hour growth, respectively. Tables 5.6.5, 5.6.6, and 5.6.7 contain the single variable models developed from the regression analyses for 1970 mean diurnal, nocturnal, and 24-hour growth, respectively. Notice that no single variable consistently dominated all intervals.

During the peak of the growing season, temperature and precipitation were the most influential variables for height growth. As Boyer (1970) found with loblolly pine, temperature and degree-hour accumulations seem to explain more variability in nocturnal and 24-hour growth than any of the other variables. All significant variables in the 1969 diurnal analyses were lagged variables. This shows that growth during the diurnal period is influenced by environmental conditions from the day before. Precipitation from the day before explained about 58% of the variation in diurnal height growth, which was greater than any other variable. Analyses from the 1970 diurnal data showed measures of temperature as better explanatory variables for mean diurnal height growth. Degree-hour accumulations, greater than 40˚ F (4.4 ˚C), explained about 46% of the variation in diurnal height growth. However, the degree-hour accumulations greater than 45˚ F (7.2˚ C) and 50˚ F (10˚ C) were also significant and explained about the same amount of variability in diurnal height growth in 1970. Lagged vapor pressure deficit was significant for both the 1969 and 1970 data.

Temperature was the most influential variable in explaining the variation in nocturnal and 24-hour growth rates. Degree-hour accumulations above 55˚ F (12.8 ˚C) and 45˚ F for the 24-hour periods influenced mean nocturnal growth more than any other selected environmental variables for 1969 and 1970, respectively. Degree-hour accumulations above 40˚ to 55˚ F for the 24-hour periods seemed to have the greatest influence on mean 24-hour growth. However, mean 24-hour temperature explained about the same amount of the variability in mean 24-hour growth for both years as degree-hour accumulations did. The results from mean diurnal, nocturnal, and 24-hour growth from both years consistently show temperature as the most influential environmental variable.

Table 5.6.1 Diurnal and nocturnal growth regression keywords

Diurnal Interval	
HGDR	mean height growth rate (cm/hour)
TIMED	time interval (0.1hour)
TMAXD	maximum temperature (˚C)
TMIND	minimum temperature (˚C)
TMEAND	mean temperature (˚C)
WINDD	wind speed (total miles)
RHxDay	relative humidity (percent)
VPDD	vapor pressure deficit (mm Hg)
D40D	degree-hours above 40˚ F (4.4˚ C)
D45D	degree-hours above 45˚ F (7.2˚ C)
D50D	degree-hours above 50˚ F (10˚ C)
D55D	degree-hours above 55˚ F (12.8˚ C)
Nocturnal Interval	
HGNR	mean height growth rate (cm/hour)
TIMEN	time interval (0.1 hour)
TMAXN	maximum temperature (˚C)
TMINN	minimum temperature (˚C)
TMEANN	mean temperature (˚C)
WINDN	wind speed (total miles)
RHxNight	relative humidity (percent)
VPDN	vapor pressure deficit (mm Hg)
D40N	degree-hours above 40˚ F (4.4˚ C)
D45N	degree-hours above 45˚ F (7.2˚ C)
D50N	degree-hours above 50˚ F (10˚ C)
D55N	degree-hours above 55˚ F (12.8˚ C)
24 hour Interval	
H24R	mean growth rate (cm/hour)
TIME24	time interval (0.1 hour)
MAXT	maximum temperature (˚C)
MINT	minimum temperature (˚C)
TDIFF	difference between MAXT and MINT (˚C)
TMEAN24	mean temperature during (˚C)
PREC	total daily precipitation (cm)
WINDT	wind speed (total miles)
RHx24Hr	relative humidity (percent)
VPD24	vapor pressure deficit (mm Hg)
SRO	solar radiation open (langleys cal/cm3)
SRS	solar radiation shaded (langleys cal/cm3)
D40T	degree-hours above 40˚ F (4.4˚ C)
D45T	degree-hours above 45˚ F (7.2˚ C)
D50T	degree-hours above 50˚ F (10˚ C)
D55T	degree-hours above 55˚ F (12.8˚ C)

L# prefix to any variable means values have been lagged # of intervals

Table 5.6.2 1969 mean diurnal growth rate (HDR) regressions

Independent Variable	Equation	R^2	Adj-R^2
L1PREC	HDR = 0.05534 - 0.00769 L1PREC	0.5795	0.5532
L1VPDD	HDR = 0.3918 + 0.3283L1 VPDD	0.3296	0.2877
L1RHX24	HDR = 0.6843 - 0.00029562 L1RHX24	0.3171	0.2245
L1TMAXD	HDR = -0.0487 + 0.00223 L1MAXD	0.2731	0.2276
L1VPD24	HDR = 0.3971 + 0.08709 L1VPD24	0.2669	0.2211
L1MAXT	HDR = -0.00050303 + 0.00202 L1MAXT	0.2103	0.1609
L1SRO	HDR = 0.04072+ 0.0002178 L1SRO	0.2062	0.1566

Table 5.6.3 1969 mean nocturnal growth rate (HNR) regressions

Independent Variable	Equation	R^2	Adj-R^2
D55T	HNR = 0.01368 + 0.00010629 D55T	0.5623	0.5365
D40T	HNR = 0.00082248 + 0.00007421 D40T	0.5262	0.4983
D50T	HNR = 0.01352 + 0.00008531 D50T	0.5258	0.4979
D45T	HNR = 0.00811 + 0.00007705 D45T	0.5257	0.4978
TMEAN24	HNR = -0.01128 + 0.00308 TMEAN24	0.5076	0.3224
L1VPDN	HNR = 0.05670 - 0.17396 L1VPDN	0.3867	0.3484
D40N	HNR = 0.02464 + 0.00006372 D40N	0.3646	0.3272
TMEANN	HNR = -0.00758 + 0.00231 TMEANN	0.3601	0.3224
D45N	HNR = 0.02900 + 0.00006576 D45N	0.3563	0.3185
D55N	HNR = 0.3448 + 0.00009185 D55N	0.3551	0.3171
D50N	HNR = 0.03239 + 0.00007247 D50N	0.3424	0.3037
L1RHXN	HNR = -0.01841 + 0.00073727 L1RHXN	0.3392	0.2979
TMINN	HNR = 0.03143 + 0.00115 TMINN	0.3044	0.2635
TMIND	HNR = 0.00147 + 0.00224 TMIND	0.2624	0.2191
L2TMIND	HNR = 0.09174 - 0.0024 L2TMIND	0.2506	0.2006
TMEAND	HNR = -0.00662 + 0.00228 TMEAND	0.2334	0.1884
L1VPD24	HNR = 0.05672 - 0.07690 L1VPD24	0.2277	0.1795
L1RHX24	HNR = 0.01263 + 0.00043405 L1RHX24	0.2230	0.1744
D55D	HNR = 0.02266 + 0.00015566 D55D	0.2217	0.1759
D50D	HNR = 0.01696 + 0.00015336 D50D	0.2207	0.1748
D45D	HNR = 0.01240 + 0.00014641 D45T	0.2056	0.1588

Table 5.6.4 1969 mean 24 hour growth rate (H24R) regressions

Independent Variable	Equation	R^2	Adj-R^2
D55T	H24R = 0.02680 + 0.00007391 D55T	0.3977	0.3622
D50T	H24R = 0.0254 + 0.00005777 D50T	0.3527	0.3146
D40T	H24R = 0.01696 + 0.0000500 D40T	0.3491	0.3111
D45T	H24R = 0.02200 + 0.00005166 D45T	0.3457	0.3072
TMEAN24	H24R = 0.0088 + 0.00207 TMEAN24	0.3357	0.2966
L2TMIND	H24R = 0.08638 - 0.00190 L2TMIND	0.2740	0.2256
TMIND	H24R = 0.0186 + 0.0007544 TMIND	0.2625	0.2191
D55N	H24R = 0.0392 + 0.00006456 D55N	0.2566	0.2129
D40N	H24R = 0.03313 + 0.00004256 D40N	0.2379	0.1931
TMEANN	H24R = 0.02697 + 0.00126 TMEANN	0.2355	0.1906
D45N	H24R = 0.3609 + 0.00004378 D45N	0.2311	0.1858
D50N	H24R = 0.3820 + 0.00004902 D50N	0.2291	0.1838

Table 5.6.5 1970 mean diurnal growth rate (HDR) regressions

Independent Variable	Equation	R^2	Adj-R^2
D40D	HDR = -0.00277 + 0.00014822 D40D	0.458	0.4128
D45D	HDR = 0.00338 + 0.00014713 D45D	0.449	0.4031
D50D	HDR = 0.00927 + 0.00014713 D50D	0.449	0.4031
L1VPDN	HDR = 0.2659 + 0.16156L1 VPDN	0.412	0.363
L1WINDN	HDR = 0.03222 + 0.00083362 L1WINDN	0.385	0.3338
D55D	HDR = 0.1784 + 0.00013458 D55D	0.3732	0.3210

Table 5.6.6 1970 mean nocturnal growth rate (HNR) regressions

Independent Variable	Equation	R^2	Adj-R^2
D45T	HNR = -0.04964 + 0.00019681 D45T	0.9696	0.9562
D50T	HNR = -0.03292 + 0.00020939 D50T	0.9617	0.9585
D40T	HNR = -0.07109 + 0.00019405 D40T	0.9590	0.9556
TMEAN24	HNR = -0.11006 + 0.00848 TMEAN24	0.9471	0.9427
D50N	HNR = -0.00041073 + 0.00027755 D50N	0.9453	0.9407
D55N	HNR = 0.0127 + 0.0003173 D55N	0.9432	0.9384
D55T	HNR = -0.0172 + 0.0002330 D55T	0.9385	0.9334
D40N	HNR = -0.03069 + 0.00024429 D40N	0.9295	0.9236
TMINN	HNR = -0.00970 + 0.00504 TMINN	0.9226	0.9161
D45N	HNR = -0.01253 + 0.00024829 D45N	0.9215	0.9257
TMEANN	HNR = -0.06173 + 0.00698 TMEANN	0.9202	0.9140
D40D	HNR = -0.15141 + 0.000692 D40D	0.7869	0.7691
D45D	HNR = -0.12292 + 0.00068773 D45D	0.7733	0.7544
D50D	HNR = -0.09541 + 0.00068773 D50D	0.7733	0.7544
TMEAND	HNR = -0.19139 + 0.00979 TMEAND	0.7606	0.7406
TMAXD	HNR = -0.22491 + 0.01018 TMAXD	0.7083	0.6840
D55D	HNR = -0.05908 + 0.00064978 D55D	0.6858	0.6597
TMIND	HNR = -0.07181 + 0.00617 TMIND	0.6339	0.6034
L2D55N	HNR = 0.03415 + 0.00023597 L1D55N	0.5011	0.4512
L1D55N	HNR = 0.03221 + 0.00021267 L1D55N	0.4711	0.4232
L1TMAXD	HNR = -0.14964 + 0.00762 L1TMAXD	0.4593	0.4101
L1WINDN	HNR = 0.02303 + 0.00291 L1WINDN	0.3628	0.3097

Table 5.6.7 1970 mean 24-hour growth rate (H24R) regressions

Independent Variable	Equation	R^2	Adj-R^2
D40T	H24R = -0.04281 + 0.00014364 D40T	0.9480	0.9437
D45T	H24R = -0.0269 + 0.00014563 D45T	0.9479	0.9436
D50T	H24R = -0.01445 + 0.00015475 D50T	0.9476	0.9432
TMEAN24	H24R = -0.07160 + 0.00627 TMEAN24	0.9354	0.9300
D50N	H24R = 0.01027 + 0.0002009 D50N	0.9275	0.9214
D55N	H24R = 0.01947 + 0.00023309 D55N	0.9182	0.9114
D40N	H24R = -0.0127 + 0.00018055 D40N	0.9161	0.9091
TMEANN	H24R = -0.03566 + 0.00515 TMEANN	0.9054	0.8981
D40D	H24R = -0.10305 + 0.00051479 D40D	0.7857	0.7679
D45D	H24R = -0.08185 + 0.00051163 D45D	0.7721	0.7531
D50D	H24R = -0.06138 + 0.00051143 D50D	0.7721	0.7531
TMEAND	H24R = -0.13298 + 0.0729 TMEAND	0.7610	0.7411
TMAXD	H24R = -0.15845 + 0.00760 TMAXD	0.7121	0.6881
TMIND	H24R = -0.04292 + 0.00455 TMIND	0.6211	0.5895
L2D50N	H24R = 0.02713 + 0.00015439 L2D50N	0.5612	0.5173
L1D50N	H24R = 0.02616 + 0.00014190 L1D50N	0.5255	0.4823
L1WINDN	H24R = 0.02599 + 0.00223 L1WINDN	0.3867	0.3356
RHX24	H24R = -0.06338 + 0.00167 RHX24	0.3555	0.3059
RHXN	H24R = -0.09761 + 0.00181 RHXN	0.3168	0.2642

5.7 Height and Diameter Yearly Measurements

Height measurements were made for the 13 growing seasons from 1969 through 1981, while diameter measurements are limited to the 1972 through 1981 growing seasons since the trees were measured at dbh during this period

Mortality and damage affected 6 trees during the remeasurement period. Trees 1 and 12 were reported as having broken tops during the 1979 measurement. Tree 17 was identified as being dead in 1978, while tree 27 was identified as dead in 1973. Tree 22 was also reported as having a broken top in 1980. Tree 33 was reported as having a broken top in 1973, but by 1975 a new leader emerged. Tree 40 was identified as a leaning tree, but this did not seem to affect its growth during this interval. No cause of death or injury was recorded for the trees except for tree 17 which had a stem canker caused by fusiform rust (*Cronartium quercumm* f.sp *fusiforme*). Data associated with these trees were removed from the data set where appropriate.

Average height growth over the 13 seasons of the entire study was 13.7 m. Over the 10 growing seasons of the remeasurement period, average height growth was 10.3 m. Average diameter growth during the remeasurement period was 7.8 cm. Appendix 5.7.1 contains plots of height and diameter measurements and yearly growth by year.

An analysis of variance at the 0.05 level of significance was conducted to test for significant differences of heights and diameters with respect to soil type and the possibility of a shade treatment residual effect. Appendix 5.7.1 contains the tests used in the analysis of height growth. The same procedures for evaluating mean differences in Appendix 5.1.1 were followed. All regression analyses followed the same procedures as Appendix 5.6.1.

There were no significant differences in height growth with respect to soil condition or residual effects from the shade treatment. Table 5.7.1 is the effects table associated with the test of overall height growth over the entire study. The normality assumption did not seem to be violated. The QQ plot was acceptable and the Anderson-Darling test resulted in a nonsignificant p-value. Neither Barlett’s nor Levene’s test for homogeneity of variance were significant, indicating no violations of the assumption of constant variance. Height growth during the remeasurement period was also tested, but there were no significant results.

Table 5.7.1 Testing overall height growth from 1969
through 1981 using GLM procedure

Source	DF	Type III SS	Mean Square	F Value	Pr > F
SOIL	1	4793.1668	4793.1668	0.78	0.3831
SHADE	1	12315.851	12315.85055	2.01	0.1661
SOIL*SHADE	1	1721.1232	1721.1232	0.28	0.5998

*Means significantly different ($\alpha=0.05$)

There was a significant difference in average diameter growth during the remeasurement period for soil type. The average diameter growth for trees on the Lucy loamy sand was 8.8 cm and 6.3 cm on the Wagram loamy sand with a significant p-value of 0.0002. The difference in mean yearly diameter growth seemed to increase throughout the yearly measurements interval as seen in Figure 5.7.1. Diameter growth on the Lucy soil is possibly better because of the shallow B-horizon, which could provide roots in this horizon with more soil moisture due to higher clay content. The effects table from this test can be found in Table 5.7.2. There were no significant residual differences between shade treatments or significant interactions. The QQ plot was acceptable and the Anderson-Darling test resulted in a nonsignificant p-value of > 0.250. However, both Barlett's and Levene's tests for homogeneity of variance were significant, indicating violations of the assumption of constant variance. Performing a log transformation of diameter growth solved the homogeneity of variance problem. Testing the transformed diameter growth resulted in a significant difference in soil type. A nonparametric Kruskal-Wallis test was used to test overall diameter growth with respect to soil condition. The results were consistent with the results from Table 5.7.3. The same nonparametric test was used to test for shade treatment effects, but the shade treatment was not significant.

Table 5.7.2 Testing overall diameter growth from 1972 through 1981 using GLM procedure

Source	DF	Type III SS	Mean Square	F Value	Pr > F
SOIL	1	56.355012	56.35501209	18.11	0.0002*
SHADE	1	4.1262009	4.12620089	1.33	0.2583
SOIL*SHADE	1	2.0410904	2.0410904	0.66	0.4242

*Means significantly different (α=0.05)

Table 5.7.3 Testing overall diameter growth from 1972 through 1981 using nonparametric Kruskal-Wallis Test

Chi-Square	12.7883
DF	1
Pr > Chi-Square	0.0003

*Means significantly different (α=0.05)

Table 5.7.4 contains the regression keywords for the yearly remeasurement regressions. Table 5.7.5 contains yearly height and diameter regression results. Regression analyses showed temperature and precipitation explained the most variation in yearly height and diameter growth. In the single variable equations, dormant season minimum temperature and precipitation seem to explain the most variability in yearly height growth. Dormant season temperature difference and precipitation seem to be the best predictors for yearly diameter growth, with yearly diameter growth having a positive relationship with dormant season precipitation and a negative relationship with the difference between average maximum and minimum daily temperature. Zahner (1956) and Shoulders and Tiarks (1980) both cite water as one of the most important resources to a tree. As the amount of precipitation during the dormant season increases, the amount of yearly height and diameter growth also increases. Coile (1936) saw a positive correlation between longleaf pine growth and February through April rainfall. A build up of soil moisture reserves during the dormant season aides a tree in peak photosynthesis during the beginning of the growing season.

Table 5.7.4 Yearly remeasurement regression keywords

Independent Variable	Description
HGT	Yearly height growth (cm)
DIA	Yearly diameter growth (cm)
MAXT	Average maximum temperature during the year (˚C)
MINT	Average minimum temperature during the year (˚C)
TDIFF	Difference between MAXT and MINT (˚C)
PREC	Sum of precipitation during the year (cm)
GSMAXT	Average maximum temperature during the growing season (˚C)
GSMINT	Average minimum temperature during the growing season (˚C)
GSTDIFF	Difference between GSMAXT and GSMINT (˚C)
GSPREC	Sum of precipitation during the growing season (cm)
DSMAXT	Average maximum temperature during the dormant season (˚C)
DSMINT	Average minimum temperature during the dormant season (˚C)
DSTIFF	Difference between DSMAXT and DSMINT (˚C)
DSPREC	Sum of precipitation during the dormant season (cm)

Growing Season (March –October), Dormant Season (November-February)

Table 5.7.5 Yearly height and diameter regressions

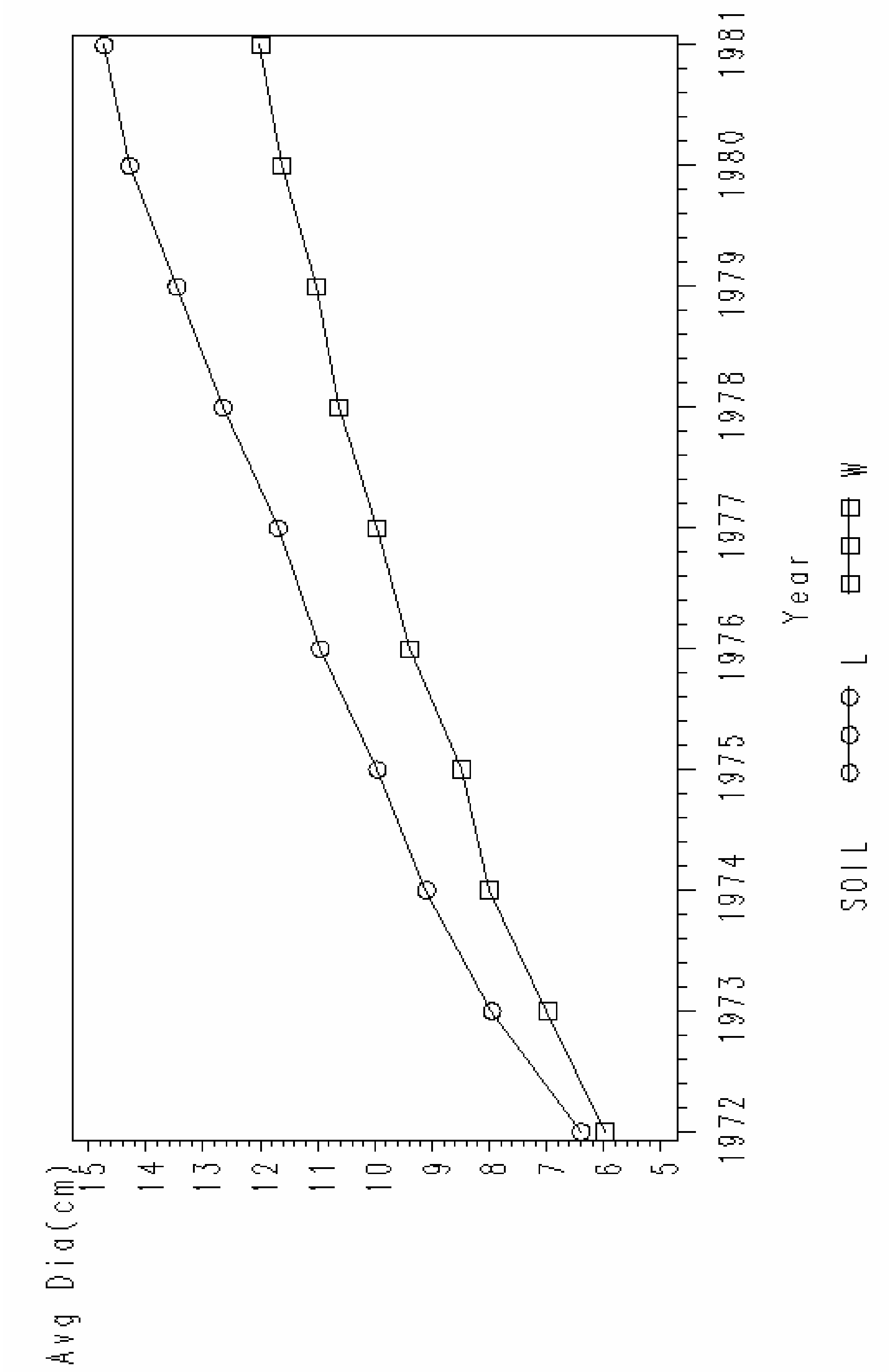
Yearly height growth (HGT) from 1969 through 1981

MODEL	R^2	ADJ-R^2
HGT = 71.9410 + 7.2793DSMINT	0.1681	0.1659
HGT = 63.2694 + 0.8957DSPREC	0.1343	0.1320
HGT = 280.112 - 12.8963TDIFF	0.0975	0.0951
HGT = 21.3574 + 4.5378DSMAXT	0.0723	0.0699
HGT = 253.657 - 10.855TDIFF	0.0376	0.0350
HGT = 123.885 - 0.1894 GSPREC	0.0223	0.0197
HGT = 60.1002 + 3.5218MINT	0.0149	0.0123
HGT = 42.2710 + 6.3953DSMINT + 0.7534DSPREC	0.2607	0.2567
HGT = -32.8265 + 0.9661DSPREC + 5.1655DSMAXT	0.2272	0.2230
HGT = 366.687 - 0.4649GSPREC -15.2431GSTDIFF	0.0707	0.0657

Yearly diameter growth (DIA) from 1972 through 1981

MODEL	R^2	ADJ-R^2
DIA = 3.4356 - 0.1951DSTDIFF	0.1716	0.1694
DIA = 0.2535 + 0.0113DSPREC	0.1636	0.1614
DIA = 3.6789 - 0.02106TDIFF	0.1083	0.1060
DIA = 2.4162 - 0.1190GSTDIFF	0.0443	0.0418
DIA = 0.6050 + 0.0356DSMINT	0.0305	0.0280
DIA = 0.3870 + 0.0024PREC	0.0297	0.0272
DIA = 1.5440 - 0.0302MAXT	0.0117	0.0092
DIA = 1.7921 - 0.0351GSMAXT	0.0104	0.0078
DIA = 2.1606 + 0.0066DSPREC - 0.1235DSTDIFF	0.2035	0.1994
DIA = 0.0997 + 0.0114DSPREC + 0.0083DSMAXT	0.1654	0.1640
DIA = 4.8875 - 0.0050GSPREC - 0.2565GSTDIFF	0.1026	0.1013

Figure 5.7.1 Average diameter measurements by year and soil type from 1972 through 1981



6. CONCLUSIONS

The desire to identify and develop a better understanding about the many relationships that exist between the environment and tree growth was the main purpose of this research effort. To determine this, height and diameter growth were evaluated over numerous intervals during various portions of the growing and dormant seasons. It was necessary to examine seasonal patterns of growth to understand how trees grow before attempting to determine what is affecting growth.

Both height and diameter growth displayed cyclic patterns during the two years the sample trees were measured intensively. The growing season began in March and tended to peak in April or May. Height growth occurred in flushes throughout the growing season with continuous growth of up to two flushes at one time. The proceeding flush began as the previous flush's growth rate slowed down. Trees flushed at least five times in 1969 and four times in 1970. During both years, over 30% of total height growth occurred in the month of April and in the first flush of the growing season. Height growth and flush lengths declined from this point on completing 90% of the year's growth by the end of August and finally ceasing in early November. Diameter growth was not as consistent as height growth. Diameter growth was variable from June to October of both years and even persisted into the winter months. However, 90% of the years total diameter growth was completed by September or October for both years. The variation in diameter growth was not consistent over the two years.

This potentially showed that diameter growth was being influenced by the environment more than height growth.

To evaluate height growth better, a more intense analysis was conducted during the April of each year, which was the peak of seasonal height growth. Growth during this period was divided into diurnal and nocturnal growth. The majority of the growth occurred during the nocturnal period accounting for 65% and 75% of total daily growth during 1969 and 1970, respectively. The nocturnal measurements include growth before 8:00 am and after 4:00 pm. These are peak times for photosynthesis when solar radiation is down and moisture is more plentiful, which is why the amount of growth during the nocturnal growth period is dramatically larger than that of the diurnal period. With a better understanding of height and diameter growth patterns, it is now possible to evaluate how the environment affects these patterns.

Longleaf pine is commonly known to be very shade intolerant. To determine how much light intensity affects the growth of longleaf pine, a shading treatment was randomly installed to half of the sampled trees. The shading treatment resulted in a reduction in direct solar radiation of about 38% during the growing season of 1969. The treatment seemed to have no significant effect on height growth of young longleaf pines over any of the intervals analyzed except for a significant effect on average height growth for trees on Wagram soils when looking at growth over the two year period. This could be a residual effect from the shading treatment. Weekly diameter growth of both 1969 and 1970 were significant with respect to the shade treatment. Mean diameter growth was also lower, however not significant, for shaded trees on both soil types. The lack of an overall effect on height growth potentially occurred because of several reasons. The shading treatment was maintained at a meter or greater above the growing tip of each tree. This allowed the terminal bud to receive latent rays of sunlight in the morning and evening which are the most important times for growth during the diurnal cycle. Duration is another key factor. The treatment was only applied for one growing season. It may take a longer duration of shading to see an effect on growth.

Soil type was another key factor that needed to be evaluated in determining a possible influence on growth. The sample trees were on two different soil types and the two measures of growth were affected in different ways. Soil type did not seem to have a significant effect on height growth except for the fifth flush of 1970, but there were differences in diameter growth. Soil type significantly affected diameter growth over all intensities measured during the first two years of the study including the dormant season measurements. Diameter growth for trees on the Lucy loamy sands was greater than diameter growth for trees on the Wagram loamy sands. The difference in growth seemed to increase as the trees got older. This could possibly be due to a moisture gradient caused by the higher clay content and shallower B-horizon in the Lucy loamy sands. The significant differences in mean diameter growth by soil type may also be due to competition of surrounding trees instead of soil differences, but without more detailed data about surrounding tree and vegetation this concept cannot be explored further.

Temperature and precipitation seemed to be the most influential environmental conditions in predicting height and diameter growth. Measures of temperature and precipitation during the dormant season seem to explain most of the variability in yearly height and diameter growth. Dormant season minimum temperature and dormant season precipitation seemed to explain more of the variability in yearly height growth than other measured factors. Dormant season temperature difference and precipitation seem to be the best predictors for yearly diameter growth, with yearly diameter growth having a positive relationship dormant season precipitation and a negative relationship with dormant season temperature difference.

During the peak of the growing season, temperature and precipitation also seemed to be the most influential variables for mean height growth rates. Mean diurnal growth rates seemed to be influenced more by temperature, vapor pressure deficit, and precipitation from the night or 24-hour period before. Temperature and degree-hour accumulations for the 24-hour periods influenced mean nocturnal and mean 24-hour growth rates more than the other selected environmental variables. Degree-hour accumulations above 45˚ and 55˚ F for the 24-hour periods seemed to have the greatest influence on mean diurnal growth rates and mean 24-hour growth rates. This shows that a temperature was the most influential environmental variable affecting mean height growth during the peak of the growing season.

This study found temperature and precipitation to be the most influential environmental variables affecting the growth of the sampled young longleaf pine. However, there are still many unanswered questions about influences of the environment on the growth of young longleaf. Understanding more about relationships between tree growth and the environment is very important to discovering more about patterns of tree growth. To develop a better understanding of these relationships, a larger dataset is required to measure trees across different sites and over more time.

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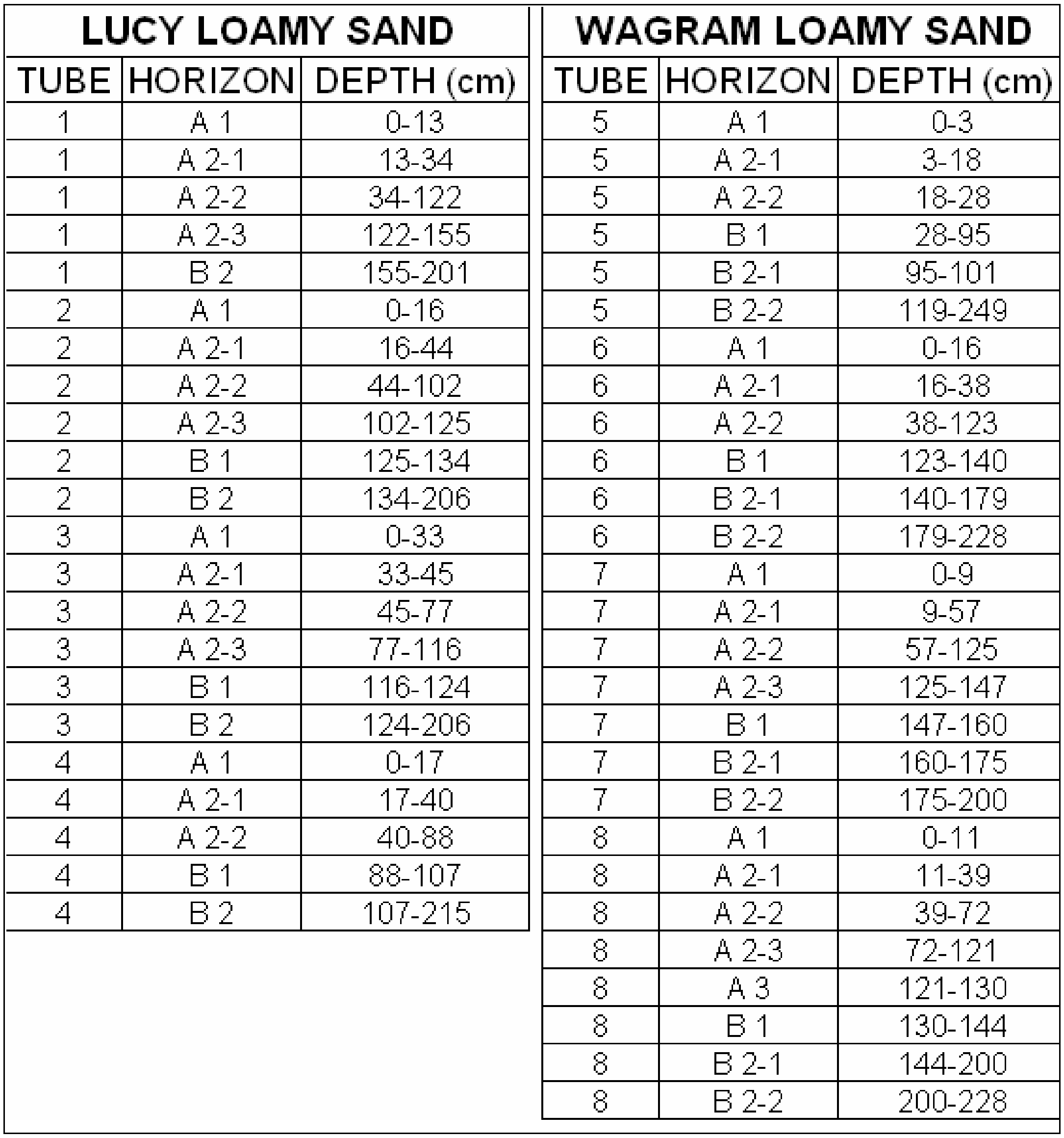
APPENDICES

Appendix 4.1.1 Soil core information from neutron probe tubes



LUCY LOAMY SAND		
TUBE	HORIZON	DEPTH (cm)
1	A 1	0-13
1	A 2-1	13-34
1	A 2-2	34-122
1	A 2-3	122-155
1	B 2	155-201
2	A 1	0-16
2	A 2-1	16-44
2	A 2-2	44-102
2	A 2-3	102-125
2	B 1	125-134
2	B 2	134-206
3	A 1	0-33
3	A 2-1	33-45
3	A 2-2	45-77
3	A 2-3	77-116
3	B 1	116-124
3	B 2	124-206
4	A 1	0-17
4	A 2-1	17-40
4	A 2-2	40-88
4	B 1	88-107
4	B 2	107-215

WAGRAM LOAMY SAND		
TUBE	HORIZON	DEPTH (cm)
5	A 1	0-3
5	A 2-1	3-18
5	A 2-2	18-28
5	B 1	28-95
5	B 2-1	95-101
5	B 2-2	119-249
6	A 1	0-16
6	A 2-1	16-38
6	A 2-2	38-123
6	B 1	123-140
6	B 2-1	140-179
6	B 2-2	179-228
7	A 1	0-9
7	A 2-1	9-57
7	A 2-2	57-125
7	A 2-3	125-147
7	B 1	147-160
7	B 2-1	160-175
7	B 2-2	175-200
8	A 1	0-11
8	A 2-1	11-39
8	A 2-2	39-72
8	A 2-3	72-121
8	A 3	121-130
8	B 1	130-144
8	B 2-1	144-200
8	B 2-2	200-228

This is a chart of the soil core information from the study site. It shows the breakdown of depths to each horizon.

Appendix 4.4.1 Soil moisture plots and precipitation correlation output

PREC = Precipitation
PREC1 = Precipitation lagged 1 interval
PLAG2 = Precipitation lagged 2 interval
PLAG3 = Precipitation lagged 3 interval
PLAG4 = Precipitation lagged 4 interval
D## = Soil moisture at depth (##) in cm
Pvalues less than the 0.05 level of significance are considered significant

```
             PREC    PREC1    PLAG2    PLAG3    PLAG4      D10      D25

PREC            1  0.18889  0.15449  0.12003  0.08549  0.02839  -0.0577
                    <.0001   <.0001   0.0025    0.032   0.4762   0.1472
              632      632      631      630      629      632      632

PREC1     0.18889        1  0.86404    0.728  0.59186  0.51332  0.54091
           <.0001            <.0001   <.0001   <.0001   <.0001   <.0001
              632      640      639      638      637      640      640
```

Pearson Correlation Coefficients
Prob> |r| under H0: Rho=0
Number of Observations

```
          D50      D75      D100     D125     D150     D175

PREC    -0.1015  -0.1092   -0.061  -0.0473  -0.0441  -0.0383
         0.0107    0.006   0.1258   0.2349   0.2683    0.336
            632      632      632      632      632      632

PREC1   0.53745  0.51694  0.25576  0.16919  0.11441  0.07605
        <.0001   <.0001   <.0001   <.0001    0.0038   0.0545
            640      640      640      640      640      640
```

```
                 Pearson Correlation Coefficients
                   Prob> |r| under H0:  Rho=0
                     Number of Observations

             PREC     PREC1     PLAG2     PLAG3     PLAG4       D10       D25

PLAG2     0.15449   0.86404         1   0.86401   0.72792     0.478   0.51292
           <.0001    <.0001              <.0001    <.0001    <.0001    <.0001
              631       639       639       638       637       639       639

PLAG3     0.12003     0.728   0.86401         1   0.86397   0.44597   0.48861
           0.0025    <.0001    <.0001              <.0001    <.0001    <.0001
              630       638       638       638       637       638       638

PLAG4     0.08549   0.59186   0.72792   0.86397         1   0.41484   0.46003
            0.032    <.0001    <.0001    <.0001              <.0001    <.0001
              629       637       637       637       637       637       637

  D10     0.02839   0.51332     0.478   0.44597   0.41484         1   0.92691
           0.4762    <.0001    <.0001    <.0001    <.0001              <.0001
              632       640       639       638       637       640       640

  D25     -0.0577   0.54091   0.51292   0.48861   0.46003   0.92691         1
           0.1472    <.0001    <.0001    <.0001    <.0001    <.0001
              632       640       639       638       637       640       640

  D50     -0.1015   0.53745   0.51392   0.49127    0.4703    0.7414   0.89453
           0.0107    <.0001    <.0001    <.0001    <.0001    <.0001    <.0001
              632       640       639       638       637       640       640

  D75     -0.1092   0.51694   0.49429   0.47474    0.4575    0.6829   0.82711
            0.006    <.0001    <.0001    <.0001    <.0001    <.0001    <.0001
              632       640       639       638       637       640       640

 D100      -0.061   0.25576   0.22431   0.21534   0.20683    0.4271   0.45079
           0.1258    <.0001    <.0001    <.0001    <.0001    <.0001    <.0001
              632       640       639       638       637       640       640
```

	PREC	PREC1	PLAG2	PLAG3	PLAG4	D10	D25
D125	-0.0473 0.2349 632	0.16919 <.0001 640	0.13596 0.0006 639	0.12994 0.001 638	0.12776 0.0012 637	0.34235 <.0001 640	0.34809 <.0001 640
D150	-0.0441 0.2683 632	0.11441 0.0038 640	0.07867 0.0468 639	0.07786 0.0493 638	0.07324 0.0647 637	0.18106 <.0001 640	0.12318 0.0018 640
D175	-0.0383 0.336 632	0.07605 0.0545 640	0.06027 0.128 639	0.06024 0.1285 638	0.05435 0.1707 637	0.12012 0.0023 640	-0.0148 0.7081 640

Pearson Correlation Coefficients
Prob> |r| under H0: Rho=0
Number of Observations

	D50	D75	D100	D125	D150	D175
PLAG2	0.51392 <.0001 639	0.49429 <.0001 639	0.22431 <.0001 639	0.13596 0.0006 639	0.07867 0.0468 639	0.06027 0.128 639
PLAG3	0.49127 <.0001 638	0.47474 <.0001 638	0.21534 <.0001 638	0.12994 0.001 638	0.07786 0.0493 638	0.06024 0.1285 638
PLAG4	0.4703 <.0001 637	0.4575 <.0001 637	0.20683 <.0001 637	0.12776 0.0012 637	0.07324 0.0647 637	0.05435 0.1707 637
D10	0.7414 <.0001 640	0.6829 <.0001 640	0.4271 <.0001 640	0.34235 <.0001 640	0.18106 <.0001 640	0.12012 0.0023 640
D25	0.89453 <.0001 640	0.82711 <.0001 640	0.45079 <.0001 640	0.34809 <.0001 640	0.12318 0.0018 640	-0.0148 0.7081 640

	D50	D75	D100	D125	D150	D175
D50	1	0.95947	0.51248	0.39095	0.03135	-0.1961
	<.0001	<.0001	<.0001	0.4284	<.0001	
	640	640	640	640	640	640
D75	0.95947	1	0.60244	0.46181	0.0617	-0.178
	<.0001		<.0001	<.0001	0.1189	<.0001
	640	640	640	640	640	640
D100	0.51248	0.60244	1	0.84882	0.26115	0.10183
	<.0001	<.0001		<.0001	<.0001	0.0099
	640	640	640	640	640	640
D125	0.39095	0.46181	0.84882	1	0.58413	0.36127
	<.0001	<.0001	<.0001		<.0001	<.0001
	640	640	640	640	640	640
D150	0.03135	0.0617	0.26115	0.58413	1	0.81106
	0.4284	0.1189	<.0001	<.0001		<.0001
	640	640	640	640	640	640
D175	-0.1961	-0.178	0.10183	0.36127	0.81106	1
	<.0001	<.0001	0.0099	<.0001	<.0001	
	640	640	640	640	640	640

Appendix 4.6.1 Precipitation and temperature over the range of available data

Year	Precipitation (cm)	Avg. Maximum Temperature (ºC)	Avg. Minimum Temperature (ºC)
1964	195.56	26	14
1965	157.86	25	12
1966	152.27	25	11
1967	133.22	26	11
1968	112.27	25	11
1969	176.78	25	11
1970	195.83	25	11
1971	111.53	25	12
1972	145.92	27	13
1973	155.96	26	13
1974	136.14	26	12
1975	229.74	24	11
1976	124.08	25	11
1977	140.84	27	13
1978	144.53	29	15
1979	172.34	25	12
1980	167.89	26	12
1981	126.37	26	11
1982	137.82	27	13
1983	183.49	26	12
1984	133.12	27	13
1985	172.75	27	14
1986	120.63	27	14
1987	129.52	28	14
1988	161.85	26	13
1989	190.50	27	15
1990	120.88	28	15

Appendix 5.1.1 Height growth analysis and plots

Table 5.1.1.1 Testing overall height growth from March 1969 through December 1970 using GLM procedure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.54693174	0.18231058	2.62	0.0666
Error	34	2.36562954	0.6957734		
Corrected Total	37	2.91256128			

R-Square	Coeff Var	Root MSE	HGTD Mean
0.187784	12.57756	0.263775	2.097189

Source	DF	Type III SS	Mean Square	F Value	Pr > F
SOIL	1	0.00380718	0.00380718	0.05	0.8146
SHADE	1	0.00733278	0.00733278	0.11	0.7474
SOIL*SHADE	1	0.54488824	0.54488824	7.83	0.0084*

*Means significantly different (α=0.05)

The test shows a significant shade/soil interaction.

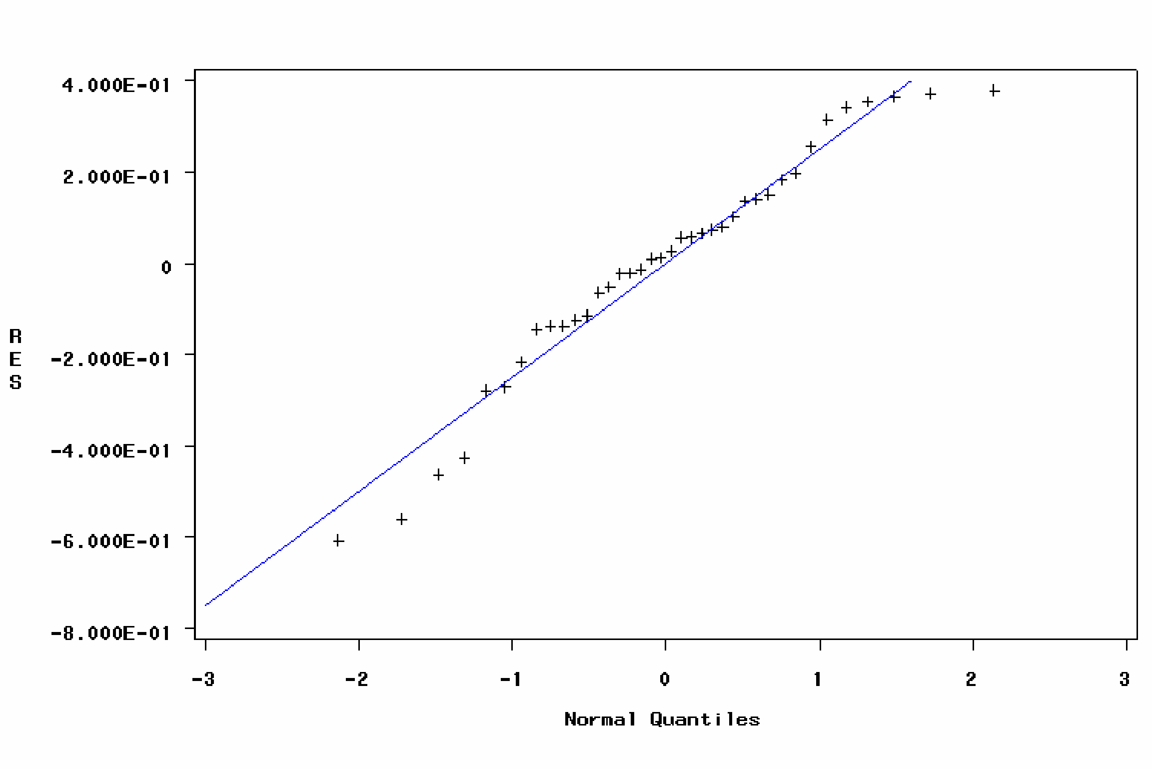
Table 5.1.1.2 Testing normality of the residuals using the UNIVARIATE Procedure

Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	0.953729	Pr < W	0.1182
Kolmogorov-Smirnov	D	0.097890	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.059277	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.453636	Pr > A-Sq	>0.2500

Univariate tests show no significant deviations from normality. The Anderson-Darling test resulted in a non significant p-value.

Figure 5.1.1.1 Testing normality of the resuiduals (res) using a QQ plot



QQ plot shows slight deviations from the line with tails, but the normality assumption is not violated.

Table 5.1.1.3 Testing homogeneity of variance of the residuals using Levene's and Bartletts's tests

Levene's Test for Homogeneity of HGTD Variance

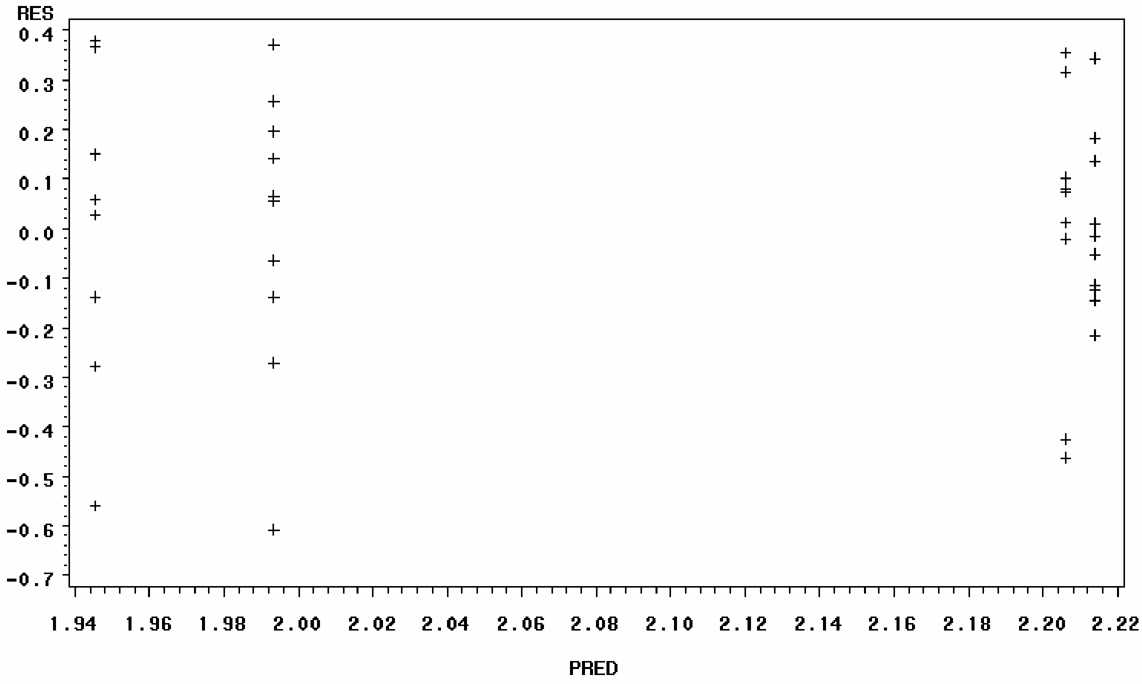
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
SOIL	1	0.000605	0.000605	0.04	0.8410
Error	36	0.533100	0.533100		

Bartlett's Test for Homogeneity of HGTD Variance

Source	DF	Chi-Square	Pr > ChiSq
SOIL	1	0.0425	0.8369

Levene's and Bartlett's tests for homogeneity of variance show no violations to the assumptions at this level of significance.

Figure 5.1.1.2 Plot of predicted (PRED) values against residuals (RES) for overall height growth



This plot does show a gap between residuals, but there does not seem to be a violation of the homogeneity of variance.

Table 5.1.1.4 Testing overall height growth from March of 1969 through December of 1970 using PROC MIXED

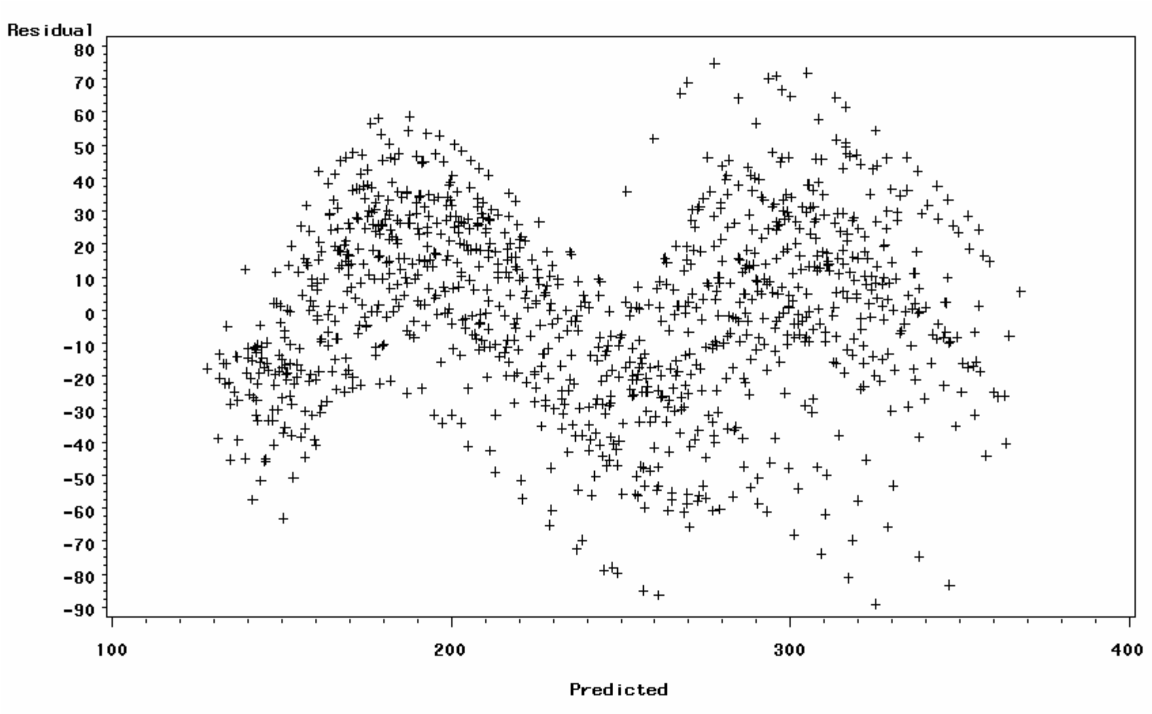
The Mixed Procedure
Type 3 Tests of Fixed Effects

Effect	DF	F Value	Pr > F
TIME	1069	4755.63	<.0001*
SOIL	1069	0.24	0.6255
SHADE	1069	0.10	0.7558
SOIL*SHADE	1069	12.67	0.0004*
TIME*SHADE	1069	0.10	0.7493
TIME*SOIL	1069	0.01	0.9277
TIME*SOIL*SHADE	1069	16.37	<.0001*

*Means significantly different (α=0.05)

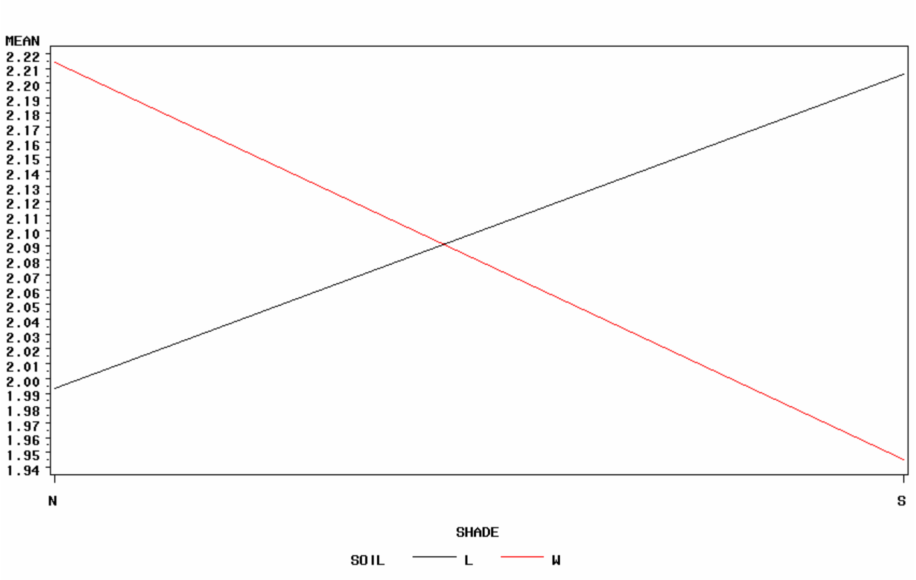
The output from PROC MIXED shows the same significant shade/soil interaction as the PROC GLM output. The normality of the residuals was tested using the same procedure used with the PROC GLM output.

Figure 5.1.1.3 Plot of predicted values against residual for overall height growth using PROC MIXED procedure



The plot shows some systematic error, but the assumptions do not seem to be violated.

Figure 5.1.1.4 Example interaction plot for soil type using PROC GLM output



To test the significant interaction from the PROC GLM output, interaction plots were created. This plot shows a significant interaction. The same plot was produced for the shade treatment, which showed an almost identical relationship.

Figure 5.1.1.5 Example interaction plot for the shade treatment using PROC GLM output

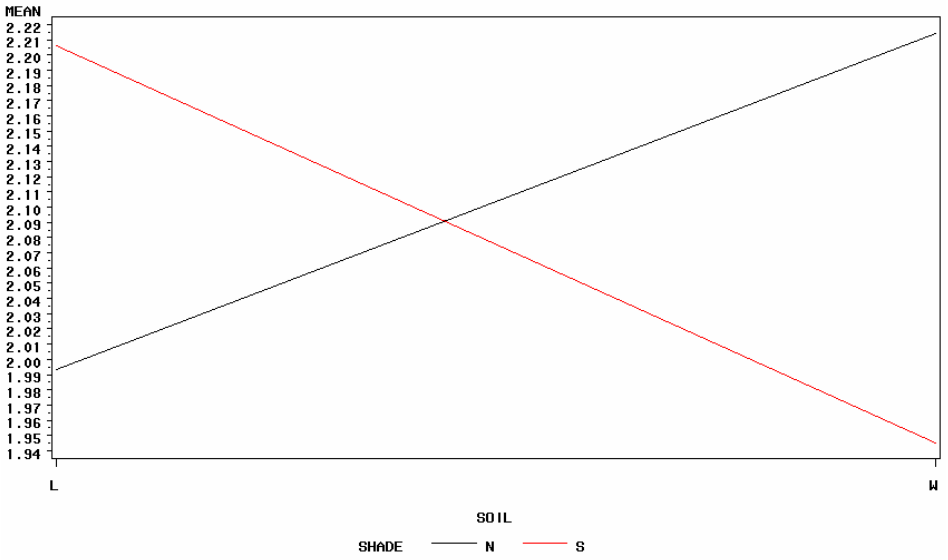


Table 5.1.1.5 Testing the for shade/soil interactions using LSD (least significant difference) multiple comparison

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t-tests (LSD) for HGM

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	34
Error Mean Square	0.069577
Critical Value of t	2.03224
Least Significant Difference	0.2471
Harmonic Mean of Cell Sizes	9.411765

NOTE: Cell sizes are not equal.

```
t Grouping   Mean        N     SSC

       A     2.2138     10     NW
       A
       A     2.206      10     SL
       A
B      A     1.9933     10     NL
B
B            1.9453      8     SW
```

Means with the same letter are not significantly different (α=0.05)

SSC = shade/soil combination, NL = no shade, Lucy soil; NW = no shade, Wagram soil; SL = shade, Lucy soil; SW = shade, Wagram soil

---

This test shows a significant difference in height growth for the shade treatment on Wagram soils. There is also a significant difference in height growth for shaded trees on both soil types.

Table 5.1.1.6 Testing the for shade/soil interactions using a ttest to test for significant differences between shade treatments within the Wagram soil type

Variable	SHADE	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev
HGM	N	10	2.0903	2.2138	2.3373	0.1188
HGM	S	8	1.6781	1.9453	2.2124	0.2113
HGM	Diff (1-2)		0.0192	0.2685	0.5178	0.1846

Variable	SHADE	Upper CL Std Dev	Std Err	Minimum	Maximum
HGM	N	0.3153	0.0546	1.997	2.556
HGM	S	0.6504	0.1130	1.385	2.324
HGM	Diff (1-2)	0.3773	0.1176		

T-Tests

Variable	Method	Variances	DF	t Value	Pr > |t|
HGM	Pooled	Equal	16	2.28	0.0364*
HGM	Satterthwaite	Unequal	10.2	2.14	0.0575

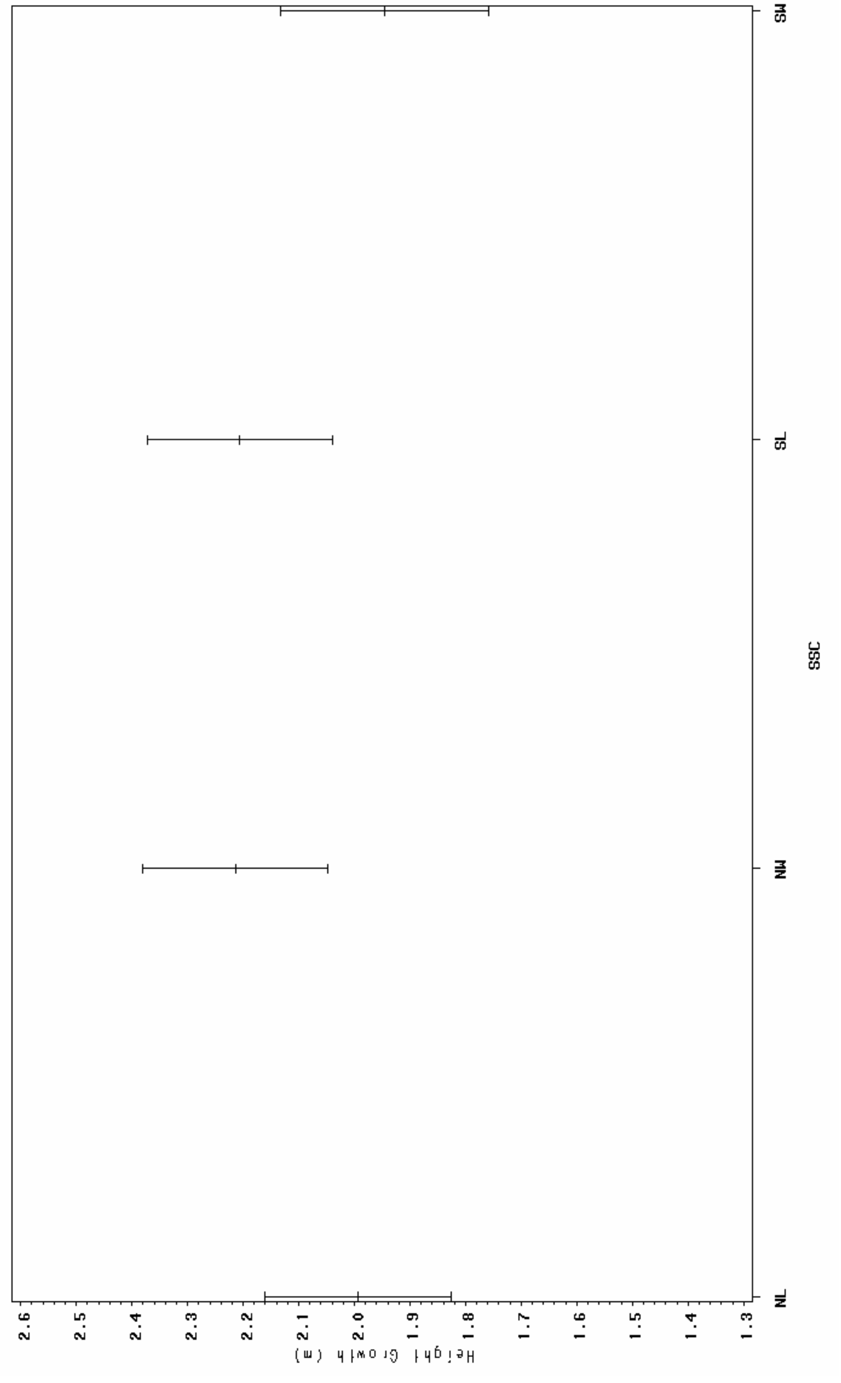
Equality of Variances

Variable	Method	Num DF	Den DF	F Value	Pr > F
HGM	Folded F	7	9	3.42	0.0899

Means with an * are significantly different (α=0.05)

This test reinforces the significant the LSD test for the significant interaction.

Figure 5.1.1.6 Plot of overall height growth means by shade/soil combination with two standard deviations: (SSC= shade/soil combination, NL = no shade, Lucy soil; NW = no shade, Wagram soil;SL = shade, Lucy soil; SW = shade, Wagram soil)



Appendix 5.4.1 Diameter growth plots

Diameter growth was evaluated over each year separately because of calibration issue during a January 1970 measurement and because of negative growth values. All tests and assumption diagnostics were conducted using the same procedures outlined in Appendix 5.1.1.

Figure 5.4.1.1 Average monthly diameter measurements by soil type

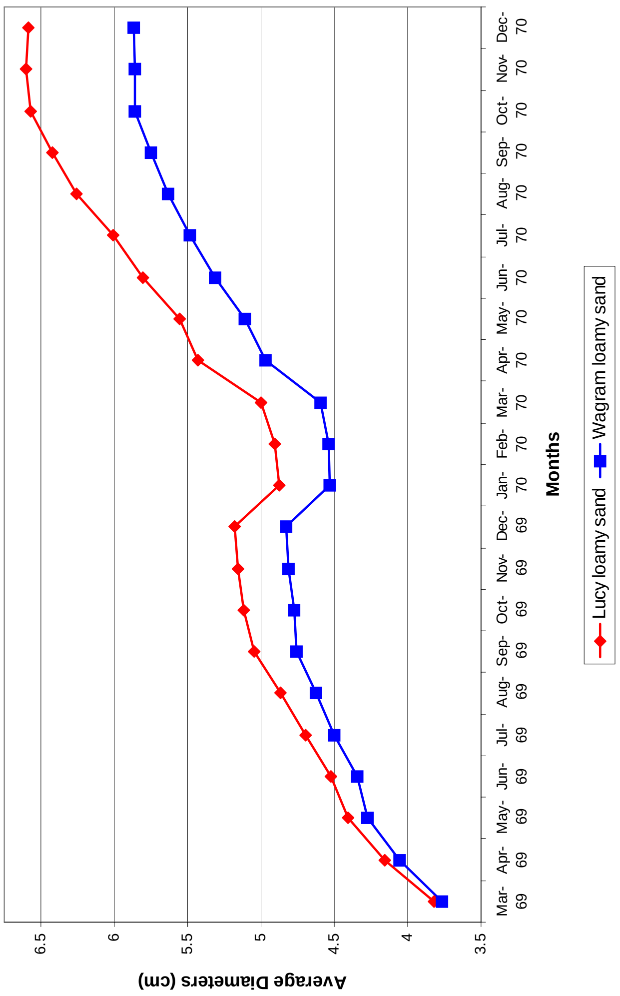


Figure 5.4.1.2 Average diameter growth by shade/soil combination for 1969 showing two standard errors: (SSC= shade/soil combination, NL = no shade, Lucy soil; NW = no shade, Wagram soil;SL = shade, Lucy soil; SW = shade, Wagram soil)

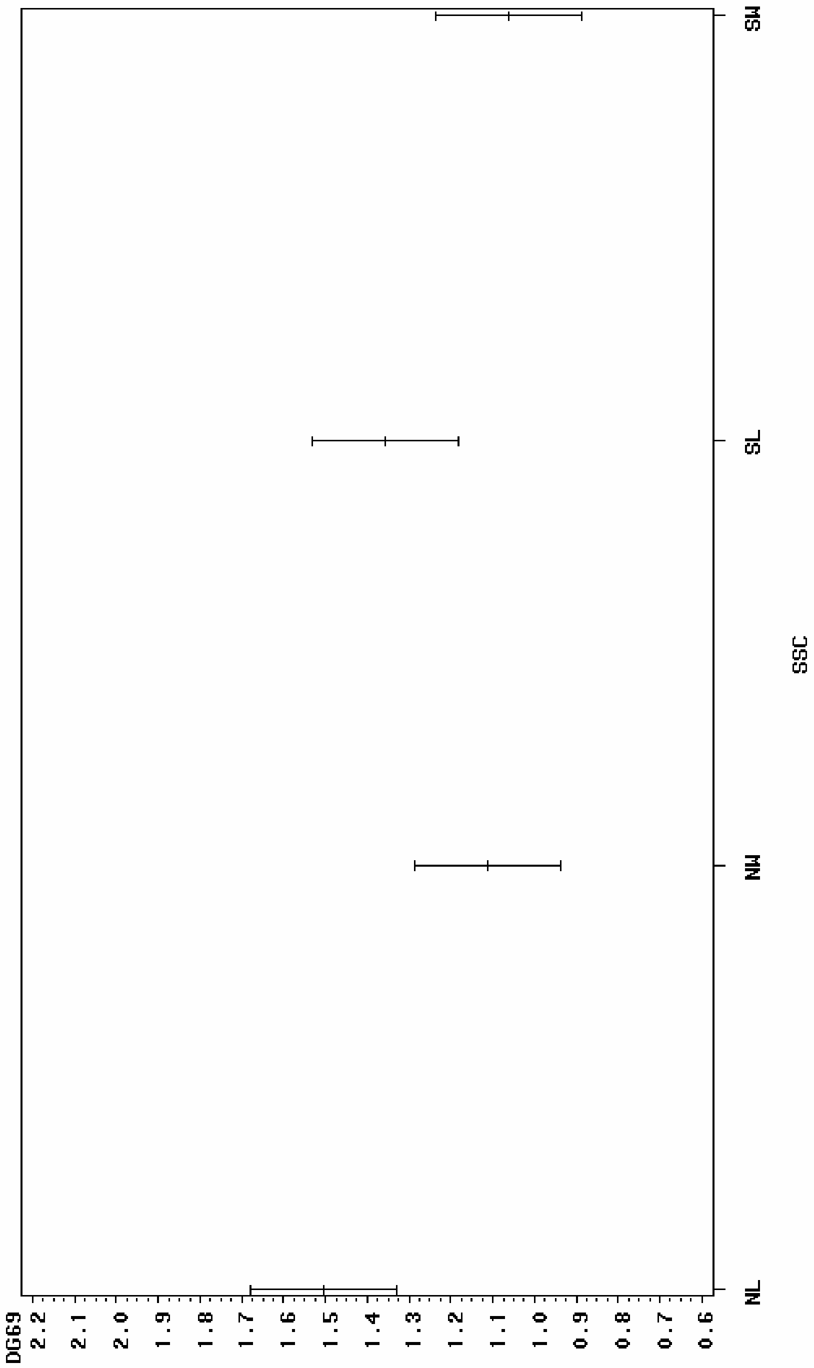
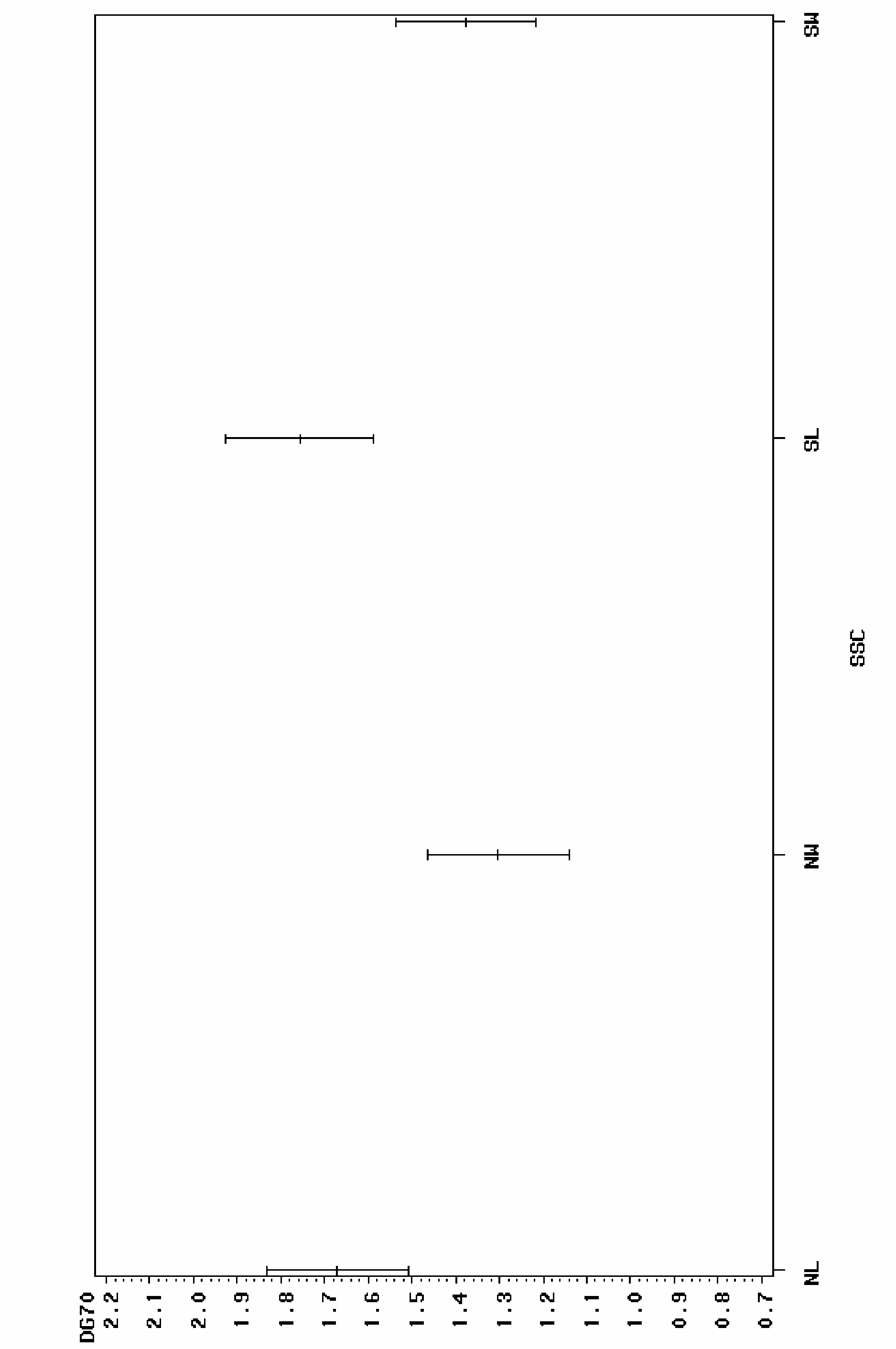


Figure 5.4.1.3 Average diameter growth by shade/soil combination for 1970 showing two standard errors: (SSC= shade/soil combination, NL = no shade, Lucy soil; NW = no shade, Wagram soil;SL = shade, Lucy soil; SW = shade, Wagram soil)



Appendix 5.6.1 Diurnal and nocturnal growth example regression

This is an example regression procedure.

Table 5.6.1.1 Regression model for dependent variable: mean nocturnal growth rate and independent variable: D55T

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.00131	0.00131	21.84	0.0002
Error	17	0.00102	0.00006019		
Corrected Total	18	0.00234			

Root MSE	0.00776	R-Square	0.5623
Dependent Mean	0.04642	Adj R-Sq	0.5365
Coeff Var	16.71326		

Parameter Estimates

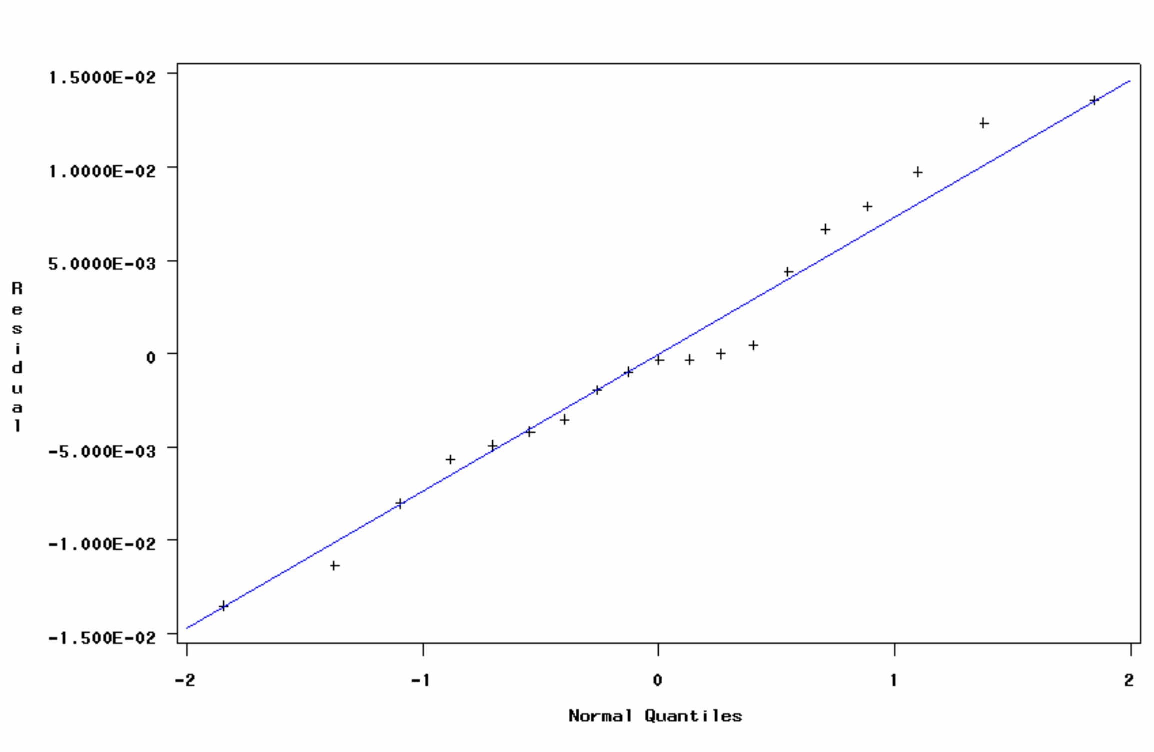
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > | t |
Intercept	1	0.01638	0.00667	2.46	0.0251
D55T	1	0.00010628	0.00002275	4.67	0.0002

Table 5.6.1.2 UNIVARIATE Procedure tests for rormality

Test		--Statistic---	-----p Value------	
Shapiro-Wilk	W	0.969524	Pr < W	0.7669
Kolmogorov-Smirnov	D	0.160899	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.047908	Pr > W-Sq	0.2500
Anderson-Darling	A-Sq	0.261653	Pr > A-Sq	0.2500

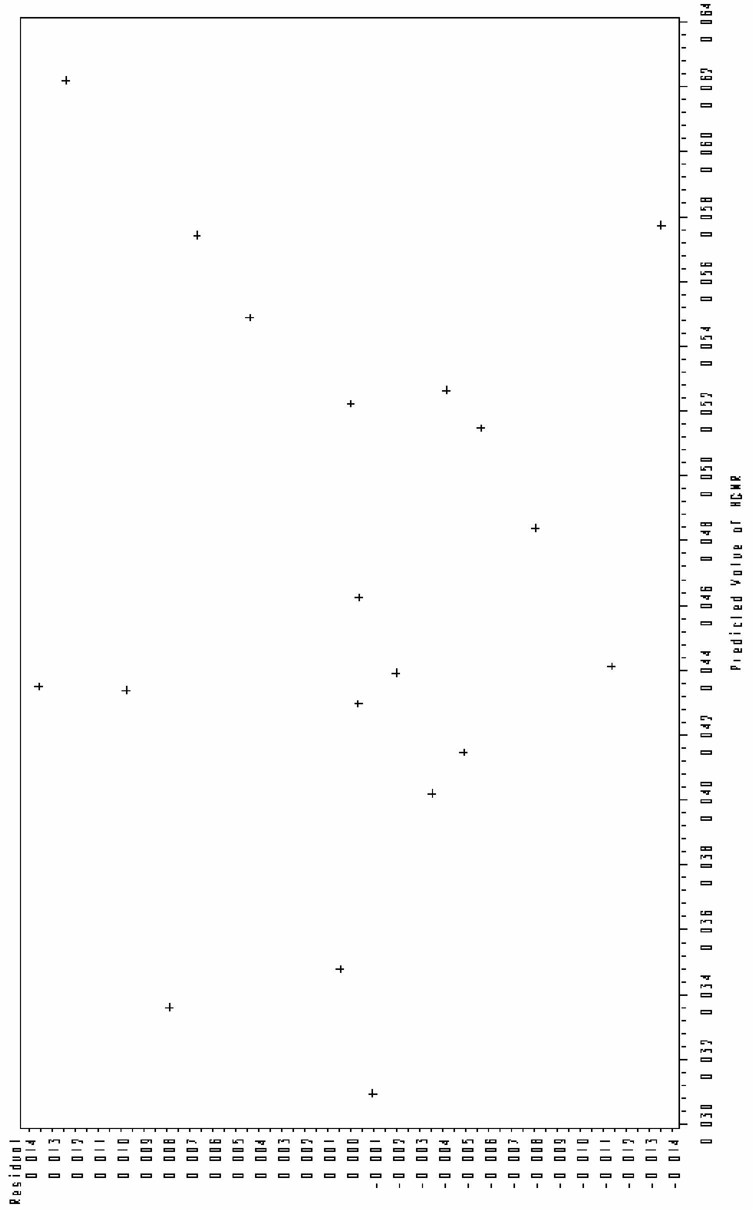
Univariate tests show not significant deviations from normality. The Anderson-Darling test resulted in a non significant p-value.

Figure 5.6.1.1 QQ plot



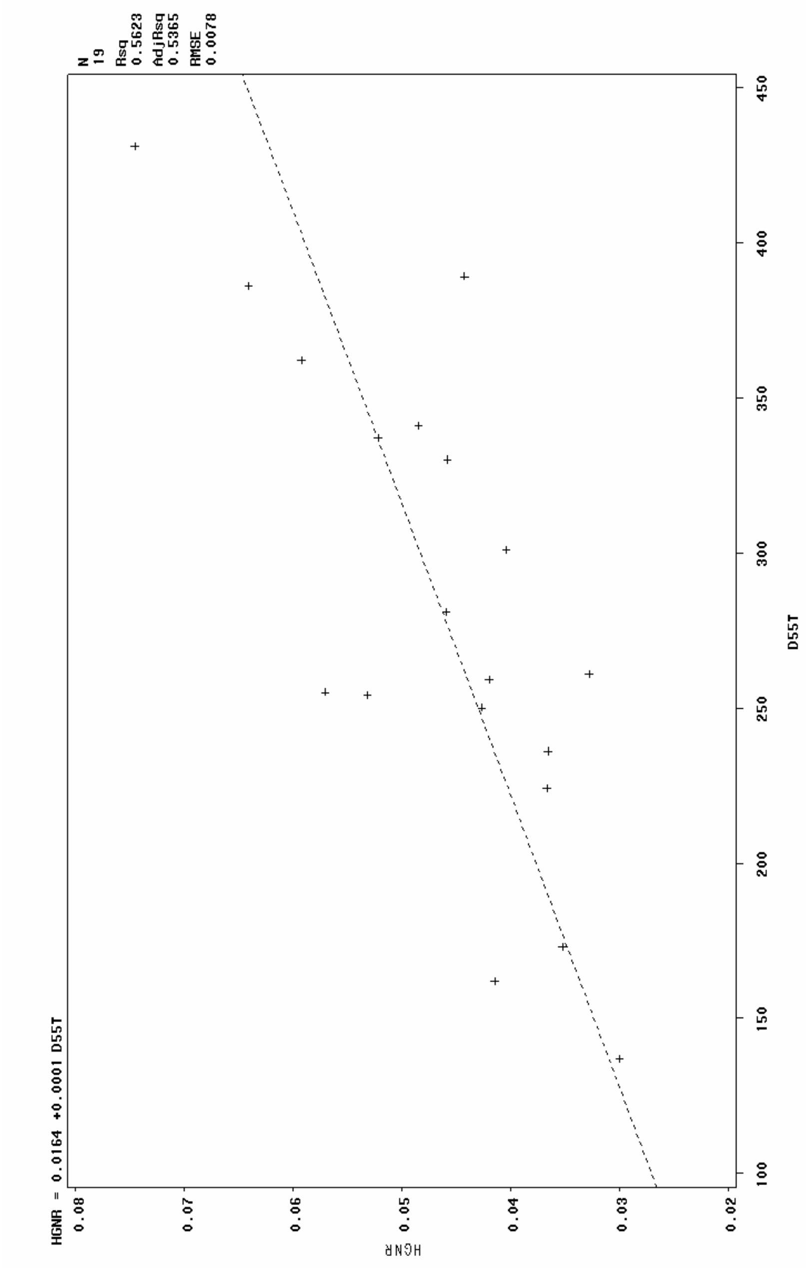
QQ plot shows slight deviations from the line with tails, but the normality assumption is not violated.

Figure 5.6.1.2 Plot of predicted values against residual for regression model
Dependent Variable: Mean Nocturnal Growth Rate
Independent Variable: D55T



This plot does not show a violation of the homogeneity of variance because of the even scatter of residuals.

Figure 5.6.1.3 Plot of regression line
Dependent Variable: Mean Nocturnal Growth Rate
Independent Variable: D55T



The plot shows even scatter of points along the regression line with no significant deviations from the assumptions.

Appendix 5.7.1 Yearly measurements analysis and plots

Table 5.7.1.1 Checking soil condition using nonparametric tests
Wilcoxon Scores (Rank Sums) for Variable Height Growth 1969 through 1981
Classified by Variable SOIL

SOIL	N	Sum of Scores	Expected Under HO	Std Dev. Under HO	Mean Score
L	17	336	306	30.298515	19.764706
W	18	294	324	30.298515	16.333333

Wilcoxon Two-Sample Test

Statistic	3.36E+02
Normal Approximation	0.9736
One-Sided Pr > Z	0.1651
Two-Sided Pr > |Z|	0.3302
t Approximation	
One-Sided Pr > Z	0.1686
Two-Sided Pr > |Z|	0.3371

Z includes a continuity correction of 0.5

Kruskal-Wallis Test

Chi-Square	0.9804
DF	1
Pr > Chi-Square	0.3221

The test showed no significant difference in mean height growth by soil type because the pvalues (Pr >) were greater than the 0.05 level of significance.

Figure 5.7.1.1 Average yearly height measurements from 1969 through 1981

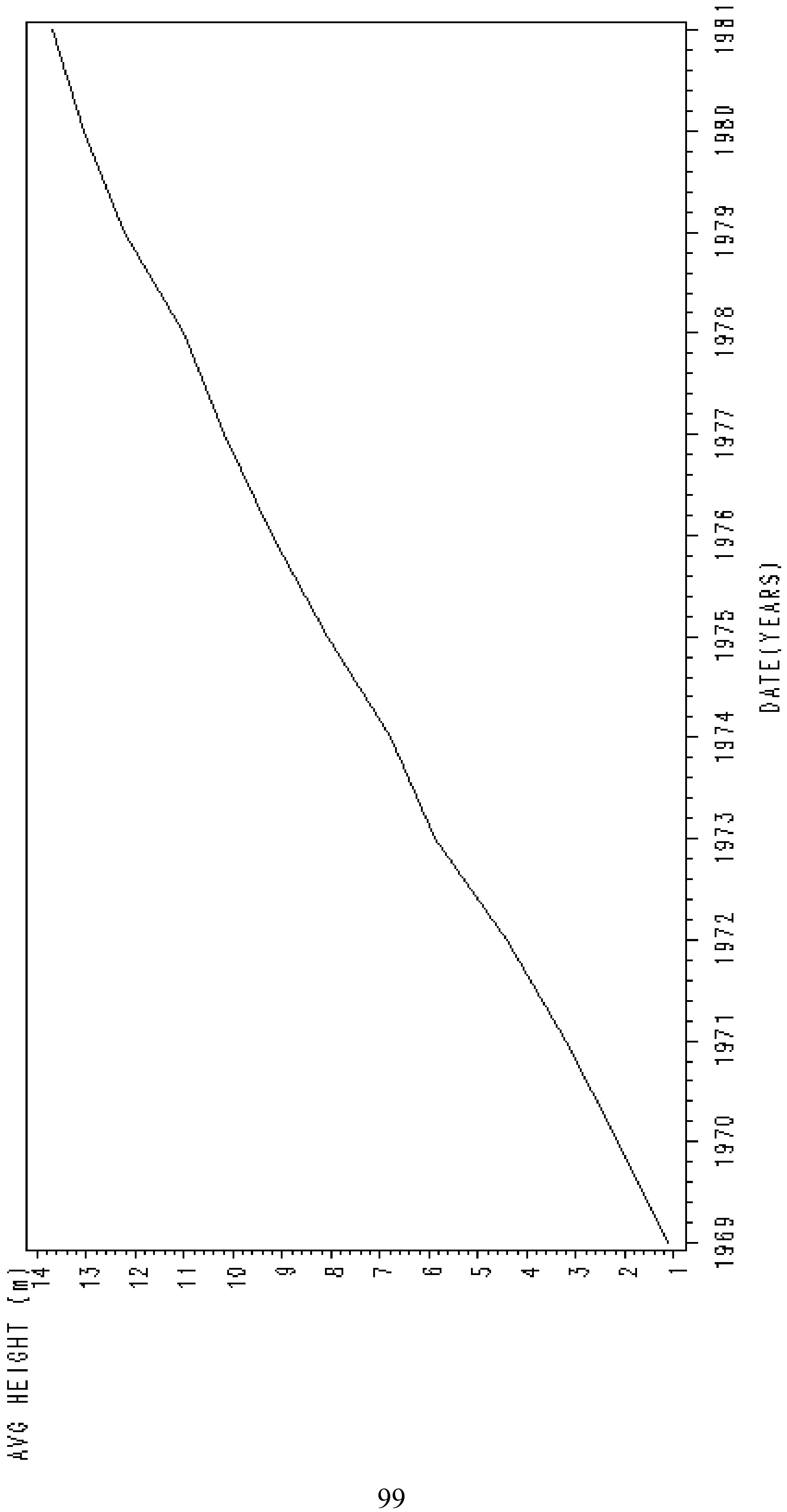


Figure 5.7.1.2 Average yearly height growth from 1969 through 1981

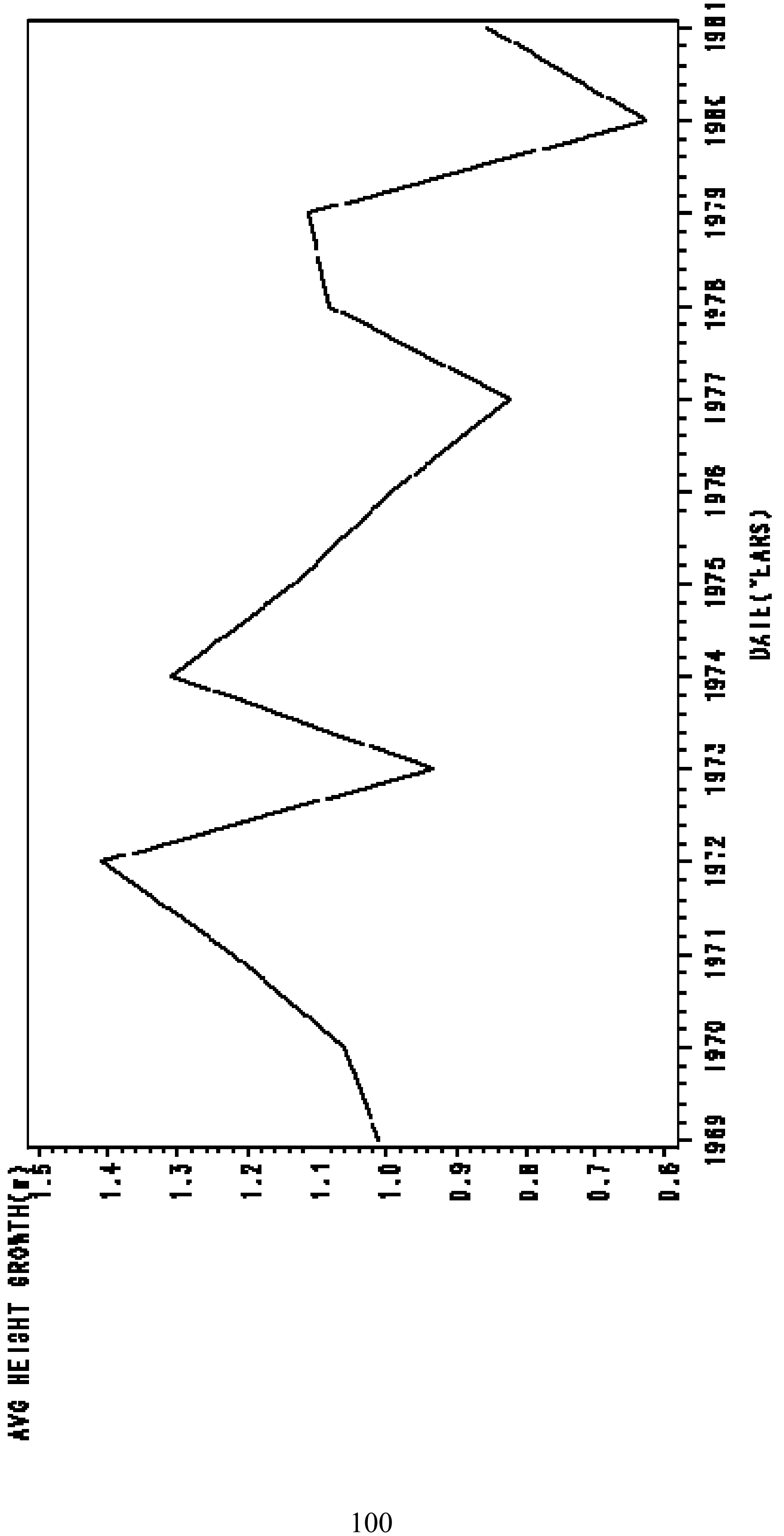


Figure 5.7.1.3 Average yearly diameter growth from 1972 through 1981

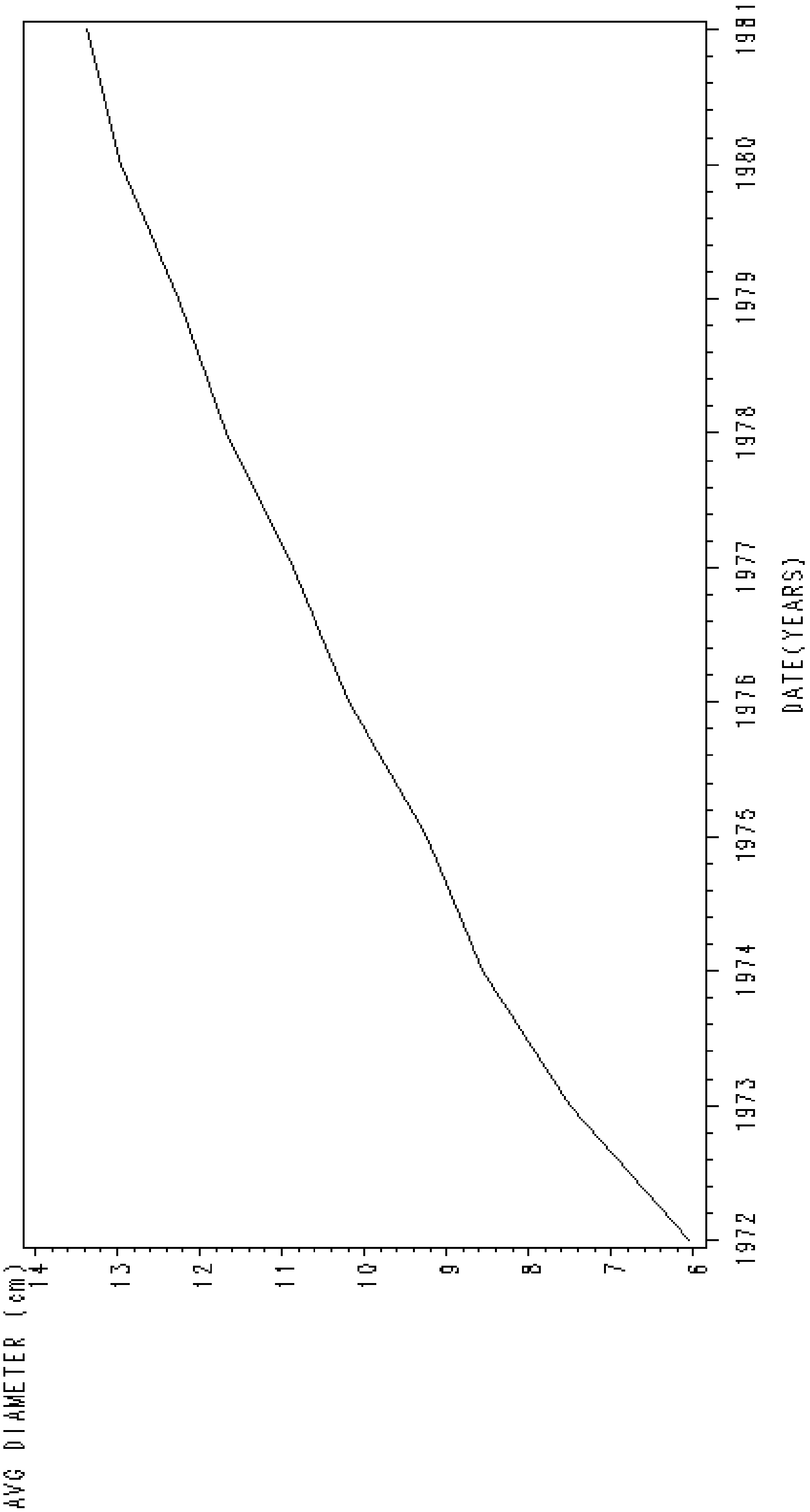


Figure 5.7.1.4 Average yearly diameter growth from 1972 through 1981