CLIMATIC EFFECTS ON THE FIRST AND SECOND ROTATION DOMINANT AND CODOMINANT HEIGHTS FOR FLATWOODS SLASH PINE PLANTATIONS: AGE 20 RESULTS

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EXECUTIVE SUMMARY

A slash pine (*Pinus elliottii* Engelm.) successive rotation plantation study was established in 1978-79 for the North Florida and South Georgia flatwoods. Five installations were established in four soil types for a total of 20 installations. Plantations that were drained or fertilized were excluded from this experiment. Installations selected were at least 20 years old and based upon uniformity of site index and soil classes. One plot at each installation was designated as the second rotation productivity plot. The second rotation productivity plots duplicated the first rotation's seed source, site preparation, planting method and density. The other 12 plots at each installation encompass a slash pine site preparation, fertilization, and vegetation control study, and results from these plots have been reported in several publications, e.g. Shiver et al. (1990), Pienaar and Rheney (1993), Pienaar et al. (1996). The study objective is to compare the mean dominant/codominant height growth for the first and second rotation productivity plots.

The first rotation was harvested in 1978 and site preparations were applied in 1978-79. The productivity plots were established using 1-0 slash pine seedlings during the 1979-80 planting season. Prior to harvesting rotation 1, six dominant/codominant trees were randomly selected for stem analysis. For rotation 2, one-half of the trees within each plot were randomly selected for height measurement with the heights of these trees recorded at each measurement period. The height measurements for rotation 2 have been recorded on a 3-year cycle beginning at age 2, and currently are recorded to age 20.

A mixed model was used to obtain point estimates by rotation and plot for ages 2, 5, 8, 11, 14, 17, and 20. A split plot unbalanced mixed model was used to compare rotation differences by age using the point estimates. The soil type was treated as the whole plot and rotation as the split plot. The soil types and rotations were considered fixed effects and the plots within a soil type were considered the random effect. The comparison between the two rotations is based upon the mean dominant/codominant height differential across a range of soil types and ages. There is a significant rotation 1 minus rotation 2 mean dominant/codominant height difference across the sites for all ages.

Rotation 1 is 1.9 and 5.4 feet higher, on average, for mean dominant/codominant height at ages 2 and 20, respectively. The height differential is generally more significant for the spodosol soil type than the non-spodosol soil type.

The climatic surface data was obtained from the National Climatic Data Center (NCDC). A total of 12 different weather stations were obtained. The climatic surface data was used to detect climatic differences between the rotations, primarily for precipitation. An unbalanced split-plot mixed model was used to test for precipitation differences between the rotations. The plots within a rotation are treated as random to make region wide inferences. In addition, the Standardized Precipitation Index (SPI) and its classification system developed by McKee et al. (1993) were computed to determine if and when any drought events occurred for both rotations. Rotation 1 generally experienced more favorable precipitation, for both the total amount and timing of the precipitation within a year, than rotation 2. Rotation 2 experienced drought events and high growing season average temperatures during the first two growing seasons, while rotation 1 was near normal for this period.

The second rotation, on average, exhibits a mean dominant/codominant height reduction relative to rotation 1. The main competition for both rotations is gallberry and saw palmetto, but not necessarily at the same densities, therefore competition is unlikely the main factor for the mean dominant/codominant height growth loss experienced by rotation 2. Genetics is unlikely the major factor for the height differential between rotations 1 and 2 because the genetic stock was the same for both rotations. A nutrient deficiency can't be eliminated as a major contributor to the R1-R2 height differential because no nutrient information is available. This study's evidence implies that, although there are some plot anomalies, climate is likely a major source contributing to the decrease in mean dominant/codominant height for rotation 2. The evidence from the second rotation productivity and site preparation, fertilization, and vegetation control study plots suggest that, given less favorable climatic conditions, the mean dominant/codominant height growth may be maintained or enhanced using intensive forest management techniques.

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INTRODUCTION

Plantation forestry has an enormous economic impact on the Southeastern United States. As the demands for forest products to increases, there has been an escalating interest in accessing successive plantation productivity. Maintaining or increasing site productivity is an important economic consideration in the Southeastern United States. During the past several decades, there have been conflicting reports with respect to successive rotation productivity (e.g., Thomas 1961, Keeves 1966, Boardman 1978, Haywood 1994). This issue was addressed by implementing a successive rotation productivity study for slash pine (*Pinus elliottii* Engelm.) plantations in the North Florida and South Georgia flatwoods. A treatment plot at each installation was selected to duplicate the first rotation seed source, site preparation, planting method, and density. The assumption is that the only difference between the two rotations is the intrinsic productivity of the site, which includes competition and climatic fluctuations.

Keeves (1966) presented evidence that successive plantations of Monterey pine (*Pinus radiata* D. Don) in South Australia had declined from one to three site quality classes across a spectrum of sites. There was a significant drop in basal area per acre for the second rotation versus the first rotation, but a correlation between the loss of productivity and site quality was not found. There was a reported decline for a second rotation Monterrey pine plantation in South Australia (Thomas 1961), but an analysis performed by Boardman (1978) confirmed no long-term loss in site productivity for the same sites under three successive rotations. Boardman (1978) inferred that the decline in the second rotation site productivity reported by Thomas (1961) was likely caused by severe weather during the first three years of the second rotation. The evidence in South Australia points to a net effect from several mitigating factors (e.g., nutrient deficiency, precipitation, temperatures) rather than a single dominant cause that results in a decline in successive pine plantation productivity (DeVries et al. 1972, Boardman 1978).

There is some controversy over reported declining forest growth in the Southeastern United States. The Forest Inventory and Analysis unit (FIA) of the Southeastern Forest

Experiment Station has reported decreasing average radial growth in the Southeast for naturally regenerated southern pines (Sheffield et al., 1985). Two studies using FIA data to analyze naturally regenerated forest stands have reported declining growth in Georgia and Alabama (Bechtold et al., 1991 and Ruark et al., 1991). After analyzing the FIA data used by Sheffield et al. (1985), Bechtold et al. (1991), and Ruark et al. (1991), Zeide (1992) concluded that by changing the FIA data collection protocol for the third inventory in 1961, when the Forest Service switched from fixed plots to point sampling, "no reliable evidence of reduction in basal area growth of southern pines after 1972 can be derived from the FIA data." A pattern of declining growth was reported for Southeastern forests using tree data from Georgia, North Carolina, and South Carolina (Zahner, 1989). This study reported a decline of 36% in radial growth between 1949 and 1984 after factoring for stand structure, tree age, and drought. Plots maintained by International Paper Company were analyzed, and it was reported that some dbh classes increased basal area growth while other dbh classes had no growth rate change from 1972-82 (Cleveland et al., 1992).

There is some evidence of declining second rotation growth rates for loblolly (*Pinus taeda* L.) and slash pines when grown on the same sites (Haywood 1994, Haywood and Tiarks 1995). This study minimized woody competition and maintained grass as the principle competitor. By age seven, loblolly dramatically and slash pine moderately decreased in height growth rates for the second rotation. A study limitation is that it was undertaken at only one site for both loblolly and slash pine. The rainfall pattern during the first seven years was not significantly different for the two rotations. Loblolly pine is known to be more sensitive than slash pine to phosphorus deficiencies on aquult and udult soils in the lower Gulf Coast (Tiarks and Shoulders 1982). The greater decline in loblolly height growth in comparison to slash pine likely indicates that a nutrient deficiency is a major contributing factor in average height reduction growth in the second rotation.

Site productivity is the sum of environmental factors that includes soils, topography, temperature, competition, and precipitation. A major contributor for decreasing forest growth is likely nutrient deficiency, which accelerates as a tree ages (Proe and Dutch, 1994). A disadvantage of whole tree harvesting versus conventional harvesting is the additional loss of nutrients (Kimmins 1987). Additionally, silvicultural treatments and variations in allogenic factors can have an impact on successive rotation productivity (Squire et al. 1985, Boardman 1978). Second rotation productivity for slash pine may be maintained if harvesting disturbance is minimized and nutrient levels are maintained (Tiarks and Haywood 1996).

The objectives of this study are to compare the productivity and climatic surface data (precipitation and temperature) for the first and second rotation slash pine for North Florida and South Georgia flatwoods plantations. The productivity comparison will be based upon the average dominant/codominant height differential between rotations 1 and 2 across a range of sites and ages. Rotations 1 and 2 are contrasted by soil types and across the soil types at ages 2, 5, 8, 11, 14, 17, and 20. The precipitation comparison will be based upon the yearly and monthly total precipitation for the respective rotation. The climatic surface data will also be used to assess any drought events and/or extreme temperature fluctuations by rotation.

DATA

During the spring of 1978, 20 installations were established on non-old-field plantation slash pine sites in the flatwoods of South Georgia and North Florida. One plot at each installation was designated as the second rotation productivity plot. The other 12 plots at each installation encompass a slash pine site preparation, fertilization, and vegetation control study, and results from these plots have been reported in several publications, e.g. Shiver et al. (1990), Pienaar and Rheney (1993), Pienaar et al. (1996). This study focuses on the second rotation productivity plots. Plantations that were drained or fertilized were excluded from this experiment. Installations selected were at least 20 years old and based upon uniformity of site index and soil classes. Five installations were established in each of the following four soil classes:

I) poorly drained non-spodosol,
II) somewhat poorly to moderately drained non-spodosol,
III) poorly to moderately drained spodosol with an underlying argillic horizon, and
IV) poorly to moderately drained spodosol with no underlying argillic horizon.

Each installation consists of 13 0.5-acre treatment plots with one plot considered the plantation productivity (previous treatment) plot. A soil profile description was made from auger cores on the “previous treatment" plot. The site index (base age 25) was based upon measurements taken on trees from the first rotation. The site indexes ranged from 55 to approximately 80 for the 20 installations. The previous treatment plot at each installation was designed to replicate, as accurately as possible, the characteristics and preparations of the first rotation for a given installation. The previous treatment plot’s seed source, site preparation method, planting method and density replicated those of the first rotation at each installation. Currently only 16 of the original 20 installations remain.

The first rotation was harvested in 1978, and site preparation treatments were applied in 1978-79. The previous treatment plots were hand planted using the first rotation spacing design, which varied by location, during the 1979-80 planting season with 1-0 slash pine seedlings.

First Rotation Data Collection

The following information was collected from the plot randomly chosen to be considered the "previous treatment" plot at each location prior to harvesting the first rotation plots in 1978. All trees within the plot were measured for dbh, total height, crown class, and presence or absence of cronartium (*Cronartium fusiforme*, Hedgc. and Hunt). Additionally, six dominant/co-dominant trees were randomly selected from the previous treatment plot for stem analysis, with disks cut at six inches above the ground, five feet above ground, and thereafter, at five-foot intervals. Ring counts and radius from the pith to the first ring was determined for each disk, and the top disk was also measured for diameter inside bark. The outside bark diameter was measured for each disk.

Second Rotation Data Collection

A 0.2-acre measurement plot was approximately centered in the previous treatment plots. The plot corners were established halfway between rows and trees within rows when possible to remove bias of plot characteristics on a per acre basis. All trees within the measurement plots were measured for dbh with the crown class and presence or absence of cronartium recorded. Additionally, one-half of the trees were randomly selected for height measurement with the height being measured on these trees at each measurement period. The second rotation previous treatment plots have been measured on a three-year cycle beginning at age 2 and currently are recorded to age 20.

Climate Data

The climate surface data for a given installation was obtained from the National Climatic Data Center (NCDC), which is a division of the National Oceanographic and Atmospheric Administration (NOAA), via their web site. The climate data was obtained from the nearest viable weather station for a given plot. A viable weather station was defined as a station containing the monthly precipitation and temperature information for both rotations. Twelve different weather stations were obtained using this selection method. Most of the viable weather stations were within 5-10 miles of the plots, but some weather stations were approximately 25 miles from the plots. Since there are 16 plots and only 12 viable weather stations, some plots used the climatic surface data from the same weather station. Not all the plantations harvested in 1978 were the same age, therefore the first rotation initial year used for these duplicate weather stations may differ depending upon the year in which a plot's first rotation was planted. The climatic surface data from these weather stations contains the monthly mean temperatures and total monthly precipitation. Unfortunately these stations do not contain information about total monthly evaporation or the length of time for the evaporation data was insufficient.

METHODOLOGY

A two step process was used to assess the mean dominant/codominant height differential for rotations 1 and 2. The first step was to obtain estimates of the mean dominant/codominant heights by rotation and plot for the age classes 2, 5, 8, 11, 14, 17, and 20. Secondly, the mean dominant/codominant height point estimates were used to perform an ANOVA by age class. The ANOVA was used to test for mean dominant/codominant height differences between rotations for all age classes by soil type. An ANOVA was also performed to test for average annual precipitation differences between the rotations. In addition, the climatic surface data was also used to assess drought events and extreme temperature fluctuations by rotation.

Mean Dominant/Codominant Height Estimation

Point estimates for the first and second rotation mean dominant/codominant height at ages 2, 5, 8, 11, 14, 17, and 20 were obtained for each rotation and plot. The rotation 1 stem analysis data for the six trees sampled within each plot were pooled to model mean dominant/codominant height for each plot. For rotation 2, a random sample of six dominant/co-dominant trees was selected from each plot at age 20; and the dominant/codominant heights were obtained for ages 8, 11, 14, 17 and 20. These rotation 2 six randomly selected trees can't be traced back to age 2, because tag numbers don't exist for ages 2 and 5. Therefore the following alternative method was devised for randomly selecting six trees at ages 2 and 5 for rotation 2. The height classes for each installation were expressed by age 11 and the percentage of trees at age 11 in the dominant/codominant height class was estimated. A subset of trees for ages 2 and 5 was selected by using the percentage, e.g., if the percentage was 50.0, then the tallest 50.0% of the observed trees were retained in the subset. Then six trees were randomly selected from these subsets at ages 2 and 5 for each plot.

A mixed model was used to obtain point estimates of mean dominant/codominant height by rotation and plot to account for within and between tree(s) correlations. Rotations 1 and 2 were fitted to the following model separately by plot to obtain point estimates for the mean dominant/codominant heights at ages 2, 5, 8, 11, 14, 17, and 20.

$$H_{ij} = \beta_0 + \beta_1 A + \beta_2 A^2 + \varepsilon_{ij} \qquad \mathbf{(1)}$$

Where:

H_{ij} is the height of the j^{th} tree on the i^{th} installation,
A is the tree age,
ε_{ij} is the random error associated with the j^{th} tree on the i^{th} installation and
β's are plot and rotation specific.

Model 1 was chosen based upon preliminary results of fitting the model by rotation and plot using ordinary least squares (OLS). The OLS results revealed a good fit ($r^2 > 0.90$ for all plots) and no serious departures from the homogeneous variance assumption. Model 1 was fitted using SAS PROC MIXED, with the RANDOM statement modeling the variation between trees on the same plot, and the REPEATED statement modeling the variation within a tree over time (Littell et al. 1996). Thus, trees within a plot were treated as random.

The covariance structure specification is an important part of the model identification process to insure the reliability of predictions (Gregoire et al. 1995). The criteria used to determine which covariance function provided the best fit were Akaike's Information Criterion (AIC) and Schwarz's Bayesian Criterion (BIC). The AIC and BIC criteria are analogous to the adjusted r^2 in multiple regression in that they impose a penalty for additional parameters. A log-likelihood ratio test for Model 1 was performed to determine if the among and within trees correlation's modeled using the RANDOM and REPEATED statements in SAS PROC MIXED for trees within a plot were significant.

Mean dominant/Codominant Height ANOVA Methods

A split-plot model was used to test for rotation differences using the point estimates for each rotation by plot obtained from Model 1. The current data results in an unbalanced split-plot model because the replications per soil type are not equal due to the loss of some plots. Soil type was treated as the whole plot and rotation as the split-plot. The plots within a soil type were treated as random effects to make inferences across the region. The statistical model used is:

$$H_{ijk} = \mu + \tau_i + \varepsilon_{ij} + \beta_k + (\tau\beta)_{ik} + e_{ijk} \tag{2}$$

Where:

H_{ijk} is the mean dominant/codominant height for the j^{th} plot and i^{th} soil type of rotation k,

μ is the overall mean,

τ_i is the i^{th} soil type effect (whole plot),

ε_{ij} is the whole plot error term (random error on plot j in soil type i),

β_k is the rotation effect,

$(\tau\beta)_{ik}$ is the soil type and rotation interaction effect, and

e_{ijk} is the split plot error term (random error for plot j in soil type i and rotation k).

Climatic Surface Data Assessment Methods

An unbalanced split-plot mixed model was used to test for precipitation differences between the rotations. The rotations are treated as the whole plot effect and time is the split-plot effect. The plots within a rotation are treated as random to make region wide inferences. The serial correlation for a plot within a rotation was modeled using the REPEATED statement in SAS PROC MIXED. The serial correlation is a function of the distance (d) between times i and j, ($f(d_{ij})$). The split-plot statistical model is

$$P_{ijk} = \mu_{\dots} + \rho_{i(j)} + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \delta_{ijk} \qquad \textbf{(3)}$$

where:

P_{ijk} is the annual precipitation for plot i of rotation j at time k,

$\mu_{\dots}$ is the overall mean,

$\rho_{i(j)}$ is the plot (rotation) main effect and are independent $N(0, \sigma_\rho^2)$

α_j is the rotation main effect,

β_k is the age main effect,

$(\alpha\beta)_{jk}$ is the rotation and age interaction effect,

δ_{ijk} is the within plot serial correlation error and are independent $N(0, \sigma^2 [f(d_{jk})])$,

$\rho_{i(j)}$ and δ_{ijk} are independent, $i = 1, 2, \dots, n_k$: $j = 1, 2$; $k = 1, 2, \dots, 20$.

The Standardized Precipitation Index (SPI) and its classification system developed by McKee et al. (1993) (Table 1) was computed to quantify yearly and monthly precipitation by rotation. The SPI was calculated using the 69 years of precipitation data available from these weather stations. The precipitation data is fitted to an appropriate probability distribution, which is then transformed into a standard normal distribution. The positive and negative SPI values indicate wetter and dryer than normal precipitation, respectively. McKee et al. (1993) defined a drought event as when the SPI is continuously negative and falls to -1.0 or less. The drought event ends when the SPI becomes positive, therefore the drought event length is defined. The drought magnitude is the sum of the absolute values for all the months or years within a drought event.

Table 1. The Standardized Precipitation Index (SPI) values and their interpretation (McKee et al. 1993).

SPI value	Interpretation
2.0 and greater	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2.0 and less	Extremely dry

The average annual and summer temperatures were computed by installation and for the region to assess when or if a rotation experienced extreme temperature fluctuations. The annual and summer temperatures were calculated both as an average for the 16 installations and for each installation individually by rotation. A 69-year weighted average for temperature and precipitation was computed for the average of the 16 installations. The weighted average was used for the 16 installations because the number of years available for the climatic surface data fluctuated among the stations.

Dominant/Codominant Height Growth Results

The mixed model used to obtain point estimates of mean dominant/codominant height by rotation and plot (Model 1) revealed that the among trees within a plot and within a tree variance components are significant. The among trees within a plot log-likelihood ratio test statistic for plot 1 of rotation 1 is 18.65, and the corresponding $\chi^2_{(1)}$ p-value is less than 0.005. Similarly, the within tree and plot serial correlation p-value is less than 0.05 for the log-likelihood ratio test for plot 1 of rotation 1. This indicates a significant amount of within tree and among tree correlation for plot 1 of rotation 1 with the other plots for both rotations exhibiting similar results.

The point estimates obtained from Model 1 by plot and rotation for the mean dominant/codominant heights are summarized in Tables 2 and 3. The summary statistics for the average of the 16 plots illustrate that by age 2, rotation 1 mean dominant/codominant height is substantially higher than rotation 2. The rotation 1 minus rotation 2 (R1-R2) height differential increased by age 20 to 5.7 feet. The mean dominant/codominant heights for rotation 2 are smaller for all soil types and ages. The standard error is smaller for rotation 2 with respect to the younger age classes except for soil type IV. Soil type II exhibits the greatest R1-R2 height differential for ages 2-14 and soil type IV has the largest height differential for ages 17 and 20.

Table 2. Summary statistics by rotation for the slash pine average dominant/codominant height (ft) by pooled, spodosols, and non-spodosols soil types obtained using Model 1.

		Soil Type					
		Pooled		Spodosols		Non-Spodosols	
Age		Rotation 1	Rotation 2	Rotation 1	Rotation 2	Rotation 1	Rotation 2
2	Mean Height	3.9	2.0	3.4	2.0	4.5	2.0
	Standard Error	0.33	0.20	0.37	0.33	0.53	0.20
5	Mean Height	13.8	10.6	12.7	9.70	15.2	11.7
	Standard Error	0.70	0.55	0.72	0.68	1.14	0.75
8	Mean Height	23.3	18.9	21.7	17.4	25.3	20.9
	Standard Error	0.99	0.92	0.99	1.03	1.64	1.37
11	Mean Height	32.3	27.1	30.4	25.1	34.7	29.7
	Standard Error	1.19	1.22	1.18	1.32	1.98	1.90
14	Mean Height	40.7	35.1	38.7	32.9	43.3	38.0
	Standard Error	1.31	1.48	1.35	1.59	2.16	2.40
17	Mean Height	48.7	43.0	46.7	40.7	51.3	45.9
	Standard Error	1.39	1.73	1.58	1.88	2.20	2.92
20	Mean Height	56.3	50.6	54.4	48.5	58.6	53.3
	Standard Error	1.49	2.03	1.93	2.25	2.14	3.55

Table 3. The slash pine average dominant/codominant height (ft) summary statistics by soil types I, II, III, and IV for both rotations using Model 1.

		Soil Type							
		I		II		III		IV	
Age		R1	R2	R1	R2	R1	R2	R1	R2
2	Mean Height	3.5	2.1	5.2	2.0	3.6	2.1	3.1	1.9
	Standard Error	0.55	0.47	0.62	0.16	0.75	0.52	0.44	0.47
5	Mean Height	13.4	11.5	16.6	11.8	13.3	10.4	11.6	9.10
	Standard Error	0.88	1.04	1.64	1.18	1.40	1.20	0.61	0.77
8	Mean Height	22.9	20.5	27.1	21.2	22.6	18.7	21.0	16.4
	Standard Error	1.38	1.81	2.46	2.20	1.75	1.59	1.17	1.30
11	Mean Height	32.1	29.3	36.6	29.9	31.4	26.8	29.5	23.8
	Standard Error	1.73	2.37	3.06	3.12	1.82	1.70	1.61	1.87
14	Mean Height	40.9	37.8	45.2	38.2	39.8	34.9	37.9	31.3
	Standard Error	1.89	2.96	3.45	3.96	1.63	1.56	2.14	2.49
17	Mean Height	49.3	45.9	52.9	45.9	47.6	42.9	46.0	38.9
	Standard Error	1.86	3.89	3.66	4.72	1.24	1.27	2.78	3.17
20	Mean Height	57.3	53.8	59.6	53.0	55.0	50.8	54.0	46.6
	Standard Error	1.63	5.41	3.74	5.41	0.99	1.17	3.57	3.94

The point estimates by rotation and plot were used to make inferences for the seven age classes across the spectrum of sites and by soil type. The profile plots for height by rotation for soil type and across the spectrum illustrate that the mean height for rotation 1 is consistently higher than rotation 2. The profile plot by rotation for the spectrum of soil types (Figure 1) illustrates little interaction, which implies that height is an additive effect of rotation and age. The R1-R2 height differential gradually increases across the data range. Figure 2 illustrates the profile plots for non-spodosol soil types I and II. The profiles of soil types I and II indicates no interaction between rotation and age. The R1-R2 height differential for soil type I is less severe than the other soil types but does gradually increase as age increases. For soil type II, the R1-R2 height differential gradually increases between ages 2 and 8. After age 8, the profiles appear parallel across the range of the data. Figure 3 illustrates the profile plots for the spodosol soil types III and IV. Soil types III and IV exhibit no substantial interaction and the R1-R2 height differential gradually increases from age 2 to approximately age 11. The profile plots for spodosol and non-spodosol soil types (Figure 4) illustrate no substantial interaction between the two rotations and the R1-R2 height differential gradually increases to about age 11. The profile plots reveal that the height differential is approximately equal for the spodosols and non-spodosols soil types. The R1-R2 height differential appears consistent after age 11 for all soil types.

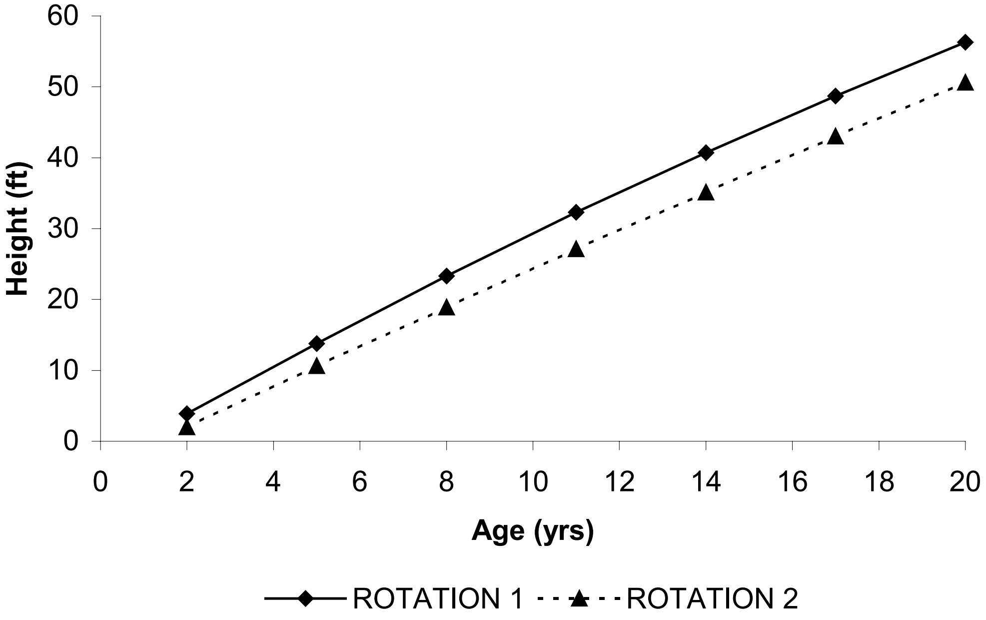
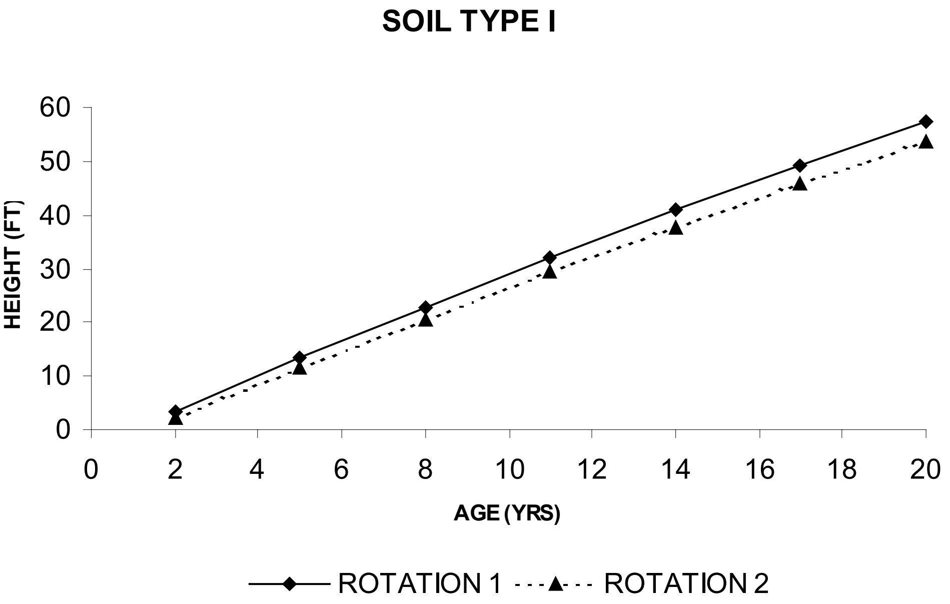


Figure 1. Average dominant/codominant height by rotation for all soil types.

Model 2 was used to perform an ANOVA and contrast the R1-R2 mean heights for the seven ages using the point estimates obtained in Model 1. The covariance parameter estimates for the whole plot and split plot errors revealed increasing variability with age. The among plots error component for ages 2 and 20 are 0.22 and 0.85, respectively. The random error component for ages 2 and 20 are 22.35 and 31.95, respectively. Hence, the among plots variance increases faster relative to the random error component. Thus, the among plots variance explains more of the among plots and random total variability at age 20 than 2.



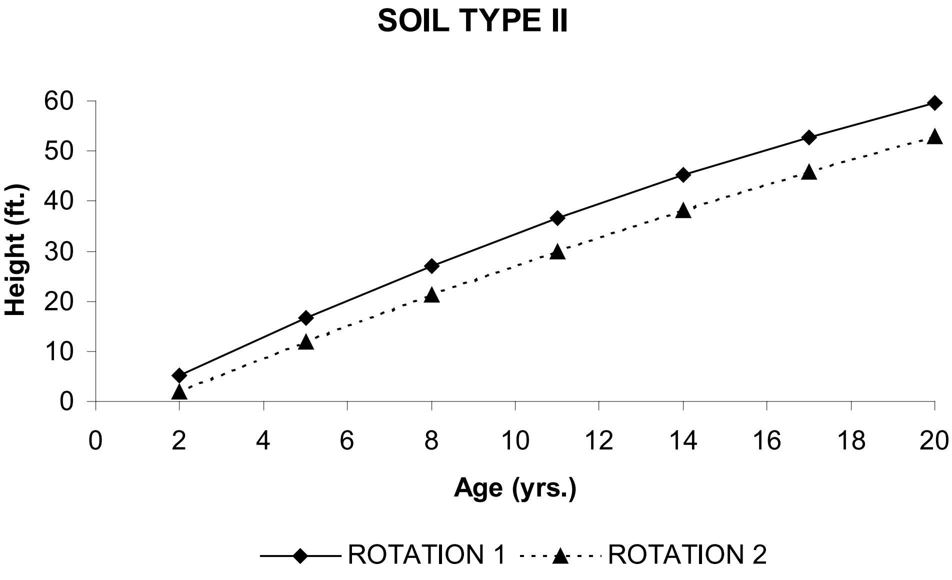
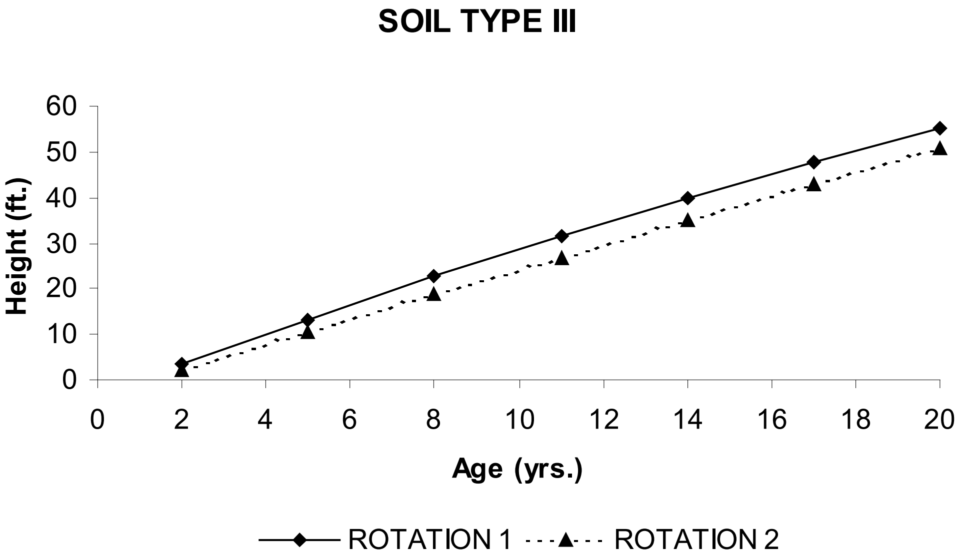


Figure 2. Average dominant/codominant height by rotation for soil types I (poorly drained non-spodosol) and II (somewhat poorly to moderately drained non-spodosol).



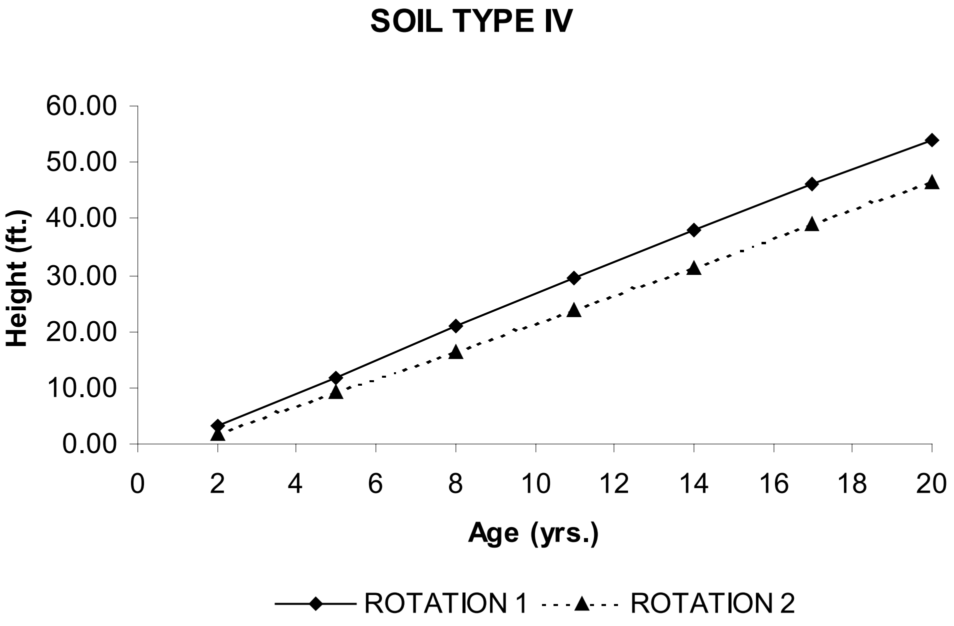


Figure 3. Average dominant/codominant height by rotation for soil types III (poorly to moderately drained spodosol with an underlying argillic horizon) and IV (poorly to moderately drained spodosol with no underlying argillic horizon) .

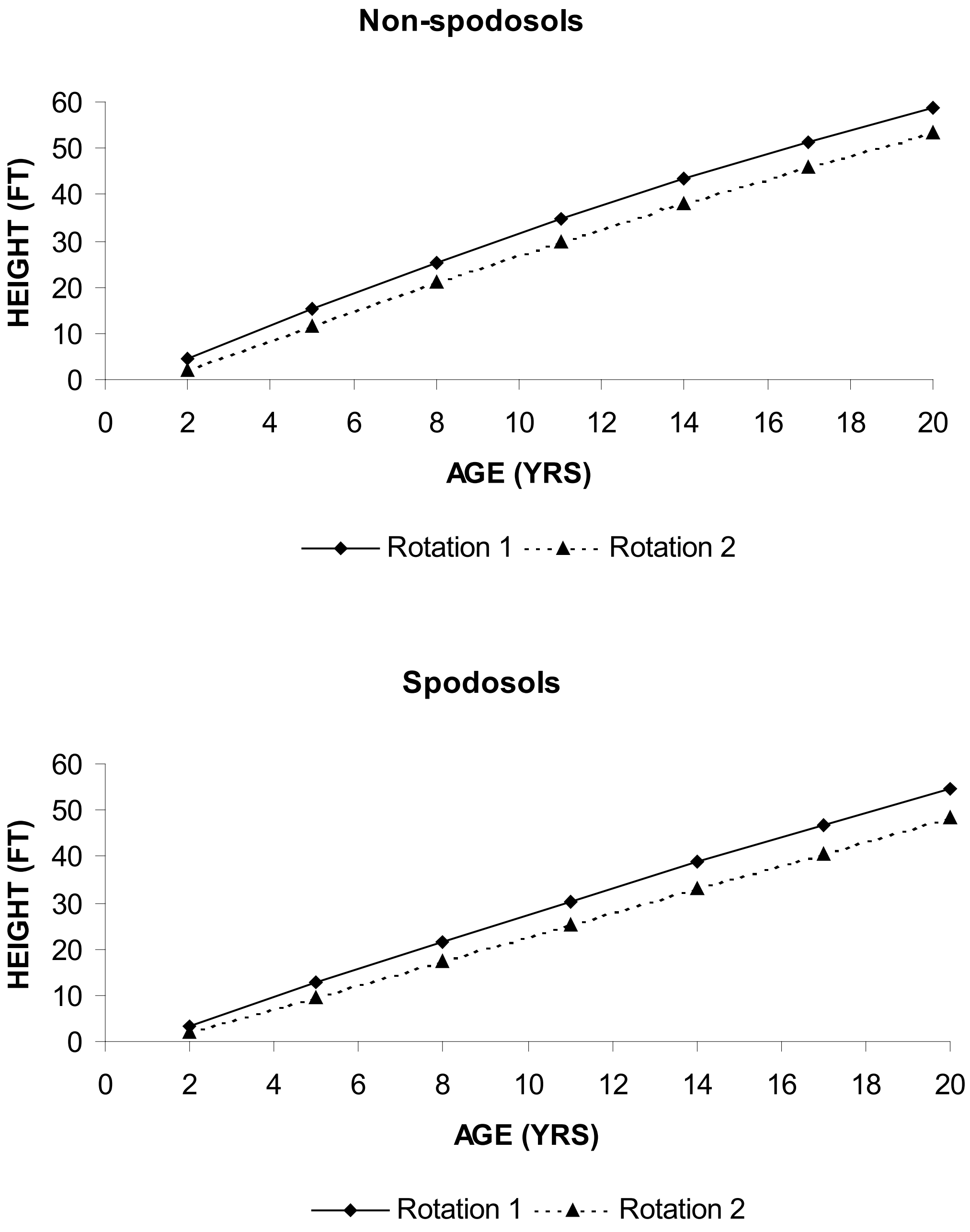


Figure 4. Average dominant/codominant height by rotation for spodosol and non-spodosol soil types.

The interaction and main effects test results by age for Model 2 (Table 4) indicate no significant interaction between soil and rotation. Therefore, the effect of soil and rotation on height is an additive effect. Hence, the effect of rotation on height does not depend upon soil type and vice versa. Since the interaction is not significant, it is appropriate to test the rotation and soil main effects across the soil types or rotations. The soil factor is not significant for all ages ($\alpha = 0.05$). There is a significant height difference between rotations for all ages, but the significance decreases as age increases.

Table 4. The Model 2 ANOVA tests for the fixed effects by age.

Source of Variation	NDF	DDF	Type III F	Pr > F
Age 2				
Soil	3	12	1.34	0.3083
Rotation	1	12	31.99	0.0001
Soil*Rotation	3	12	1.92	0.1810
Age 5				
Soil	3	12	3.02	0.0719
Rotation	1	12	19.88	0.0008
Soil*Rotation	3	12	0.62	0.6137
Age 8				
Soil	3	12	2.95	0.0757
Rotation	1	12	15.45	0.0020
Soil*Rotation	3	12	0.41	0.7481
Age 11				
Soil	3	12	2.63	0.0982
Rotation	1	12	13.44	0.0032
Soil*Rotation	3	12	0.34	0.7999
Age 14				
Soil	3	12	2.11	0.1517
Rotation	1	12	11.78	0.0050
Soil*Rotation	3	12	0.29	0.8323
Age 17				
Soil	3	12	1.47	0.2724
Rotation	1	12	9.74	0.0089
Soil*Rotation	3	12	0.25	0.8600
Age 20				
Soil	3	12	0.84	0.4983
Rotation	1	12	7.14	0.0204
Soil*Rotation	3	12	0.21	0.8882

Contrasts for Model 2 were constructed using the ESTIMATE statement in SAS PROC MIXED to test for rotation differences by soil types, and estimate the least squares height differences for R1-R2 (Tables 5 and 6). For all contrasts, except for those by soil type, the least square means do not equal the marginal means because of the unbalanced split-plot design (unequal replication sizes within soil types). The least square means are the correct means to use for inferences across the sites even though they may be lower than the height differential for rotation 1 and 2 using the marginal means of the summary data (Table 1).

Table 5. The rotation 1 minus rotation 2 (R1-R2) contrasts results by spodosol, non-spodosol and pooled soil types.

Age	R1 - R2	Std Error	DF	t	Pr > |t|
	Spodosols (soil types III and IV)				
2	1.43	0.44	12	3.28	0.0066
5	3.03	0.94	12	3.21	0.0075
8	4.27	1.41	12	3.02	0.0106
11	5.18	1.78	12	2.91	0.0132
14	5.73	2.08	12	2.76	0.0173
17	5.93	2.35	12	2.52	0.0267
20	5.79	2.68	12	2.16	0.0518
	Nonspodosols (soil types I and II)				
2	2.32	0.50	12	4.65	0.0006
5	3.34	1.07	12	3.12	0.0089
8	4.15	1.61	12	2.58	0.0242
11	4.72	2.03	12	2.33	0.0383
14	5.07	2.36	12	2.14	0.0532
17	5.18	2.68	12	1.94	0.0768
20	5.06	3.05	12	1.66	0.1230
	Pooled for all Soil Types				
2	1.87	0.33	12	31.99	0.0001
5	3.18	0.71	12	4.46	0.0008
8	4.21	1.07	12	3.93	0.0020
11	4.95	1.35	12	3.67	0.0032
14	5.40	1.57	12	3.43	0.0050
17	5.56	1.78	12	3.12	0.0089
20	5.43	2.03	12	2.67	0.0204

Note: R1 - R2 is the least-squares estimate of the height difference between rotation 1 and 2.

Table 6. The rotation 1 minus rotation 2 (R1-R2) height differential contrast results for soil types I, II, III, and IV by age.

Age	R1 - R2	Std Error	DF	t	Pr > |t|
Soil Type I					
2	1.40	0.75	12	1.86	0.0876
5	1.91	1.62	12	1.19	0.2556
8	2.40	2.43	12	0.99	0.3427
11	2.83	3.07	12	0.91	0.3792
14	3.13	3.57	12	0.88	0.3985
17	3.37	4.05	12	0.83	0.4207
20	3.55	4.62	12	0.77	0.4562
Soil Type II					
2	3.23	0.65	12	4.95	0.0003
5	4.75	1.41	12	3.38	0.0055
8	5.89	2.11	12	2.80	0.0161
11	6.64	2.66	12	2.50	0.0279
14	7.01	3.09	12	2.26	0.0428
17	6.99	3.50	12	1.99	0.0693
20	6.58	4.00	12	1.65	0.1259
Soil Type III					
2	1.42	0.65	12	2.78	0.0497
5	2.88	1.41	12	2.05	0.0629
8	3.94	2.11	12	1.87	0.0862
11	4.61	2.66	12	1.73	0.1085
14	4.87	3.09	12	1.57	0.1415
17	4.73	3.50	12	1.35	0.2019
20	4.20	4.00	12	1.05	0.3146
Soil Type IV					
2	1.44	0.58	12	2.48	0.0292
5	3.17	1.26	12	2.52	0.0268
8	4.60	1.88	12	2.44	0.0310
11	5.75	2.38	12	2.42	0.0324
14	6.58	2.77	12	2.38	0.0348
17	7.13	3.13	12	2.28	0.0419
20	7.38	3.58	12	2.07	0.0612

Note: R1 - R2 is the least-squares estimate of the height difference between rotation 1 and 2.

The contrasts for the R1-R2 pooled height difference is significant for all the age classes ($\alpha = 0.05$) (Table 5). The R1-R2 height differential increases from age 2 to 20, with an average height differential of 5.4 feet by age 20. The contrasts for the spodosol soil types

(III & IV) illustrate that there is a significant R1-R2 height differential from ages 2-17, with borderline significance at age 20 (p-value = 0.0518). The spodosols soil type average R1-R2 height difference increases to 5.8 feet by age 20. The R1-R2 height differential increases gradually from ages 11-17, and decreases slightly from ages 17-20. The non-spodosol soil types (I & II) have a significant R1-R2 height difference at ages 2, 5, 8, and 11, and a marginal significant difference for ages 14 and 17 (p-values 0.0532 and 0.0768, respectively). The spodosol soil type has a greater R1-R2 height differential from ages 8 to 20 than the non-spodosol soil type. This height differential generally increases as a function of age.

The soil type I contrast shows no significance R1-R2 height difference for all age classes (Table 6). Soil type II does have a significant R1-R2 height difference for ages 2, 5, 8, 11, and 14; but the significance decreases so that by age 17 there is only borderline significance (p-value = 0.0693). Soil type III only has a significance R1-R2 height difference at age 2. For soil type IV, there is a significant R1-R2 height difference for the 2-17 age classes, and a marginal significance difference at age 20 (p-value = 0.0612). Soil types II and IV have the largest R1-R2 height differential for the age classes 2-14 and 17-20, respectively. There is an increase in the R1-R2 height differential as a function of age for all soil types except from age 17 to 20 of the soil types II and III.

Climatic Surface Data Results

The precipitation ANOVA (Model 3) covariance parameters estimates revealed that the within plot variation accounts for the majority of the total within and among plots variability. The estimated variance component for among plots within a rotation is 9.82, which corresponds to a standard deviation of 3.13-inches precipitation. The within plot variance component is estimated by rotation because there is a significant difference between the rotations for within plot variance. The within plot standard deviation is significantly higher for rotation 1 (10.31-inches) than rotation 2 (6.37-inches). This result is expected because the initial year for rotation 1 is not identical for all plots. The results revealed that the year to year precipitation are not highly correlated.

The ANOVA results for average annual precipitation (Model 3) are presented in Table 7. The results reveal that the interaction between rotation and year is significant (p-value = 0.0001). This implies that the effect of rotation or year on precipitation depends upon the level of the other predictor variable. Hence, it is not appropriate to test for rotation main effects across the spectrum of years, but it is appropriate to test for rotation differences by year.

Table 7. The Model 3 ANOVA tests results for the fixed effects of total annual precipitation..

Source of Variation	NDF	DDF	Type III F	Pr > F
<u>Annual Rainfall</u>				
Rotation	1	9.84	2.76	0.1280
Year	19	247	7.61	0.0001
Rotation*Year	19	247	6.91	0.0001

Note: NDF = numerator degrees of freedom and DDF = denominator degrees of freedom.

The contrasts for testing R1-R2 average annual precipitation differences are presented in Table 8. During the first two years, rotation 1 received on average, 5.6 and 14.0-inches more precipitation than rotation 2. Rotation 1 had 98% and 104%, and rotation 2 had 88% and 78% of the average precipitation during their first two respective rotation years. Rotation 1 received significantly less rainfall than rotation 2 (8.8 and 9.8-inches) during the 3rd and 4th years, but still had 88% and 97% of the average annual precipitation. The 11th and 12th rotation years exhibit the greatest differences with respect to average annual precipitation. Rotation 1 received 19.8 inches more and 11.6 inches less of average annual precipitation for these respective years than rotation 2. Rotation 2 received 68% of the average annual precipitation for the 11th year. Although rotation 1 received substantially less precipitation than rotation 2 for the 12th year, it still received 109% of average annual precipitation. Rotation 2 received 131% of average annual precipitation for the 12th year. The contrasts for years 5-12 reveal that rotation 2 received significantly less rainfall than rotation 1, except for the 9th year. Rotation 1 received significantly more precipitation for the 14th and 20th years, and significantly less for the 15th year.

Table 8. The rotation 1 minus rotation 2 (R1-R2) annual precipitation contrasts results for the pooled soil type by year.

Year	R1 - R2	Standard Error	DF	t	Pr > | t |
1	5.58	3.23	178	1.73	0.0856
2	14.01	3.23	164	4.34	0.0001
3	-8.81	3.23	163	-2.73	0.0070
4	-9.79	3.23	163	-3.04	0.0028
5	3.52	3.23	163	1.09	0.2767
6	4.14	3.23	163	1.28	0.2007
7	8.70	3.23	163	2.70	0.0077
8	5.87	3.23	163	1.82	0.0707
9	-0.99	3.23	163	-0.31	0.7603
10	6.50	3.23	163	2.02	0.0454
11	19.80	3.23	163	6.14	0.0001
12	-11.62	3.23	163	-3.60	0.0004
13	-3.90	3.23	163	-1.21	0.2281
14	6.25	3.23	163	1.94	0.0545
15	-6.46	3.23	163	-2.00	0.0469
16	1.50	3.23	163	0.47	0.6423
17	2.04	3.23	163	0.63	0.5282
18	1.61	3.23	163	0.50	0.6173
19	-1.43	3.23	167	-0.44	0.6576
20	7.66	3.58	218	2.14	0.0338

Note: R1 - R2 is the rotation 1 minus rotation 2 least-squares precipitation difference.

To compute the SPI index, a square-root transformation was necessary to normalize the precipitation data. The SPI profile plots of the average annual precipitation by rotation are presented in Figure 5. Rotation 2 exhibits more variability relative to rotation 1 for the yearly SPI index. The rotation SPI results are explained using McKee's et al. (1993) classification system (Table 1). Rotation 1 experienced one minor drought event (years 3-4), for average annual precipitation, during the 20 years. Rotation 2 has experienced two previous drought events (years 1-2, and 10-11), and is currently in the third year (1998-2000) of a drought event. Since the loss in height growth for rotation 2 relative to rotation 1 was expressed by age 2, the SPI precipitation by month was computed for the first two years of each rotation (Figure 6). The average monthly SPI revealed that rotation 1 did not experience a growing season drought event during the first two growing seasons. Rotation 2 experienced growing season drought events during both of the first two growing seasons. Rotation 2 had substantially above normal precipitation for August of the second year, but it is unlikely that this surplus negates the April-July drought event for the second growing season.

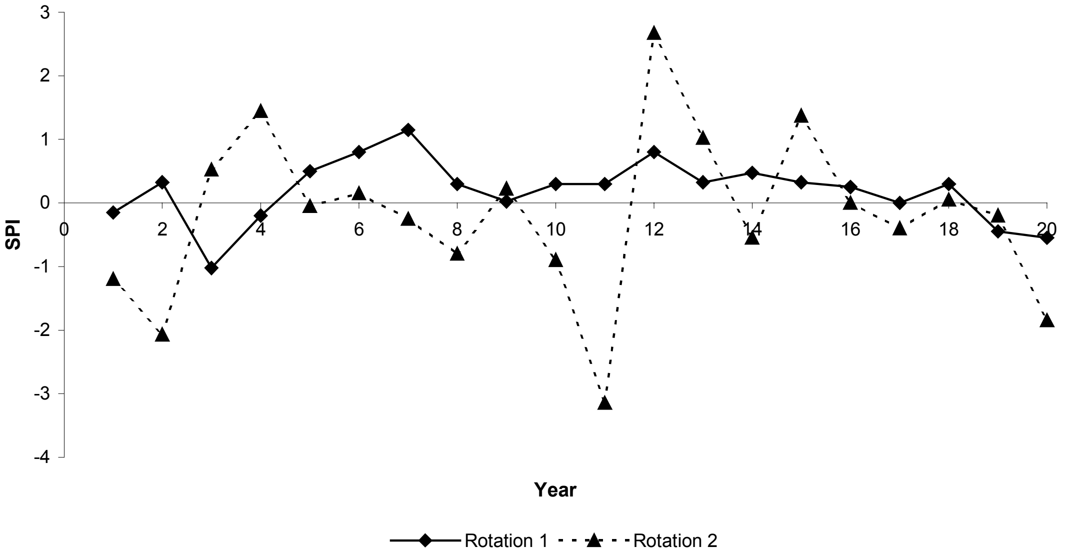


Figure 5. The standardized precipitation index (SPI) for average annual precipitation by rotation and year.

Figure 7 illustrates the mean annual and growing season temperatures for both rotations by year. Rotation 2 had below average annual temperatures during the first two years, but during the same period it had substantially above normal temperatures for the growing season. Rotation 2 average growing season temperature for the first 2 years was 77.6° F, which is substantially above the average growing season temperature of 76.9° F. As illustrated, Rotation 2 has high yearly temperature variability relative to rotation 1, which displays little variability, for both average growing season and annual temperatures.

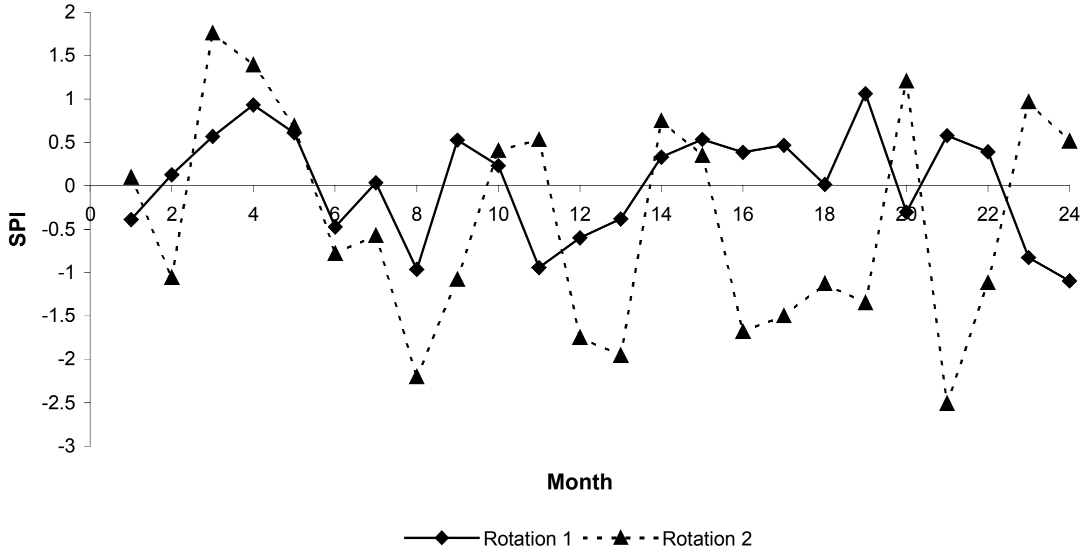


Figure 6. The average annual precipitation standardized precipitation index (SPI) by rotation and month for the first 24 months (month 1 corresponds to January of the first year).

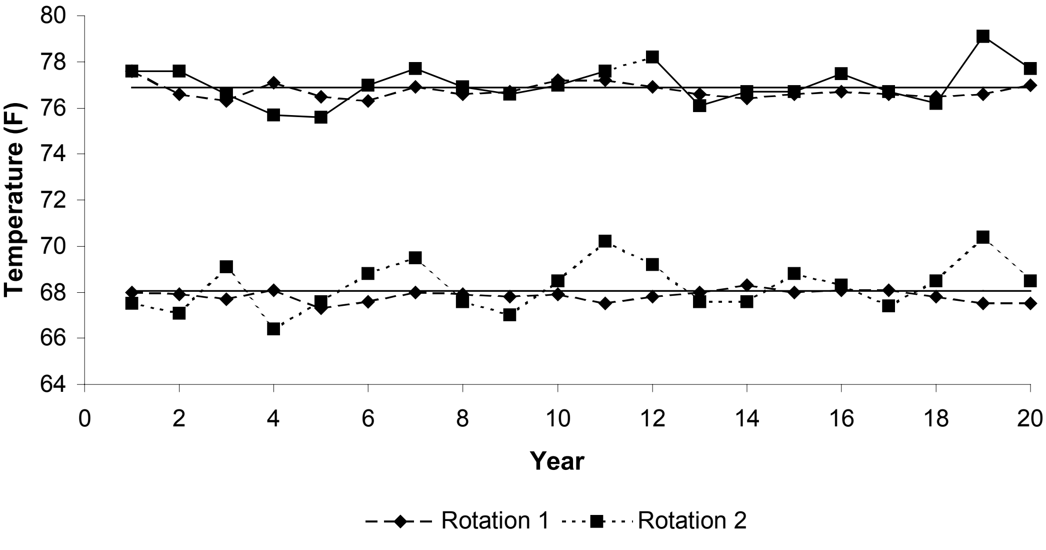


Figure 7. The average annual and summer (higher) temperatures by rotation and year. The 69-year weighted means for summer and annual temperatures are represented by the solid lines.

DISCUSSION

The results from the ANOVA for the spectrum of plots by age class revealed a significant dominant/codominant height difference between the rotations. Rotation 1 is on average, 1.9, 3.2, 4.2, 5.0, 5.4, 5.6, and 5.4 feet higher for mean dominant/codominant heights than rotation 2 at ages 2, 5, 8, 11, 14, 17, and 20, respectively. This is approximately a 48% and 10% mean dominant/codominant height reduction for ages 2 and 20, respectively. The mean height significance decreases as age increases; but an the R1-R2 mean dominant/codominant height loss of 5.4 feet at age 20 is considerable.

The contrasts by soil types don't insinuate a general trend between soil type and the R1-R2 height differential. The R1-R2 height differential for the spodosol soil type is greater than the non-spodosol soil type from ages 8 to 20. By age 20, the spodosols and non-spodosols soil types R1-R2 height differential are 5.8 and 5.1 ft, respectively. Soil types II and IV (non-spodosol and spodosol, respectively) generally have the most significant R1-R2 height differential. The contrasts by soil type reveal that the R1-R2 height differential is greater for the soil types II and IV. Since there are few replications per soil type, caution is advised for soil type inferences. The statistically most powerful inferences are for the spectrum of soil types.

The among plots within a soil type and residual variance components for the mean dominant/codominant height ANOVA revealed that the proportion of variability for among plots within a soil type increases as a function of age. This is consistent with plots expressing their respective site quality as the trees within a plot mature. The parameter estimates for the annual precipitation variance components revealed that the among plots variance is small relative to the within plot variance. This insinuates that yearly precipitation is highly variable, and that annual precipitation among the plots is similar. The small estimated serial correlation parameters by rotation implies that the precipitation next year is not highly correlated with the precipitation this year. Hence, a high degree of randomness is present in the year to year precipitation for these rotations.

There are several main factors that may have contributed to the decline in mean dominant/codominant height for rotation 2. Some of the possible factors are nutrient deficiency, competing vegetation may have increased, and/or the competing vegetation composition may have changed. But the evidence suggests that the severe drought events and warmer temperatures experienced by rotation 2 relative to rotation 1, especially during the first two growing seasons, is the main factor for rotation 2's smaller mean dominant/codominant height across the spectrum of plots and age classes.

It is difficult to quantify competing vegetation or nutrient availability for either rotation because of the lack of data for these factors. But the main competitors at most plots for both rotations are gallberry (*Ilex glabra*) and saw palmetto (*Serenoa repens*). There is no indication that the quantity of gallberry and/or saw palmetto has dramatically changed from rotation 1 to rotation 2. In addition, this region has experienced a policy of diminishing open land grazing by cattle. This may have resulted in a change in vegetation density or composition at plots 7, 8, and 11 where fencing was required to restrain cattle. The data suggests that fencing plots 7, 8, and 11 to restrain cattle may have slightly benefited rotation 2, but the age 2 mean dominant/codominant heights were substantially higher for rotation 1 at these plots. Thus, it is unlikely that competition, although density is unknown, was the major factor contributing to the decrease in mean dominant/codominant height experienced by rotation 2 across the spectrum of plots.

The climate analyses suggest that drought events and warmer growing season temperatures generally correspond with smaller mean dominant/codominant height. The evidence reveals that the decreasing mean dominant/codominant height experienced by rotation 2 was expressed by age 2. This age 2 R1-R2 height differential corresponds with less favorable growing conditions, on average, experienced by rotation 2 during the first two growing seasons. The SPI for annual precipitation by plot divulged that plots 4, 10, 13, and 20 seemingly deviate from a hypothesis of drought events and warmer temperatures equaling less mean height growth.

The annual SPI precipitation for plot 4 revealed that rotation 1 had less favorable conditions during the first two years. But the monthly SPI for the first two years revealed that rotation 1 didn't experience any growing season droughts, but rotation 2 did experience drought events during both of the first two growing seasons. Both rotations experienced similar growing season temperatures. This suggests that despite the less favorable overall climatic conditions for rotation 1 during the first two years, it had more favorable growing season conditions. Therefore, the fact that rotation 1 on average had more than twice the mean height growth as rotation 2 during the first two years is consistent with the previous findings. This also suggests that yearly drought events are important, but the timing of the drought events within a year is of more importance. The evidence also insinuates that the timing of the drought events within a rotation is more important than the fact that a drought event occurred, i.e. the early rotation drought events for rotation 2 had a more profound effect on height growth loss relative to rotation 1 than the drought events that occurred during the latter years of rotation 2.

The monthly SPI for plots 10 and 20 revealed that the climatic conditions during the first two growing seasons are not substantially different for rotations 1 and 2. But rotation 2 had, on average, approximately 40% less mean dominant/codominant height growth relative to rotation 1. It appears that climatic conditions were not a major factor for the declining mean height growth at plots 10 and 20. The monthly SPI for plot 13 revealed that rotation 1 had more favorable climatic conditions during the first two growing seasons than rotation 2. But rotation 1 had slightly less mean height growth by age 2 than rotation 2. Rotation 1 was below average and rotation 2 substantially above average for mean height growth for plot 13 at age 2. These plot specific results generally contradict a hypothesis of drought events leading to less height growth and are likely a result of other growth factors such as nutrient availability and/or competition.

The plantation productivity plots used for this study are a separate entity of the study on slash pine site preparation, fertilization, and vegetation control discussed previously. The goals of the larger study are to evaluate the growth, yield, and stand structure of slash pine plantations using a variety of site preparation, fertilization, and vegetation control methods. The site preparation methods used for the productivity study plots were, on average, similar to a chop and burn site preparation. The mean dominant/codominant heights for rotations 1 and 2 were compared to the mean dominant/codominant height of the chop and burn treatment plots. The precipitation and temperature data for the site preparation plots are the same as the productivity plots since they are located at the same 16 installations. Therefore, any differences between the second rotation productivity plots and the chop and burn plots are not likely due to climatic differences. Caution is recommended in extrapolating, because the genetic stock of the productivity plots differs from the site preparation study plots. At ages 2 and 20, the mean dominant/codominant heights for the chop and burn plots are 2.7 and 56.0 feet, respectively. The second rotation productivity plots mean heights are 2.1 and 47.7 feet, and the first rotation productivity plots mean heights are 3.4 and 57.1 feet at ages 2 and 20, respectively. The mean heights for rotation 2 at ages 2 and 20 are significantly different from those of the chop and burn plots, but are similar to the control plots mean heights of 2.2 and 46.0 feet. The site preparation for the control plots consisted of harvest and plant. The growth factors such as competition, climate, and nutrient availability are likely to be similar for the control and productivity plots. Therefore, the mean height difference between the productivity and the chop and burn plots is likely from the different genetic stock. The rotation 1 mean heights at ages 2 and 20 are slightly higher than the chop and burn plots. These heights were achieved by using similar treatments but different genetic seedlings. Rotation 1 generally had more favorable climatic conditions than the chop and burn plots. Since the competition was similar, but density is unknown, it is plausible that the more favorable growing conditions negate the inferior genetic stock. Hence, the mean height growth of rotation 1 is similar to the chop and burn. The site preparation treatments with the highest mean heights at age 20 are 1) chop, burn, and complete vegetation control, and 2) chop, burn, bed, and complete vegetation control. Their respective mean heights at age 20 are 60.4 and 61.1 feet. The complete vegetation control may have increased the nutrient availability for the slash pine. This insinuates that given less favorable climatic conditions for seedling growth, it is possible to increase the mean dominant/codominant height for successive rotations using intensive forest management without fertilization.

The canopy closure for these plots was likely achieved between ages 8 and 11. By age 11, rotation 2 had experienced approximately 93% of its age 20 mean dominant/codominant height decrease relative to rotation 1. This is consistent with Boardman's (1978) finding that the site productivity class achieved by canopy closure is generally maintained. It is generally accepted that extreme weather temperatures, marginal precipitation, competition, and nutrient deficiency can adversely affect seedling growth. The second rotation, on average, exhibits a mean dominant/codominant height reduction, but the first rotation harvest disturbance is not likely a mitigating factor because management impact was minimized to insure the second rotation duplicated the first rotation as accurately as possible. The main competition for both rotations is gallberry and saw palmetto, but not necessarily at the same densities, therefore competition is unlikely the main factor for the mean dominant/codominant height growth loss experienced by rotation 2. Since the genetic stock was the same for both rotations, genetics is not likely the major factor for the height differential between rotations 1 and 2. Because no information is available, a nutrient deficiency can't be eliminated as a major contributor to the R1-R2 height differential. This study's evidence implies that, although there are some plot anomalies, climate is the likely major factor contributing to the decrease in mean dominant/codominant height for rotation 2.

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