

## ABSTRACT

CHAMBLEE, AARON KENNETH. Variation Among Widely Planted First-Generation Loblolly Pine Across Diverse Environments in the Southeastern US. (Under the direction of Dr. Steven E. McKeand.)

Seven seed sources, 140 families, of first-generation plantation selections of loblolly pine (*Pinus taeda* L.) were evaluated for survival, height, volume, straightness, stem forking, and incidence of fusiform rust disease (caused by *Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*) in tests across most of its native range east of the Mississippi in the southeastern United States. First-generation plantation selections comprise the largest portion of the breeding population in the NC State University Cooperative Tree Improvement Program, so understanding the patterns of genetic variation and genotype by environment (GxE) interactions is critical for the success of the breeding program. The objective of this study was to define seed source and family attributes and explain significant GxE interactions with descriptive statistics.

At age 8, overall survival was high, 75%, at all but two test sites. South Carolina Coastal and Florida & Georgia Coastal seed sources exhibited the best growth and fusiform rust resistance traits. The range of individual tree narrow sense heritabilities for height, volume, and straightness were in the expected range of 0.1 to 0.6, and family mean heritabilities for all traits were larger and ranged from ~0.3 to 0.8. Type B correlation values of  $r_{Bg} < 0.67$  for height and volume at the family and seed source levels suggested that these traits had GxE interactions important to breeding. South Carolina Coastal and Virginia seed sources contributed the most to the GxE interactions of height and volume. While GxE interaction was significant for the growth traits, the results suggest that height is relatively predictable

due to average stability for most families while volume is unpredictable due to its highly variable stability parameters (i.e. slope). This means that breeding and testing for volume is more complicated than for other traits, but volume has greater potential for genetic control for response to better sites.

Variation Among Widely Planted First Generation Loblolly Pine Across Diverse  
Environments in the Southeastern US

by  
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## **DEDICATION**

This thesis is dedicated to my parents who have supported me throughout my academic career.

## **BIOGRAPHY**

Aaron Chamblee was raised in Durham, North Carolina. He graduated from Jordan High School in 2004. He then attended North Carolina State University for undergraduate study in Forest Management and graduated in 2008. He was then admitted to North Carolina State University graduate program in 2008 to pursue a Master's degree in Forestry focusing on tree breeding with the Tree Improvement Cooperative.

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I would also like to thank the forest industry professionals, state agencies, and companies that made this study possible. Though many of these companies have either gone bankrupt or have merged with other companies due to hard economic times, I hope that we can count on the support of the forest industry to continue to aid educational pursuits in the future.

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## **Chapter 1:**

# **Variation among loblolly pine seed sources across diverse environments in the southeastern US**

## 1.1 Abstract

Seven seed sources of first-generation plantation selections of loblolly pine (*Pinus taeda* L.) were evaluated for six traits in tests across most of its native range east of the Mississippi in the southeastern United States. The six traits were survival, height, volume, straightness, stem forking, and incidence of fusiform rust disease (caused by *Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*). At age 8 years, survival was very high, with most sites and seed sources having survival greater than 75% at all but two test sites. South Carolina Coastal and Florida & Georgia Coastal seed sources exhibited the best growth and fusiform rust resistance traits. The Virginia seed source exhibited the best form but had the slowest growth. Test site and seed source were significant sources of variation in all traits, and seed source by site interactions (GxE) were also significant for all traits except forking. Type B correlation values of  $r_{Bg} < 0.67$  for height, volume, and straightness suggested that these traits had GxE interactions important to breeding, and South Carolina Coastal and Virginia seed sources contributed the most to GxE interactions for growth traits.

## 1.2 Introduction

Loblolly pine (*Pinus taeda* L.) is the major timber species in the Southeastern United States, with almost 1 billion seedlings produced annually (McKeand et al 2003). The research and application of silviculture, ecology, and genetics has gone a long way in shaping the systems of today's loblolly pine plantations and management regimes. Genetic improvement through breeding and selection of loblolly pine since the 1950's has improved the productivity, form,

and disease resistance in the species, but the research and development of loblolly pine germplasm is still in its infancy compared to many agricultural crops.

The wide range of soils, climates, and other environmental factors across loblolly's natural range have led to the development of distinct geographic variation for most traits (Hocker, 1956, Wells and Wakeley 1966, Schmidting 2001, Schmidting 2007). Knowing the differences in geographic variation and adaptability of these subpopulations is important to breeders to determine the structure, gain, and selection of germplasm for breeding populations. Early provenance trials showed that local seed were often best for growth rates, disease resistance, form, and/or survival (Wakeley 1944, Wakeley and Bercaw 1965). Other experiments noted similar effects, along with a general trend of sources from lower latitudes having better growth (Perry and Wang 1957, Allen and McGregor 1962, Perry et al 1965). While these provenance trials were important for breeding programs to identify optimal sources for selections and for making gain, they often tended to suffer from limited numbers of provenances, sources, and/or test sites (St. Clair et al. 2005). This means that smaller provenance trials, while containing pertinent information, lacked the power to generate important details about traits outside a localized region.

One of the most important seed source trials was the Southwide Pine Seed Source Study (SPSSS), which covered most of the natural range of loblolly pine in both test sites and seed source selection (Wells and Wakeley 1966). The SPSSS showed a number of general trends of loblolly pine such as: trees from Atlantic Coastal sources usually grew faster than trees from western sources; western and northern seed sources had better survival rates; and some

western and northern sources had better resistance to fusiform rust (caused by the fungus *Cronartium quercuum* (Berk) Miyabe ex Shirai f. sp. *fusiforme*) (Wells and Wakeley 1966, Wells 1983, Schmidting 2001). These results contradicted some of the earlier ideas that local seed sources were best, because some non-native seed sources had better performance than local sources on test sites for growth and rust resistance. The rank changes that occurred between seed sources and sites were either due to extreme changes in latitude and longitude from the seed source or occurred among the lower ranking seed sources (Wells and Wakeley 1966, Wells 1983). Using this seed source study to move germplasm has benefitted many breeding programs (e.g. Lambeth et al. 1984, Lambeth et al. 2005), but other factors, such as minimum winter temperatures, discourage movement of germplasm too far from their origin (Schmidting 1994, Schmidting 2001).

The rank changes observed in the SPSS raised the concern for the importance of seed source by environment interactions (GxE). These interactions complicate breeding and planting decisions by influencing where certain families should be planted and bred (Falconer 1952, McKeand et al 2008). Most GxE trials for loblolly pine have not focused on seed sources as much as on open-pollinated families. Many studies have found significant GxE interaction for growth traits in individual families, but little significant rank change for families between sites (Li and McKeand 1989, McKeand et al. 1990, McKeand et al. 2006, Roth et al. 2007). The fact that a number of these families were from the same region could be used as a cursory look at how seed from these areas perform. Individual family results should only be used as a guide to seed source behavior, because the overall significance of

the individual families does not necessarily translate to significance of traits for seed sources (Sierra-Lucero et al. 2002). The results from many studies have shown that GxE interactions may occur, but the true significance of these findings for breeding is not always clear (Wells and Wakeley 1966, Wells 1983, Wells and Lambeth 1983, Lambeth et al 1984, Li and McKeand 1989, McKeand et al. 1990, Schmidting 2001, Sierra-Lucero et al. 2002, Lambeth et al 2005).

Understanding the base structure of the breeding region populations and the families within them is vital to discerning not only regional and family traits but their interactions within different environments. Since about 85% of the genetic base (~3300 selections) for the NC State University Cooperative Tree Improvement Program (henceforth called Cooperative) originated from plantation selections and not from indigenous or natural stands of loblolly pine, a study of this population would define the base characteristics for most of the germplasm used in current testing and breeding (Weir and Zobel 1975). Evaluation of these plantation selection populations would not be as straightforward as indigenous populations, such as what was done in the SPSSS, because some of the families in these populations were not necessarily local seed. The presumption is that these seedlings would be adapted to the local conditions, and could develop into a land race (Zobel and Talbert 1984).

In the 1990's, the Plantation Selection Seed Source Study (PSSSS) was initiated by the Cooperative to determine the patterns of geographic variation in first-generation plantation selections. These plantation selections were initially selected from pine plantations on phenotypic indicators, such as height, volume, stem form, and fusiform rust resistance. A key

difference between this study and other loblolly pine seed source studies was that the PSSSS assessed the base breeding population in a large, replicated and balanced field design.

The objectives of the study were to: 1) Compare seed sources across a wide range of sites for their growth, fusiform rust disease resistance, adaption (survival) and stem quality traits; 2) examine seed source by site (GxE) interactions; and 3) identify the contribution of seed sources to the variation of GxE interactions.

### **1.3 Materials and Methods**

#### *1.3.1. Plant Material and Mating Design*

Selections for this study were randomly chosen from a pool of 3300 first-generation plantation selections in seven breeding regions in the Southeastern United States. Originally there were eight regions, but the North Carolina Piedmont was divided between the Virginia (VA) region and the Piedmont of South Carolina and Georgia (PD) region. In each region, 20 selections were randomly chosen as females for a total of 140 families. These selections were then mated with a pollen mix of 40 pollen parents from each region giving a total of 280 pollen parents. The only biological criteria were that the females had to be producing female strobili, and the pollen parents were producing sufficient viable pollen to contribute to the pollen mix. The female and pollen parents were not the same in order to prevent any selfing. For each region, the 40 pollen parents from each region were bulked based on germination percentage in an attempt to achieve equal representation of male pollen parents in the offspring.

### *1.3.2. Field design*

A randomized complete block design with single-tree plots was used for all sites. The seedlings were planted at 25 test locations, but only 21 test sites were available for this study (Figure 1.1, Table 1.1). In four northern test sites, southern sources from South Carolina Coastal, Georgia and Florida Coastal, and the Lower Gulf were not used due to space limitations and the expected poor adaptability of the southern sources in the northern sites (Li and McKeand 1989, McKeand et al. 1990, Schmidting 1994). Minimum winter temperatures for each test site were estimated using weather data obtained by linear regression of county weather data from 1980 to 2010 (Dr. Benjamin Smith, NC State University, pers. com.).

Each test had 24 blocks (with the exception that one site had only 11 blocks) with a single tree from each family and four unimproved local checklot seedlings randomly distributed throughout each block for a total of 3456 trees per test site. Seedlings were planted from 1994 to 1997 with a few exceptions (Appendix C).

While most of the sites had projected site index values around 20 m (65 feet) at a base age of 25 years, there were some differences (Appendix C). Most test sites were planted on a 2.7m x 2.7 m or 2.4m x 3.0m (9'x9' or 8'x10') spacing, but a few were planted with some spacings as small as 2.1m x 2.1m (7'x7').

### *1.3.3. Measurements*

Height, diameter at breast height (DBH), straightness, the presence or absence of fusiform rust galls on the stem or branches, forking, and survival were measured for all trees at age 8.

Straightness was measured on a scale of 1 to 6 for most test sites with lower scores being straighter. Forking was determined as the presence or absence of forks or major ramicorn branching for a tree. Height and DBH were used to calculate individual-tree volume ( $\text{dm}^3$ ) using the following equation (Sherrill et al 2008):

$$\hat{V}_{ib} = 0.954560899 + 0.282415876 * \left( \frac{\text{DBH}^2 \times \text{Height}}{10} \right) \quad (\text{Eq. 1.1})$$

#### 1.3.4. Statistical Analyses

To assess seed source effects, all trees from a given seed source were bulked together (e.g. the family identity for the seedlings for a seed source was ignored). The following linear model was used to fit data to test variation among seed sources, test sites, and seed source by environment interactions:

$$y_{ijkl} = u + L_i + B(L)_{j(i)} + S_k + LS_{ik} + BS(L)_{kj(i)} + \varepsilon_{ijkl} \quad (\text{Eq. 1.2})$$

where  $y_{ijkl}$  is an observation of the  $l$ th individual in the  $i$ th test of the  $j$ th block from the  $k$ th seed source;  $L_i$  is the fixed effect of the  $i$ th location;  $B(L)_{j(i)}$  is the random effect of the  $j$ th block in the  $i$ th location  $\sim \text{iid}(0, \sigma_{b(l)}^2)$ ;  $S_k$  is the fixed effect for the  $k$ th seed source;  $LS_{ik}$  is the interaction between  $i$ th location and  $k$ th seed source;  $BS(L)_{kj(i)}$  is the interaction between  $j$ th seed source and  $k$ th block within  $i$ th location  $\sim \text{iid}(0, \sigma_{bs(l)}^2)$ ; and  $\varepsilon_{ijkl}$  is the error variance associated with the  $l$ th individual tree in the  $i$ th location of the  $j$ th block from the  $k$ th seed

source  $\sim$  iid  $(0, \sigma_e^2)$ . Least square means were found for the growth traits and straightness for seed sources with ranks given by Tukey's multiple range test.

We used  $\alpha=0.05$  as the threshold for statistical significance for the F tests. The MIXED procedure of SAS/STAT software was used to run the model for continuous traits, and the GLIMMIX procedure was used for forking and fusiform rust incidence, both binomial traits (SAS Institute Inc. 2008). When certain interactions terms (e.g., block by seed source) were included or when a level of a factor (e.g. blocks) were put in the models for binary traits, zero cell counts for which likelihood estimates were not available were found so that these parameters were not estimable (Isik et al. 2008). A reduced model was used for forking and rust, utilizing error residuals instead of effects containing block, to compensate for the non-estimable parameters.

We modified Eq. 1.2 to treat seed source and site as random effects to obtain estimates of variances due to seed source ( $\sigma_s^2$ ), site, and their interaction ( $\sigma_{ls}^2$ ). For the evaluation of stability of seed sources across sites, the following model for type B correlation coefficient was used to examine seed source by site interactions:

$$r_{Bg} = \frac{\sigma_s^2}{\sigma_s^2 + \sigma_{ls}^2} \quad (\text{Eq. 1.3})$$

where  $r_{Bg}$  is the type B correlation coefficient,  $\sigma_s^2$  is the seed source variance, and  $\sigma_{ls}^2$  is the location by seed source or GxE interaction variance (Burdon 1977). The type B correlation coefficient ( $r_{Bg}$ ) would give a general prediction of importance for interaction terms. A value

less than 0.67 for the type B correlation coefficient would suggest that there are seed source by test site (GxE) interactions that would have an effect on tree breeding (Shelbourne 1972, Isik et al 2008, Komakech 2009).

The GxE interaction term was further evaluated using Shukla's (1972) analysis to find the percent contribution to the interaction term by individual seed sources. A modified version of Shukla's analysis was used to analyze the data by running GxE values with the Mixed procedure in SAS (Kang 2002, Saxton 2004). The following model was used for the GxE evaluation:

$$y_{ijkl} = \mu + L_i + B(L)_{j(i)} + S_k + LS_{ik} + \varepsilon_{ijkl} \quad (\text{Eq. 1.4})$$

where  $y_{ijkl}$  is an observation of the  $l$ th individual in the  $i$ th test of the  $j$ th block from the  $k$ th seed source;  $L_i$  is the fixed effect of the  $i$ th location;  $B(L)_{j(i)}$  is the random effect of the  $j$ th block in the  $i$ th location  $\sim \text{iid}(0, \sigma_{b(l)}^2)$ ;  $S_k$  is the fixed effect for the  $k$ th seed source;  $LS_{ik}$  is the random term for interaction between  $i$ th location and  $k$ th seed source  $\sim \text{iid}(0, \sigma_{ls}^2)$ ; and  $\varepsilon_{ijkl}$  is the error variance associated with the  $l$ th individual tree in the  $i$ th location of the  $j$ th block from the  $k$ th seed source  $\sim \text{iid}(0, \sigma_e^2)$ . The variance component for the GxE interaction ( $LS_{ik}$ ) was then split for every  $k$ th seed source with unbiased estimators of seed source variance  $\sim \text{iid}(0, \hat{\sigma}_{LS(k)}^2)$ . They were evaluated further using Z-values and the following model:

$$\% \text{ contribution to GxE variance} = \left( \frac{\hat{\sigma}_{LS(k)}^2}{\Sigma \hat{\sigma}_{LS(k)}^2} \right) * 100 \quad (\text{Eq. 1.5})$$

where  $\hat{\sigma}_{LS(k)}^2$  is the variance component of the  $k$ th seed source for its contribution to GxE interaction and  $\Sigma \hat{\sigma}_{LS(k)}^2$  is the sum of the GxE interaction variance components. An error check of the individual seed source variances ( $\hat{\sigma}_{LS(k)}^2$ ) was performed using a verification test to check for errors (Shukla 1972). The results of this may be found in Appendix B.

To determine how much variation there was among seed sources for each site, the following model was run for each test site:

$$y_{ijk} = u + B_i + S_j + BS_{ji} + \varepsilon_{ijk} \quad (\text{Eq. 1.6})$$

where  $y_{ijk}$  is an observation of the  $k$ th individual in the  $i$ th block from the  $j$ th seed source;  $B_i$  is the random effect of the  $i$ th block  $\sim \text{iid}(0, \sigma_b^2)$ ;  $S_j$  is the random effect for the  $k$ th seed source  $\sim \text{iid}(0, \sigma_s^2)$ ;  $BS_{ik}$  is the random term for interaction between  $i$ th location and  $k$ th seed source  $\sim \text{iid}(0, \sigma_{bs}^2)$ ; and  $\varepsilon_{ijkl}$  is the error variance associated with the  $l$ th individual tree in the  $i$ th location of the  $j$ th block from the  $k$ th seed source  $\sim \text{iid}(0, \sigma_e^2)$ . The standard deviation for seed sources ( $\sigma_s = \sqrt{\sigma_s^2}$ ) and individual site means ( $\bar{\mu}_l$ ) were used to find the coefficient of variation (%CV) of seed sources for each site:

$$\%CV = \left( \frac{\sigma_s}{|\bar{\mu}_t|} \right) * 100 \quad (\text{Eq. 1.7})$$

The %CV values were then compared against minimum winter temperatures ( $^{\circ}\text{C}$ ) at each test site by utilizing the following quadratic model:

$$y = \beta_0 + \beta_1x + \beta_2x^2 + \varepsilon \quad (\text{Eq. 1.8})$$

where  $y$  is the predicted %CV value;  $\beta_0$  is the y-intercept;  $\beta_1$  is the coefficient for minimum winter temperatures ( $x$ );  $\beta_2$  is the coefficient for minimum winter temperatures squared ( $x^2$ ); and  $\varepsilon$  is the error. The coefficient of variation was modeled in this manner because it shows the trend of seed source variation by site to temperature gradients in a way that removes scale effects. The GLM procedure of SAS/STAT software was used to run the model for Eq. 1.8 (SAS Institute Inc. 2008). We used  $\alpha=0.05$  as the threshold for statistical significance for the F test of the model. The  $R^2$  values less than 0.30 were considered too low for the model to explain the variance.

#### **1.4 Results**

The site means for survival were relatively high, averaging 87% across all sites with the exception of Autauga (AL) and Northampton (NC) sites having survival below 70% (Table 1.1). These two sites also had some of the highest fusiform rust incidence, but there were no

other indicators for their lower survival rates (Table 1.1). Since survival means for all sites, except Autauga County, AL and Northampton County, NC were high, those two sites were not analyzed further. Height and volume differed greatly between sites with overall means of 9.1 m and 59.8 dm<sup>3</sup> respectively (Table 1.1). The overall mean scores were 3.25 for straightness and 36% fusiform rust infection, but the overall 20% forking incidence was low (Table 1.1).

Knowing that the main effects for test site and seed source were significant at the  $p < 0.001$  level, the least square means for seed sources were used to determine rank between seed sources for the growth and straightness traits (Table 1.2). The South Carolina Coastal seed source had the highest overall height and volume, whereas the Virginia seed source ranked the lowest for both growth traits (Figures 1.4 & 1.5). The Virginia seed source had the best ranking for straightness, while the southern seed sources had the worst rankings for straightness (Figure 1.6). There was a wide range of seed source means for fusiform rust incidence; the Upper Gulf seed source had the highest disease incidence mean (50%), and the GA&FL Coastal and SC Coastal had the lowest rust (40%) (Figure 1.2). Virginia had the lowest forking incidence, but there was little difference between seed sources for the overall forking means, only a difference of 5% between the lowest and highest forking means (Figure 1.3).

The high significance ( $p < 0.05$ ) of the seed source by location (GxE) interaction term for all of the traits, except forking incidence ( $p > 0.05$ ), showed that the main effects do not necessarily fully describe the trends for these traits (Table 1.2). More detailed analyses of the

GxE interaction, such as type B correlations, Shukla's variance analysis, range differences between seed sources by site, and individual site rankings for each trait, were then used to further describe these interactions. GxE interactions were important for height, volume, and straightness in regards to breeding, since their type B correlation coefficient ( $r_{Bg}$ ) values fall just below the 0.67 value (Table 1.3). Forking and rust incidence had much greater values for the type B correlation coefficient ( $r_{Bg} > 0.67$ ) and can be assumed to have less meaningful GxE interactions (Table 1.3).

The use of Shukla's stability analysis further explained how much each seed source contributed to the variation found in the GxE interaction (Shukla 1972). The Virginia seed source contributed the greatest amount to the GxE interaction terms for height and volume growth with a percent variance contribution of 60% for both traits (Figure 1.7). The South Carolina Coastal seed source also contributed a great amount to the GxE interaction term for height and volume with a percent variance contribution of 18% for both traits (Figure 1.7). All other seed sources showed a lower contribution for Shukla's test of  $\hat{\sigma}_{LS(k)}^2 \leq 10\%$  per seed source (Figure 1.7). Significant Z-test values supported these descriptions as South Carolina Coastal, Florida & Georgia Coastal, and Virginia seed sources were significant ( $p < 0.05$ ) for both growth traits (Table 1.4). Lower Gulf and Upper Gulf seed sources showed some significance ( $p < 0.05$ ) but not individually for both growth traits (Table 1.4). Test site contribution to the GxE interaction variances for the growth traits showed that most sites contributed significantly ( $p < 0.05$  for Z-test) to the interaction term with the exception of a few sites found in colder regions (Table 1.5).

Differences among seed sources were more prevalent at the colder test sites. By comparing the coefficient of variation among seed sources at each site, the impact of minimum winter temperatures on seed source by site variation was evaluated. The regression of CVs for seed source differences for volume and height on minimum winter temperature at each site was highly significant ( $p < 0.001$ ) and had a  $R^2 > 0.70$  showing that variation among seed sources increased dramatically as minimum winter temperatures decreased (Figures 1.8 & 1.9). Rust incidence also had increasing variation as minimum winter temperatures increased, but the model was not significant ( $p = 0.078$ ), even though it had a moderate  $R^2 = 0.31$  (Figure 1.10). Forking incidence and straightness had no discernable trends due to their poor  $R^2 < 0.30$  and very low significance (Figures 1.11 & 1.12).

## **1.5 Discussion**

The purpose of the Plantation Seed Source Selection study was two-fold for seed sources: first, identify the performance of loblolly pine seed sources for multiple traits, and second, define and explain any trends of GxE interactions. The wide variety of climates in which loblolly pine grows suggests that seed sources would vary widely from each other, and their performance would vary widely across sites for economically important traits (Hocker, 1956, Wells and Wakeley 1966, Schmidting 2001, Schmidting 2007). The highly significant F-tests ( $p \leq 0.05$ ) of seed sources for all traits measured in this study support this statement (Table 1.2).

For growth traits, seed sources from the lower Atlantic Coastal regions (South Carolina Coastal and Florida & Georgia Coastal) outperformed the seed sources from Virginia, the Gulf Coast, and inland regions. This trend was not surprising, as better growth of Coastal sources compared to inland or northern sources has been reported in several studies (Wells and Wakeley 1966, Wells 1983, Lambeth et al 1984). South Carolina Coastal and Florida & Georgia Coastal seed sources had the best rust resistance while the Upper Gulf had the worst resistance (Figure 1.2). The Virginia seed source had the best form traits (i.e. lowest forking incidence and straightness scores) across most sites (Figures 1.3 & 1.6, Appendix A Tables A3 & A5).

GxE was important for growth traits in the study, as indicated by the significance of seed source by site (GxE) interaction for volume and height ( $p < 0.05$ ) and low type B correlation coefficient ( $r_{Bg} < 0.67$ ). The relative performance of seed sources varied depending on where they were grown with some sites and seed sources contributing more than others to GxE interactions. The results from Shukla's (1972) analysis were enlightening for the GxE interactions of growth traits as they revealed the highest contribution to GxE amongst the fastest (South Carolina Coastal) and slowest (Virginia) growing seed sources for height and volume (Figure 1.7). These two seed sources accounted for approximately 80% of the GxE interaction for these growth traits. One of the causes for this is that the growth trait values of the South Carolina Coastal seed source have a greater increase in comparison to the other seed sources as minimum winter temperatures increase. The growth trait values of the Virginia seed source also increase as minimum winter temperatures increase, but at a rate

much lower than the other seed sources. This pattern in variation among seed sources can be seen with the model of %CV by minimum winter temperatures and the growth trait means in Appendix A (Figures 1.8 & 1.9, Appendix A Table A1 & A2).

The modeling of the coefficient of variance (%CV) for seed sources across an environmental index (i.e. minimum winter temperatures) helps to define variation between seed sources for GxE interaction by exploring the effect of minimum winter temperatures on variation. For growth traits, variation among seed sources increased with increasing minimum winter temperatures regardless of site means (Figures 1.8 & 1.9, Table 1.1). This indicates the possibility that some seed sources are able to take advantage of warmer climates while others do not, even when soils and site growth means are radically different (Figures 1.8 & 1.9, Table 1.1, Appendix C). As mentioned before, the South Carolina Coastal and Virginia seed sources contribute the most to these variations as they are on different ends of the growth mean ranges. These results are important for testing as they indicate minimum winter temperatures play a major role level of variation occurring in a test. For example, the differences between the South Carolina Coastal and the other seed sources did not start increasing until minimum winter temperatures were higher than -11 °C (Figures 1.8 & 1.9, Appendix A Table A1 & A2). This example shows that testing loblolly trees in colder climates reduces the chance to find variation between seed sources.

While only having a p-value of 0.078, rust incidence did show some increasing seed source variation with increasing minimum winter temperatures (Figures 1.10, Table 1.1). This may have been due to movement of the seed sources into areas more prone to fusiform rust

infection, since fusiform rust is more prevalent in the more southern and eastern regions of loblolly pine's native range (Phelps & Czabator 1978). Straightness and forking showed no significant trends ( $p>0.05$ ) in seed source variation with regards to minimum winter temperatures (Figures 1.10 & 1.11, Table 1.1). Some reasons for the non-significant trends are that variation between seed sources for both traits is widely spread for any part of temperature gradient, and the type B correlation coefficients are high for straightness ( $r_{Bg}=0.65$ ) and forking ( $r_{Bg}=0.78$ ).

While this study showed that South Carolina Coastal and Virginia seed sources were some of the best choices for breeding in regards to their traits, caution should be used when planting them far outside of their native ranges, since the data are only from 8 year field trials, and moving seed sources outside their natural range carries risk (Schmidting 1994, Schmidting 2001, Lambeth et al. 2005). For instance, moving a southern Atlantic Coastal seed source to Arkansas might not work out as higher mortality, ice damage, etc. would not make it a viable option for planting in that particular area (Wells and Lambeth 1983, Schmidting 2001). Further analyses with results from 15<sup>th</sup> year measurements from the single tree plot tests used in this study and the complementary block plot study should prove more useful for determining the exact planting ranges for the seed sources in this experiment as mortality and growth trait differences between seed sources should be clearer.

These results showed that the South Carolina Coastal seed source had the highest growth, highest rust resistance, and mediocre form traits across all sites, suggesting that this seed source would be a reasonable choice for fast growth and disease resistant trees in most

breeding programs across the southeastern US. The Virginia seed source was the opposite as it had the best overall form traits and slowest growth traits, making it better complementary breeding stock for families and seed sources that have poor form traits for the purpose of increased sawtimber quality. The evaluation of GxE interaction shows higher responsiveness (i.e. change in variation) of some seed sources compared to others with the increase of minimum winter temperatures for growth traits, but not for the other traits. This means that GxE variation for loblolly pine seed sources can be predicted by minimum winter temperatures. Individual seed source and family responsiveness and predictability will be looked at in the next chapter.

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**Table 1.1.** Trait means at age 8 years for all sites. The sites are sorted by their minimum winter temperatures (Temp °C). STRT stands for straightness score.

Temp (°C)	Site	Survival	Rust Incidence	Height (m)	DBH (cm)	Volume (dm <sup>3</sup> )	STRT	Forking
-16.4	Stewart 1, TN	0.82	0.00	7.0	13.7	39.6	2.24	0.00
-16.4	Stewart 2, TN	0.85	0.00	7.0	13.7	38.8	2.20	0.00
-15.4	Appomattox 1, VA	0.93	0.00	8.2	14.0	46.2	2.04	0.00
-15.4	Appomattox 2, VA	0.91	0.01	9.0	14.7	56.4	3.36	0.11
-14.7	McNairy, TN	0.93	0.05	9.9	16.5	79.9	3.58	0.50
-14.6	Hardin, TN	0.77	0.01	9.0	16.0	68.0	3.16	0.35
-12.7	Northampton, NC	0.63	0.84	7.9	15.2	56.9	3.51	0.17
-12.1	Laurens, SC	0.92	0.47	8.9	14.2	52.4	3.45	0.28
-10.9	Chilton, AL	0.96	0.25	10.8	15.2	76.5	3.42	0.33
-10.9	Newberry, SC	0.85	0.69	9.2	16.5	75.0	3.51	0.46
-10.6	Robeson, NC	0.85	0.49	10.4	16.3	80.1	3.50	0.24
-10.1	Autauga, AL	0.56	0.69	8.8	15.5	61.2	3.44	0.10
-10.0	Williamsburg, SC	0.93	0.45	7.7	12.2	36.2	3.30	0.05
-8.8	Randolph, GA	0.90	0.61	7.0	11.4	28.0	3.07	0.39
-8.8	Escambia 1, AL	0.89	0.09	10.5	13.7	60.6	3.44	0.30
-8.8	Escambia 2, AL	0.96	0.31	10.6	16.5	84.4	3.3	0.17
-8.6	Screven, GA	0.92	0.55	8.9	14.5	55.8	3.43	0.17
-7.7	Berkeley, SC	0.82	0.72	11.9	17.3	103.4	3.76	0.12
-7.6	Tattnall, GA	0.93	0.51	12.3	16.3	96.6	3.55	0.21
-7.6	Bradford, FL	0.92	0.62	8.4	11.2	33.7	3.55	0.08
-7.6	Ware, GA	0.94	0.23	8.0	10.4	26.6	3.38	0.08
	<b>Overall</b>	<b>0.87</b>	<b>0.36</b>	<b>9.1</b>	<b>14.5</b>	<b>59.8</b>	<b>3.25</b>	<b>0.20</b>

**Table 1.2.** F tests for height, volume, rust resistance, forking, and straightness. The main effects of test location, seed source and the seed source by location (GxE) interaction terms were all significant at  $Pr \leq 0.05$ , with the exception of interaction term for forking.

Trait	Location (L)		Seed Source (S)		S*L	
	F	Pr>F	F	Pr>F	F	Pr>F
Height	388	<.001	331	<.001	13	<.001
Volume	396	<.001	361	<.001	16	<.001
Straightness	148	<.001	43	<.001	2.17	<.001
Forking	234	<.001	9	<.001	1.24	0.057
Rust incidence	484	<.001	15	<.001	1.54	0.001

Numerator and denominator degrees of freedom (Num/deno) for location, seed source and S\*L were 20/470, 6/2544 and 108/2544, respectively, for height, volume, and straightness.

Numerator and denominator degrees of freedom (Num/deno) for location, seed source and S\*L were 16/47021, 6/47021 and 96/47021, respectively, for forking since cold regions were excluded and residuals had to be substituted for blocks. Numerator and denominator degrees of freedom (Num/deno) for location, seed source and S\*L were 16/50537, 6/50537 and 96/50537, respectively, for rust incidence since cold regions were excluded and residuals had to be substituted for blocks.

**Table 1.3.** Variance components (standard errors in parenthesis) for seed source ( $\sigma_s^2$ ), seed source by environment interaction ( $\sigma_{is}^2$ ), and type B correlation coefficient ( $r_{Bg}$ ) for height, volume, rust incidence, forking, and straightness.

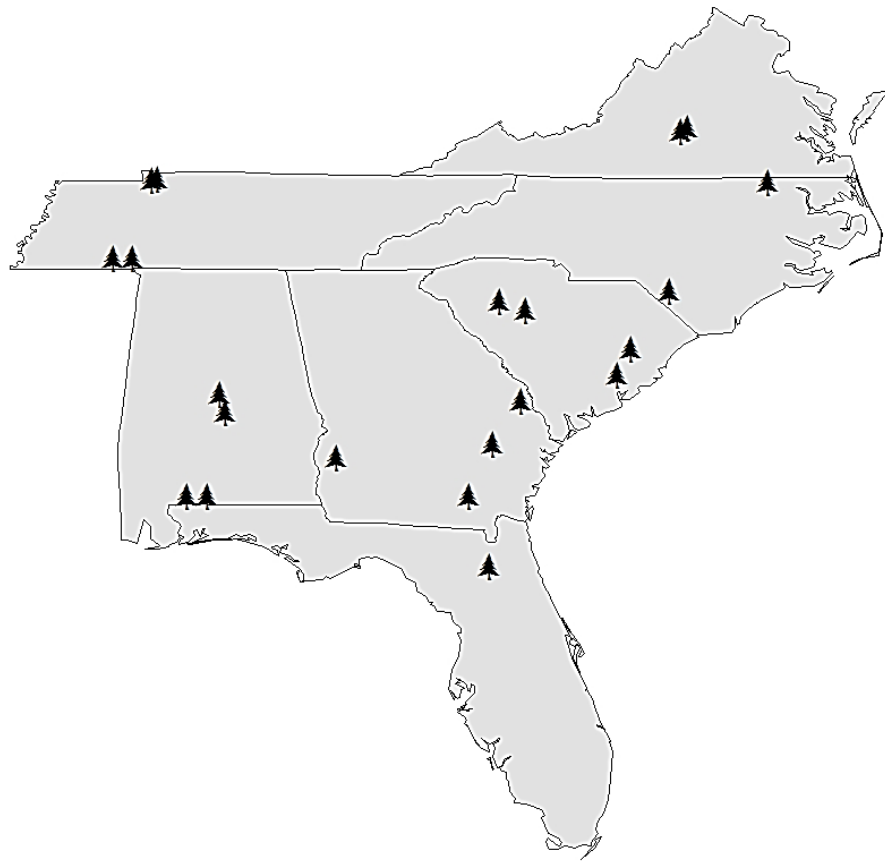
<b>Trait</b>	$\sigma_s^2$ (SE)	$\sigma_{is}^2$ (SE)	$r_{Bg}$ (SE)
Height	0.045 (0.027)	0.028 (0.004)	0.61 (0.147)
Volume	29.953 (17.936)	20.283 (2.957)	0.60 (0.149)
Straightness	0.005 (0.003)	0.003 (0.001)	0.65 (0.150)
Rust Incidence	0.035 (0.021)	0.008 (0.003)	0.82 (0.107)
Forking	0.010 (0.006)	0.003 (0.003)	0.78 (0.193)

**Table 1.4.** Variance components ( $\hat{\sigma}_{LS(k)}^2$ ) contributed by each seed source to GxE interaction total variance based on Shukla's (1972) method. Approximate estimates of standard errors (SE) are given in the parenthesis. The Z values are a ratio of the variances to their standard errors ( $\hat{\sigma}_{LS(k)}^2/SE$ ) with significance probability values.

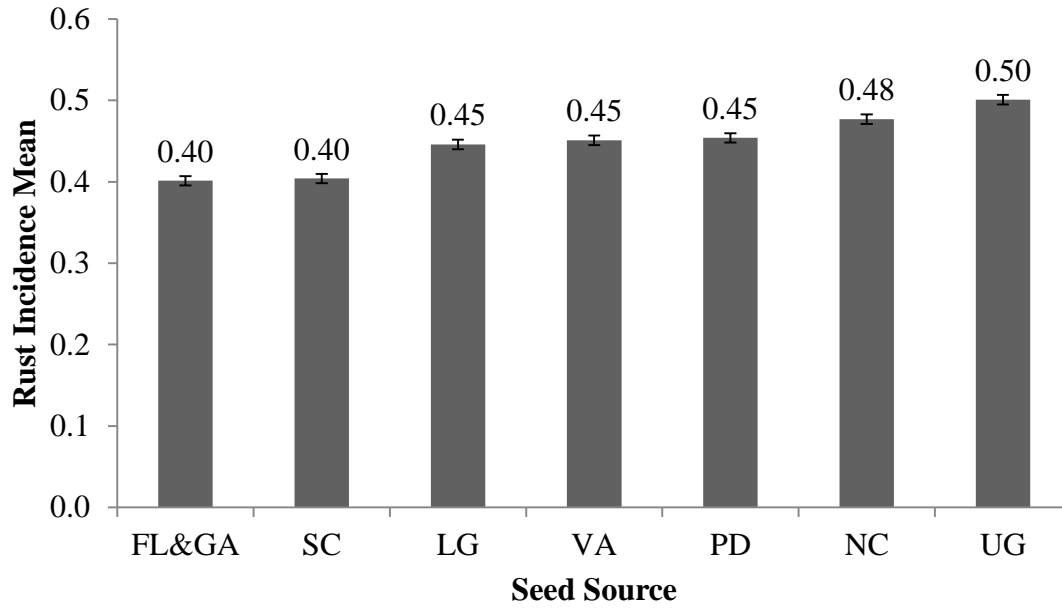
Seed Source	Height			Volume		
	$\hat{\sigma}_{LS(k)}^2$ (SE)	Z	Pr>Z	$\hat{\sigma}_{LS(k)}^2$ (SE)	Z	Pr>Z
VA	0.111 (0.037)	3.01	0.001	76.2 (25.22)	3.02	0.001
NC-C	0.003 (0.003)	1.11	0.134	4.1 (2.60)	1.60	0.055
SC-C	0.033 (0.014)	2.41	0.008	24.6 (9.98)	2.46	0.007
GA&FL-C	0.017 (0.008)	2.09	0.019	12.3 (5.86)	2.10	0.018
LG	0.011 (0.006)	1.81	0.036	5.2 (3.25)	1.60	0.055
UG	0.005 (0.003)	1.54	0.062	3.5 (2.11)	1.68	0.046
PD	0.005 (0.003)	1.45	0.073	3.6 (2.37)	1.51	0.065

**Table 1.5.** Variance ( $\hat{\sigma}_{LS(j)}^2$ ) contributed by each test site to GxE total variance based on Shukla's (1972) method. The Z values are a ratio of the variances and standard errors ( $\hat{\sigma}_{LS(k)}^2/SE$ ). Minimum winter temperatures (Temp ( $^{\circ}C$ )) are listed next to site.

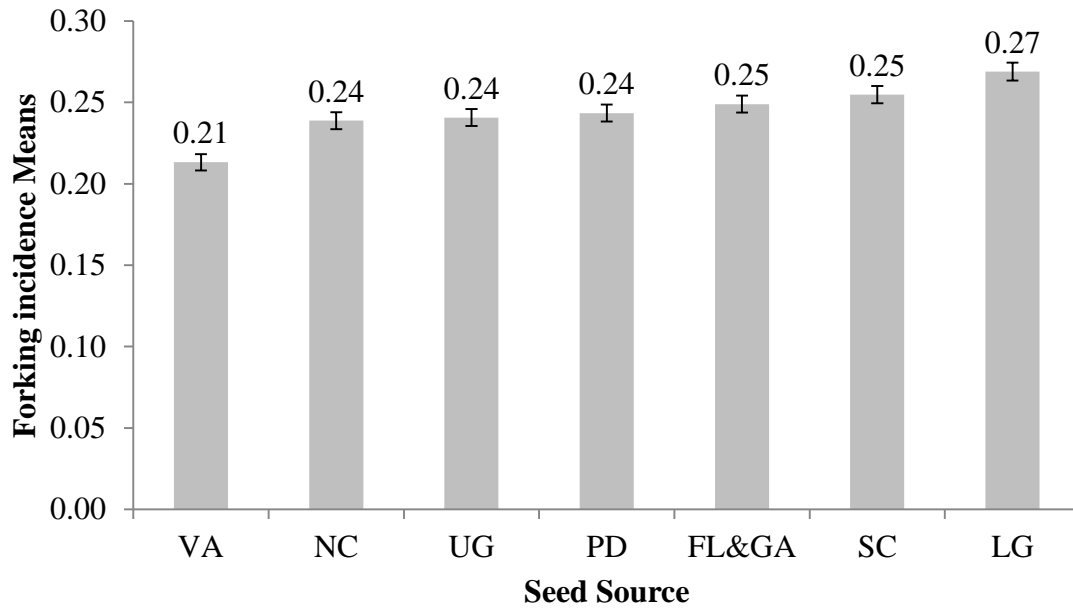
Temp ( $^{\circ}C$ )	Site	Height			Volume		
		$\sigma_{LS(j)}^2$ (SE)	Z	Pr>Z	$\sigma_{LS(j)}^2$ (SE)	Z	Pr>Z
-16.4	Stewart 1, TN	0.348 (0.246)	1.41	0.08	308 (223.3)	1.38	0.08
-16.4	Stewart 2, TN	0.357 (0.253)	1.41	0.08	319 (230.8)	1.38	0.08
-15.4	Appomattox 1, VA	0.046 (0.033)	1.39	0.08	112 (84.3)	1.33	0.09
-15.4	Appomattox 2, VA	0.002 (0.002)	1.02	0.15	7 (10.0)	0.68	0.25
-14.7	Mcnairy, TN	0.089 (0.048)	1.86	0.03	410 (225.6)	1.82	0.03
-14.6	Hardin, TN	0.001 (0.001)	1.1	0.14	86 (49.4)	1.74	0.04
-12.7	Northampton, NC	0.109 (0.059)	1.86	0.03	49 (34.7)	1.41	0.08
-12.1	Laurens, SC	0.000 (0.000)	-----	-----	80 (52.1)	1.54	0.06
-10.9	Chilton, AL	0.366 (0.196)	1.87	0.03	289 (162.1)	1.78	0.04
-10.9	Newberry, SC	0.006 (0.003)	1.73	0.04	222 (126.3)	1.76	0.04
-10.6	Robeson, NC	0.203 (0.109)	1.87	0.03	399 (220.6)	1.81	0.04
-10.1	Autauga, AL	0.002 (0.001)	1.34	0.09	1 (7.9)	0.15	0.44
-10	Williamsburg, SC	0.178 (0.095)	1.86	0.03	647 (355.3)	1.82	0.03
-8.8	Randolph, GA	0.387 (0.207)	1.87	0.03	1082 (585.5)	1.85	0.03
-8.8	Escambia 1, AL	0.255 (0.137)	1.87	0.03	45 (27.5)	1.66	0.05
-8.8	Escambia 2, AL	0.280 (0.150)	1.87	0.03	607 (335.1)	1.81	0.04
-8.6	Screven, GA	0.004 (0.002)	1.63	0.05	32 (21.1)	1.51	0.07
-7.7	Berkeley, SC	0.840 (0.449)	1.87	0.03	1808 (977.0)	1.85	0.03
-7.6	Tattnall, GA	1.120 (0.599)	1.87	0.03	1351 (734.7)	1.84	0.03
-7.6	Bradford, FL	0.051 (0.028)	1.85	0.03	756 (411.1)	1.84	0.03
-7.6	Ware, GA	0.104 (0.056)	1.86	0.03	1178 (637.5)	1.85	0.03



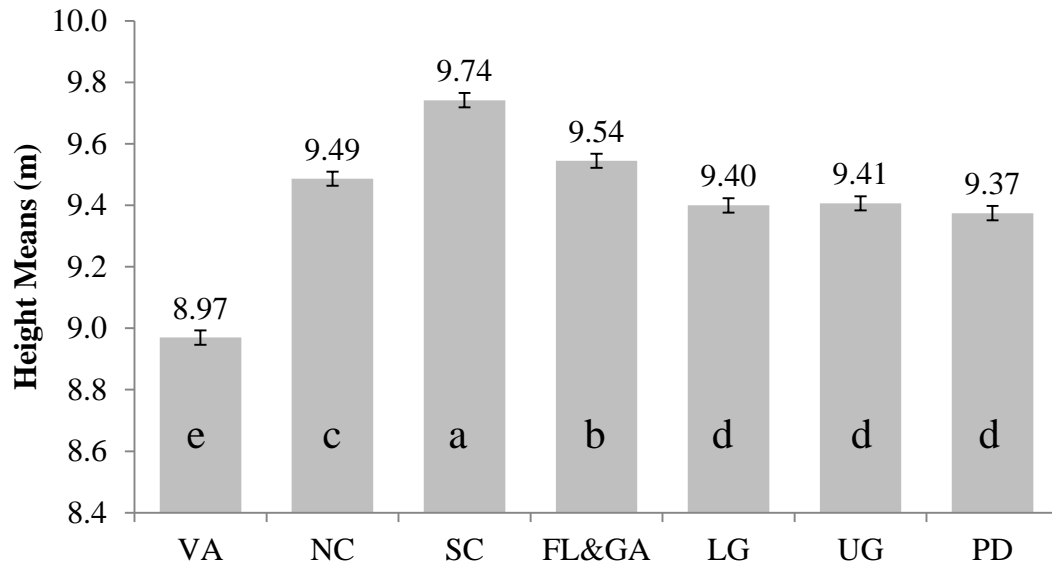
**Figure 1.1.** Test site locations for the Plantation Selection Seed Source Study (PSSSS) trials. These 21 test locations are scattered across the entirety of the loblolly range east of the Mississippi river.



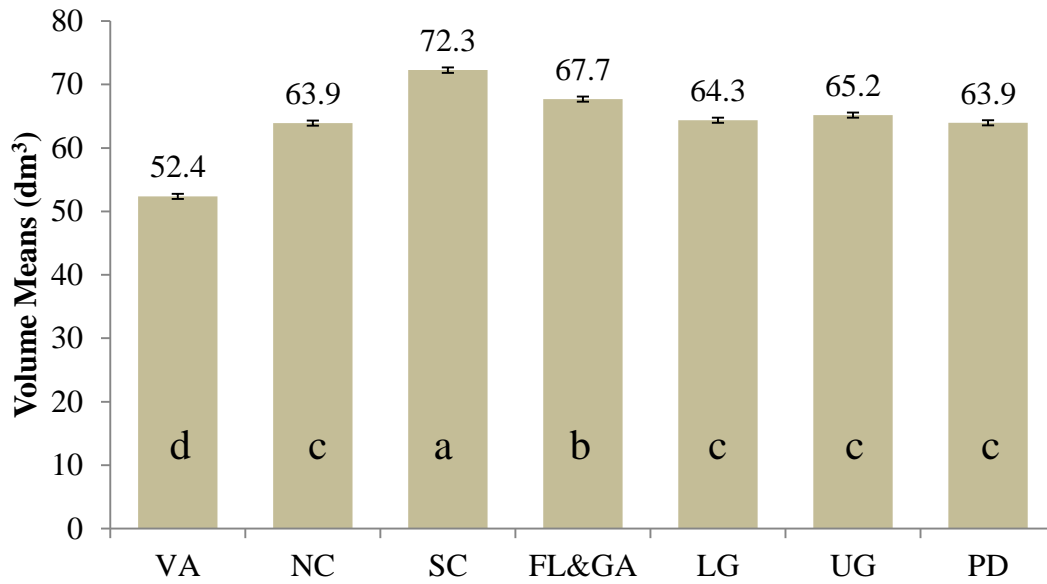
**Figure 1.2.** Seed source simple means (proportions) and their standard errors for rust incidence. These means exclude the Stewart, TN and Appomattox, VA sites since they were not measured for forking and were out of the range for fusiform rust infection.



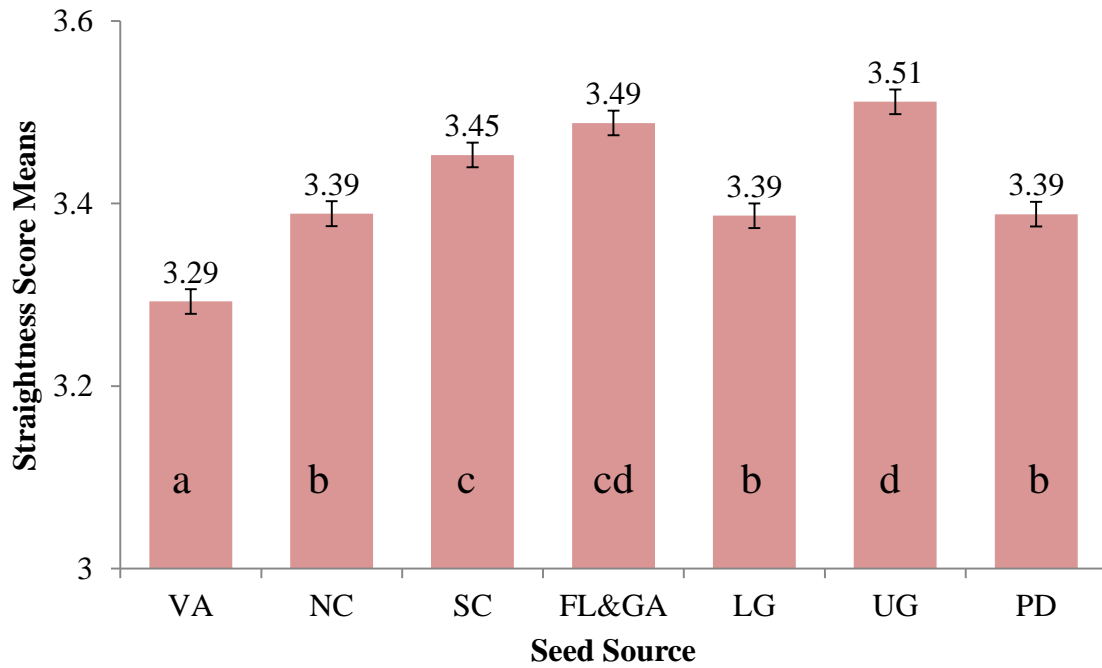
**Figure 1.3.** Seed source simple means (proportions) and their standard errors for forking incidence. These means exclude the Stewart, TN and Appomattox, VA sites since they were not measured for forking and were out of the range for fusiform rust infection.



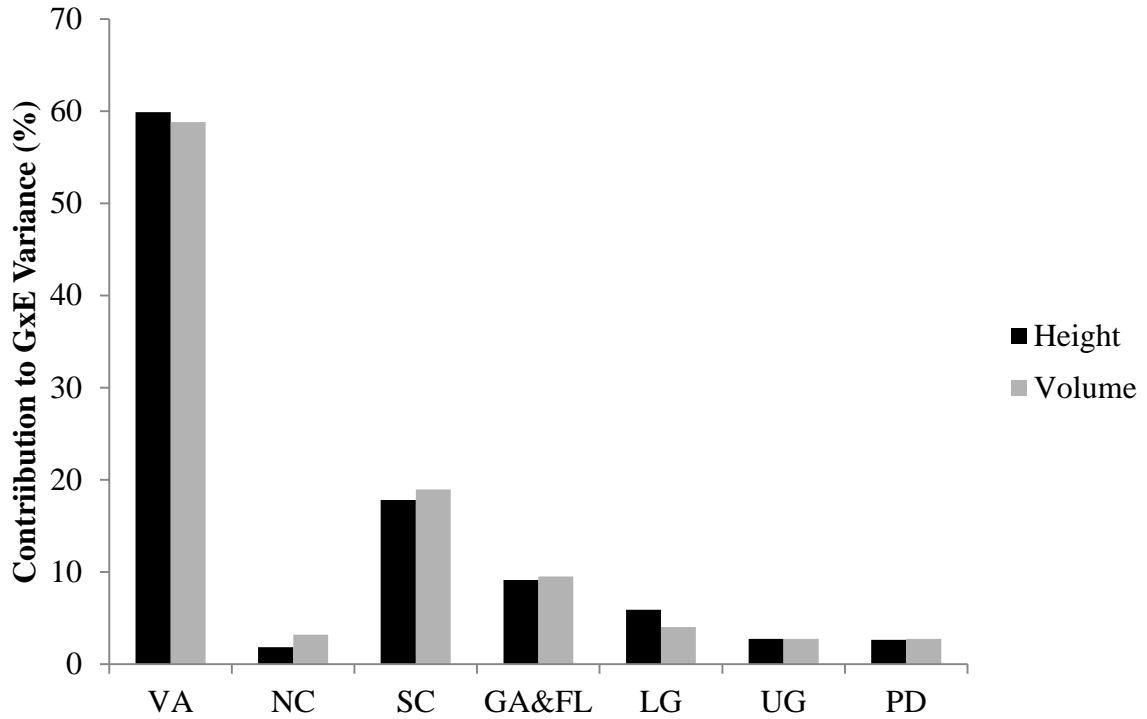
**Figure 1.4.** Seed source least squares means, their standard errors and Tukey’s multiple range test for height. Means with the same letter for a given trait are not significantly different from each other.



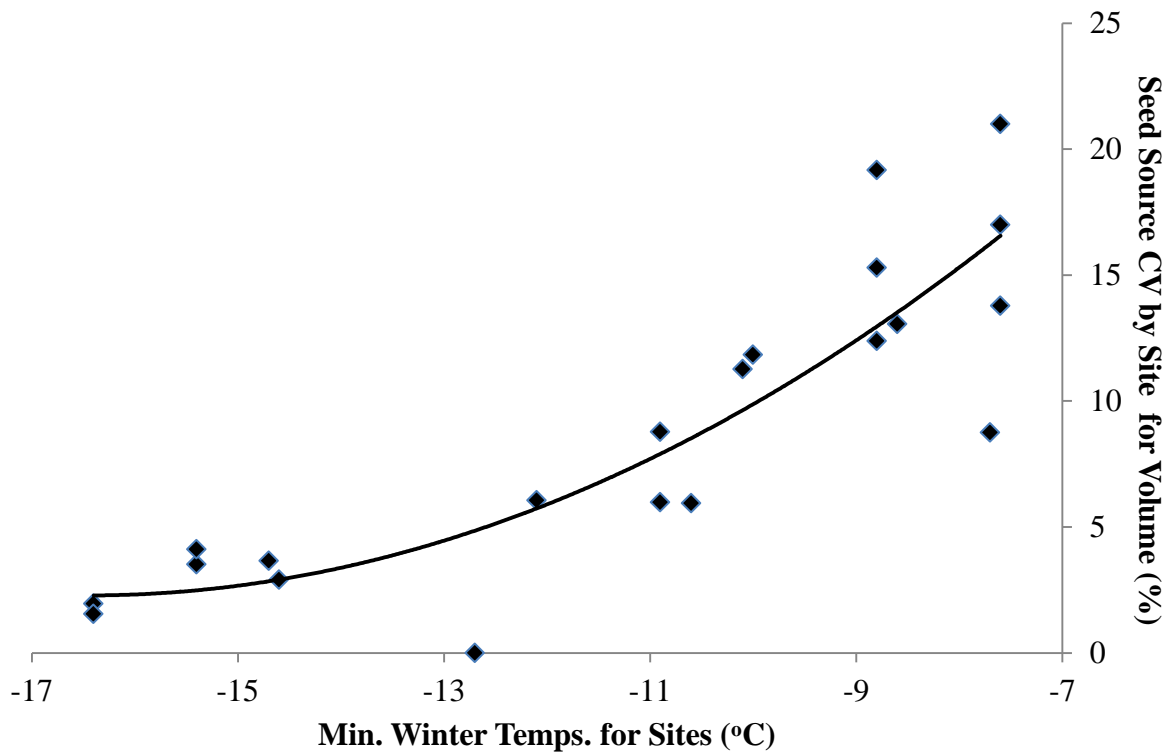
**Figure 1.5.** Seed source least squares means, their standard errors and Tukey’s multiple range test for volume. Means with the same letter for a given traits are not significantly different from each other (rank ‘a’ is the highest mean to rank ‘d’ the lowest).



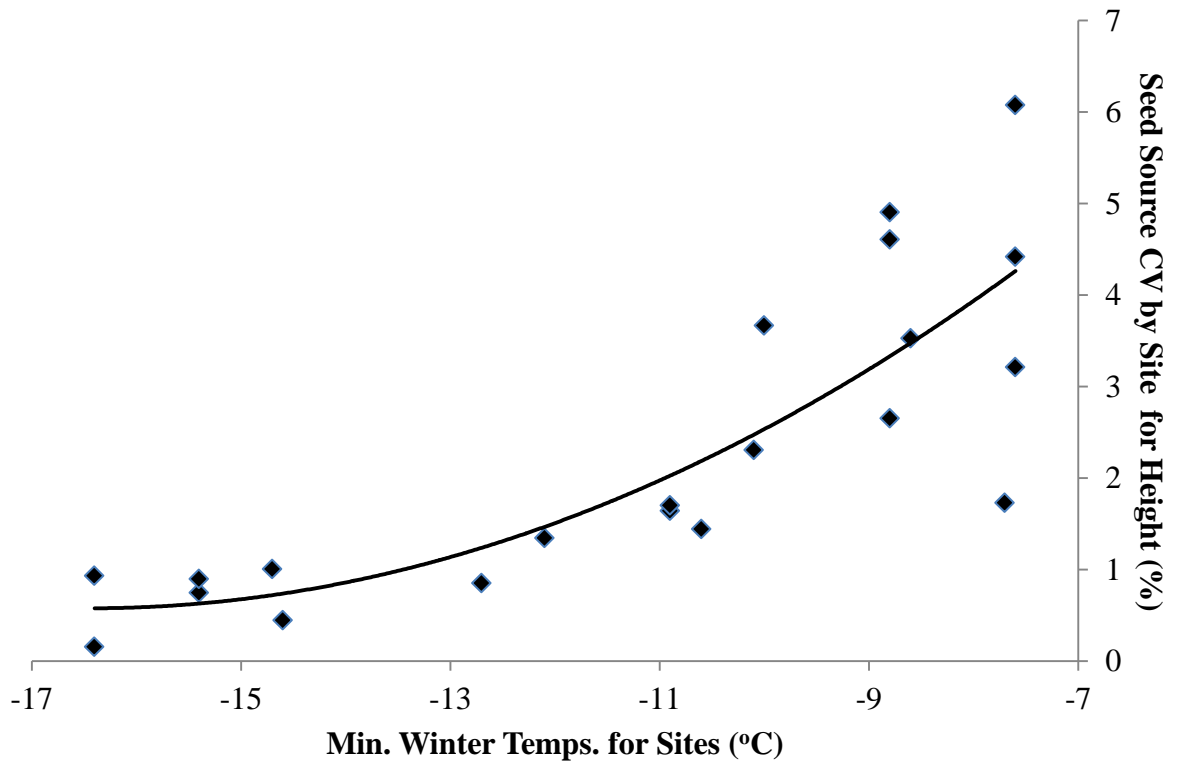
**Figure 1.6.** Seed source least squares means, their standard errors and Tukey’s multiple range test for straightness. Means with the same letter for a given traits are not significantly different from each other (rank ‘a’ is the lowest score to rank ‘d’ the highest).



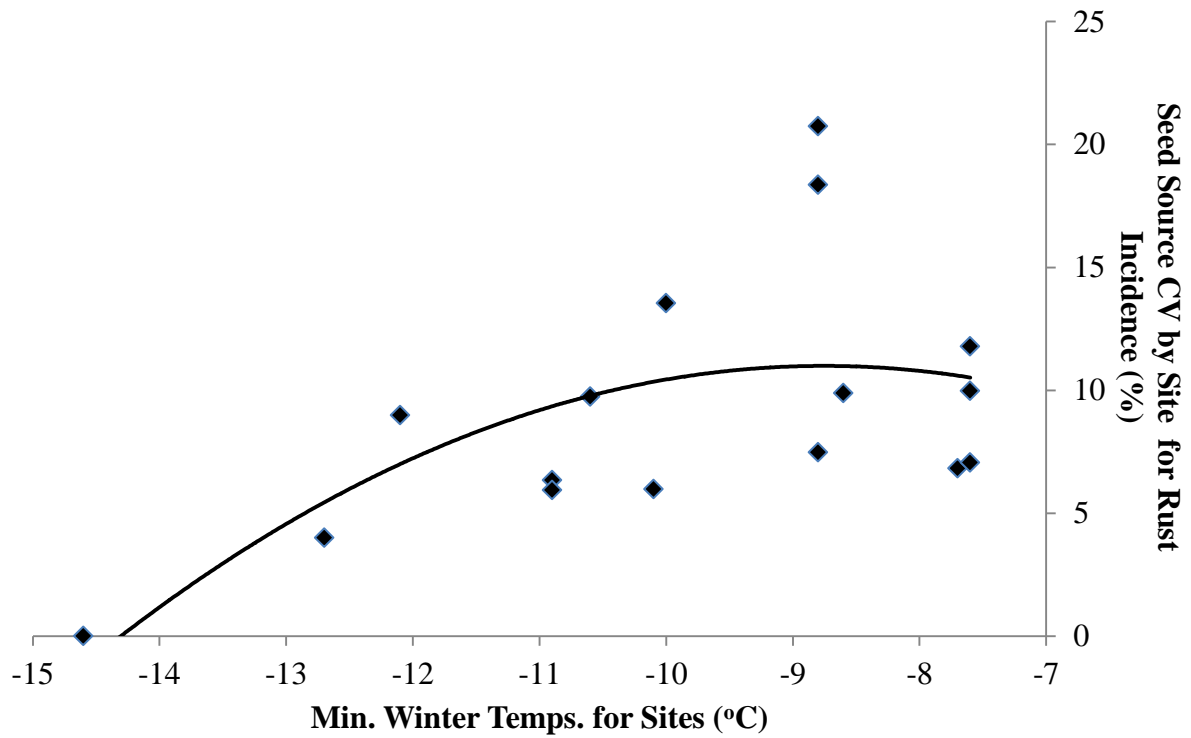
**Figure 1.7.** The percent contribution ( $\% \text{ contribution} = \sigma_{LS(k)}^2 / \sigma_{LS}^2$ ) of each seed source ( $\sigma_{LS(k)}^2$ ) to the seed source by test site (GxE,  $\sigma_{LS}^2$ ) interaction term using Shukla's method. The Virginia seed source (VA) has the highest contribution to the GxE interaction term for growth traits.



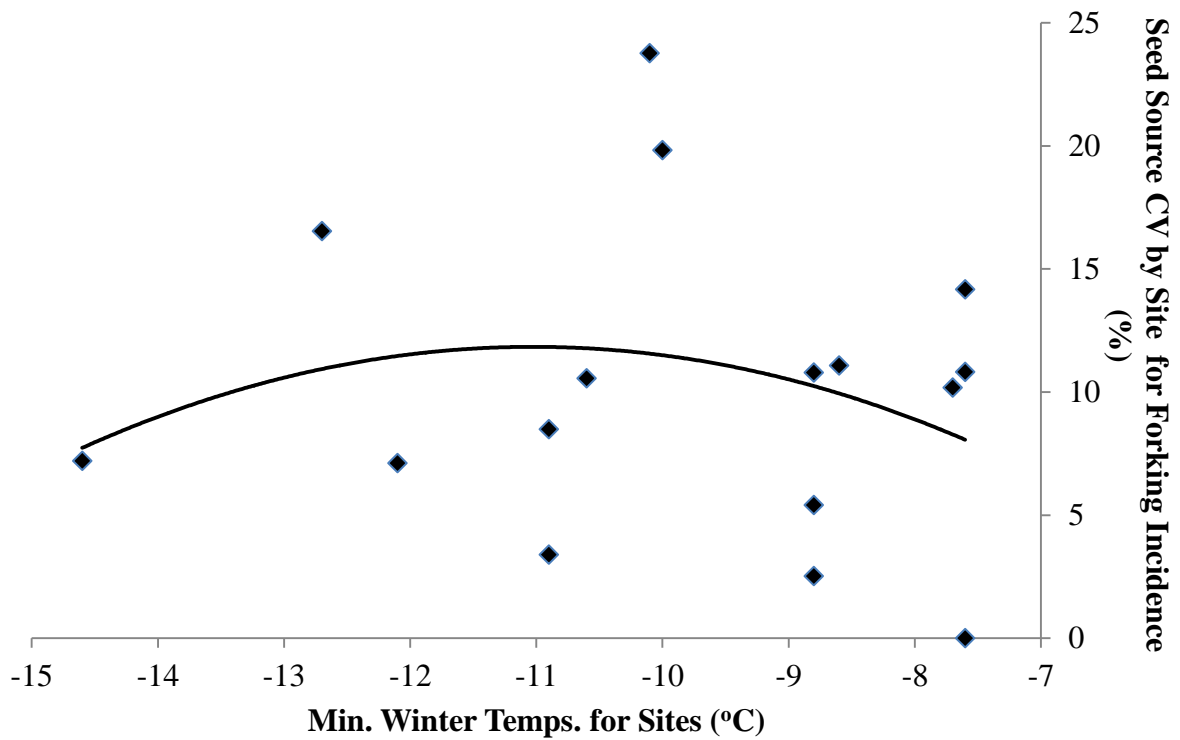
**Figure 1.8.** Seed source coefficient of variance (%CV) by site compared against minimum winter temperatures (°C) for volume growth. The quadratic model fit for these data was  $y = 5.874x + 0.178x^2 + 50.855$  with an  $R^2=0.74$ . The model's F-test was significant ( $p<0.001$ ).



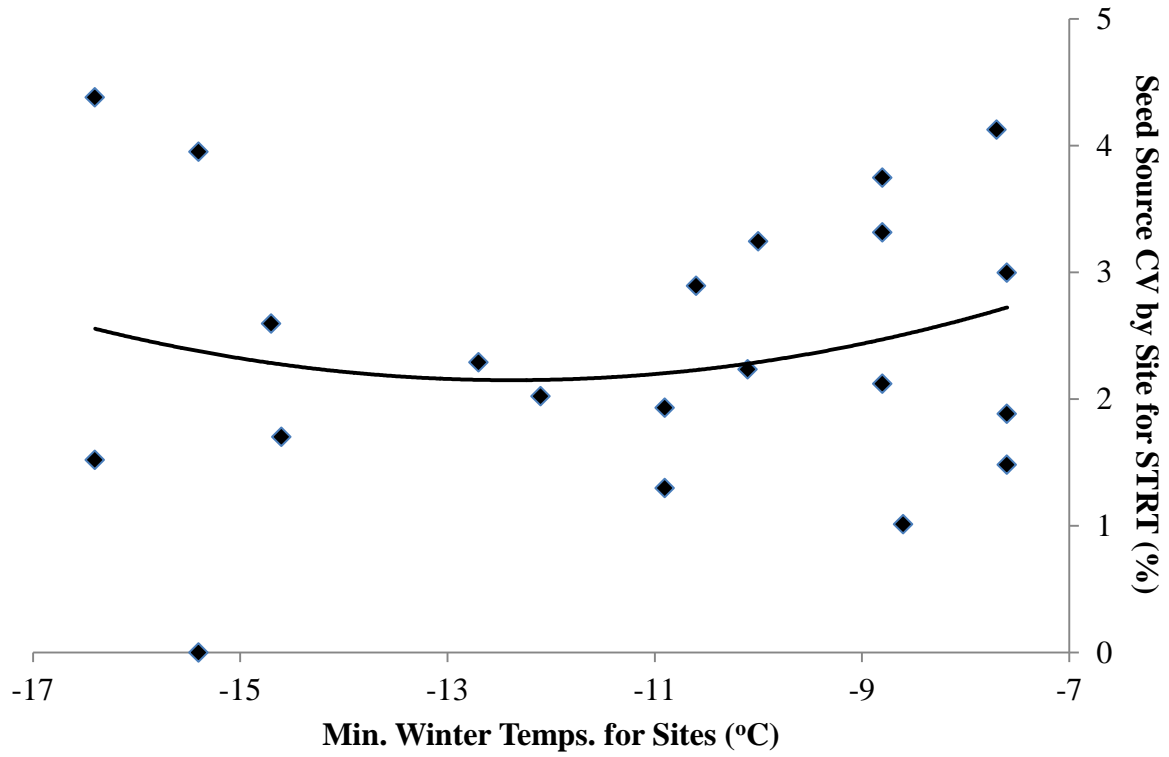
**Figure 1.9.** Seed source coefficient of variance (%CV) by site compared against minimum winter temperatures (°C) for height. The quadratic model fit for these data was  $y = 1.835x + 0.058x^2 + 15.101$  with an  $R^2=0.70$ . The model's F-test was significant ( $p<0.001$ ).



**Figure 1.10.** Seed source coefficient of variance (%CV) by site compared against minimum winter temperatures (°C) for rust incidence. The quadratic model fit for these data was  $y = -3.089x - 0.193x^2 - 1.546$  with an  $R^2=0.31$ . The model's F-test was marginally significant ( $p=0.078$ ).



**Figure 1.11.** Seed source coefficient of variance (%CV) by site compared against minimum winter temperatures (°C) for forking incidence. The quadratic model fit for these data was  $y = -8.879x - 0.414x^2 - 35.636$  with an  $R^2=0.12$ . The model's F-test was not significant ( $p=0.418$ ).



**Figure 1.12.** Seed source coefficient of variance (%CV) by site compared against minimum winter temperatures (°C) for straightness. The quadratic model fit for these data was  $y = 0.299x + 0.013x^2 + 3.959$  with an  $R^2=0.01$ . The model's F-test was not significant ( $p=0.939$ ).

## **Chapter 2:**

# **Genotype by Environment Interactions of Diverse Families of Loblolly Pine Across a Wide Range of Sites**

## 2.1 Abstract

Height, volume, straightness, stem forking, and incidence of fusiform rust disease (caused by *Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*) were assessed for genetic responses of first-generation plantation selections of loblolly pine (*Pinus taeda* L.) planted across the southeastern United States. The range of individual-tree narrow-sense heritabilities for height, volume, and straightness were in the expected range of 0.1 to 0.6. Family mean heritabilities for all traits were larger and ranged from ~0.3 to 0.8. The type B genetic correlations for height ( $r_{Bg}=0.66$ ) and volume ( $r_{Bg}=0.54$ ) suggested substantial genotype by environment (GxE) interactions exist for families across diverse sites. When families means were regressed across site means to calculate stability values, the slope ( $\beta_1$ ) for height showed average stability ( $\beta_1=1$ ) for most families and did not significantly differ ( $p=0.284$ ) among seed sources, but the intercept values did significantly differ ( $p=0.008$ ) between seed sources. Slope and intercept values were both significantly different ( $p<0.05$ ) among seed sources for volume. The results suggested that height was relatively predictable due to average stability for most families while volume was unpredictable due to its highly variable stability parameters (i.e. slope). This means that planning for breeding and testing of volume is more difficult than for height due to GxE interactions and stability parameters.

## 2.2 Introduction

Considerable genetic gains have been obtained for loblolly pine (*Pinus taeda* L.) in growth and other traits over the past 50 years of tree breeding (McKeand et al 2003). To better

understand the response of selected families to different environments and delineate breeding and deployment zones, genotype by environment (GxE) interactions has been a key research emphasis during this time. The contribution of a wide range of environmental factors, such as soil and temperature influences, across loblolly pine's natural range to the geographic variation makes analysis of variance components and GxE interaction necessary for breeding (Hocker, Jr. 1956, Schmidting 2001, Schmidting 2007).

The evaluation of GxE interaction in tree breeding is important since differences in environmental interactions with germplasm have important effects on how deployment and breeding will occur (Roth et al. 2007, McKeand et al. 1997). Some studies of GxE for loblolly pine have found high GxE significance for various traits, but also found that family rank did not change and/or stability factors related to GxE interaction were not considerable enough to warrant further analysis (Li and McKeand 1989, Matheson and Cotterill 1990, McKeand et al. 1990). In other cases, GxE interactions had significant effects that could be explained mostly by a few sites, certain families, or other factors (Sierra-Lucero et al. 2002, Roth et al. 2007). These studies showed that the underlying premise of working on GxE interactions should not just be an assessment of a breeding population as a whole, but an assessment to find the factors that lead to the significance of the GxE interaction within that whole.

The Plantation Selection Seed Source Study (PSSSS) was initiated by the NC State University Cooperative Tree Improvement Program in the 1990's as a way to determine the patterns of geographic variation in first-generation plantation selections. The PSSSS

represents a unique opportunity to evaluate loblolly pine breeding population selections by testing a large sample of all geographic varieties of the species across a wide range of environments. Plantation selections comprise about 85% of the breeding population in the NC State Cooperative (Weir and Zobel 1975), so understanding the patterns of variation is critical for the success of the breeding program.

From Chapter 1, we know that seed sources differ from each other in trait characteristics, contributions to variation, and the effect of minimum winter temperatures on variation among seed sources, mainly for growth traits. Results from Chapter 1 show that seed source performance and variation are affected by differing climates. In this chapter, we evaluate the families from each seed source in detail. The purpose of this chapter is to estimate genetic and environmental components of variation for all 140 families across 17 different tests, and understand GxE interaction and the stability of families related to environmental factors.

## **2.3 Materials and Methods**

### *2.3.1 Plant Material and Mating Design*

Selections for this study were randomly chosen from a pool of 3300 first-generation plantation selections in seven breeding regions in the Southeastern United States. Originally there were eight regions, but the North Carolina Piedmont was divided between the Virginia (VA) region and the Piedmont of South Carolina and Georgia (PD) region. In each region, 20 selections were randomly chosen as females to generate a total of 140 families. These selections were then mated with a pollen mix of 40 pollen parents from each region giving a

total of 280 pollen parents. The only biological criteria were that the females had to be producing female strobili, and the pollen parents were producing sufficient viable pollen to contribute to the pollen mix. The female and pollen parents were not the same in order to prevent any selfing. For each region, the 40 pollen parents from each region were bulked based on germination percentage in an attempt to achieve equal representation of male pollen parents in the offspring.

### 2.3.2 *Field design*

A randomized complete block design with single-tree plots was used for all sites. The seedlings were planted at 25 test locations, but only 17 test sites were available for this study (Figure 2.1, Table 2.1). Four northern test sites were not included because they were missing too many of the families present in southern sites, and four other sites did not have 8 year data available. Minimum winter temperatures for each test site were estimated using weather data obtained by linear regression of county weather data from 1980 to 2010 (Dr. Benjamin Smith, NC State University, pers. com.).

Each test had 24 blocks (with the exception that one site had only 11 blocks) with a single tree from each family and four unimproved local check lot seedlings randomly distributed throughout each block for a total of 3456 trees per test site. Test sites were planted from 1994 to 1997 with a few exceptions (Appendix C).

While most of the sites had projected site index values around 20 m (65 feet) at a base age of 25 years, there were some differences (Appendix C). Most test sites were planted on a 2.7m x

2.7 m or 2.4m x 3.0m (9'x9' or 8'x10') spacing, but a few were planted with some spacings as small as 2.1m x 2.1m (7'x7').

### 2.3.3 Measurements

Height, diameter at breast height (DBH), straightness, the presence or absence of fusiform rust galls on the stem or branches, forking, and survival were measured for all trees at age 8. Straightness score was measured on a scale of 1 to 6 for most test sites with lower scores being straighter. Straightness means were multiplied by 100 times to reduce the decimal places for its variance components. Forking was determined as the presence or absence of forks or major ramicorn branching for a tree. Height and DBH were used to calculate individual-tree volume ( $\text{dm}^3$ ) using the following equation (Sherrill et al 2008):

$$\hat{V}_{ib} = 0.954560899 + 0.282415876 * \left( \frac{\text{DBH}^2 \text{Height}}{10} \right) \quad (\text{Eq. 2.1})$$

### 2.3.4 Statistical Analysis

A linear mixed model was fit to individual site data to partition variance into observed components:

$$y_{ijkl} = u + B_i + S_j + F(S)_{j(k)} + BS_{ij} + \varepsilon_{ijkl} \quad (\text{Eq. 2.2})$$

where  $y_{ijkl}$  is the  $l$ th observation of the  $k$ th family from the  $j$ th seed source in the  $i$ th block;  $B_i$  is the random effect of the  $j$ th block  $\sim \text{iid}(0, \sigma_b^2)$ ;  $S_j$  is the fixed effect of the  $j$ th seed source;

$F(S)_{j(k)}$  is the random effect for the  $k$ th family nested in the  $j$ th seed source  $\sim \text{iid}(0, \sigma_{f(s)}^2)$ ;  $BS_{ij}$  is the random interaction between  $j$ th seed source and  $i$ th block  $\sim \text{iid}(0, \sigma_{bs}^2)$ ; and  $e_{ijkl}$  is the residual associated with the  $l$ th observation of the  $k$ th family from the  $j$ th seeds source in the  $i$ th block  $\sim \text{iid}(0, \sigma_e^2)$ .

Using the variances from individual site analyses, the individual tree narrow sense heritabilities of height, volume, and straightness were calculated for each site using the following equations:

$$h_i^2 = \frac{4\sigma_{f(s)}^2}{\sigma_{f(s)}^2 + \sigma_e^2} \quad (\text{Eq. 2.3})$$

where  $h_i^2$  is the heritability for each site,  $\sigma_{f(s)}^2$  is the pooled variance among families within seed source for each site, and  $\sigma_e^2$  is the error variance for each site.

Family mean heritabilities were calculated for each site for all traits using the following equation:

$$h_f^2 = \frac{\sigma_{f(s)}^2}{\sigma_{f(s)}^2 + \sigma_e^2/n} \quad (\text{Eq. 2.4})$$

where  $h_f^2$  is the heritability for each site,  $\sigma_{f(s)}^2$  is the pooled variance among families pooled within seed sources for each site,  $\sigma_e^2$  is the error variance for each site, and  $n$  is the average number of individuals for a family.

To determine the effect of environmental conditions on family mean heritabilities, a regression model was fit. The minimum winter temperature ( $^{\circ}\text{C}$ ) at each test site was used as the predictor variable for the following quadratic model:

$$y = \beta_0 + \beta_1x + \beta_2x^2 + \varepsilon \quad (\text{Eq. 2.5})$$

where  $y$  is the predicted family mean heritability;  $\beta_0$  is the intercept;  $\beta_1$  is the coefficient for minimum winter temperatures ( $x$ );  $\beta_2$  is the coefficient for the quadratic effect of minimum winter temperatures ( $x^2$ ); and  $\varepsilon$  is the error. The GLM procedure of SAS software was used to run the model for Eq. 2.5 (SAS Institute Inc. 2008). We used  $\alpha=0.05$  as the threshold for statistical significance for the F test of the model.

In order to examine genotype by environment interactions, the combined data from all sites was used. The following linear model was fit to partition observed variation into genetic, environment, and genotype by environment interaction components:

$$y_{ijklm} = u + L_i + B(L)_{j(i)} + S_k + F(S)_{l(k)} + LS_{ik} + LF(S)_{il(k)} + BS(L)_{kj(i)} + \varepsilon_{ijklm} \quad (\text{Eq. 2.6})$$

where  $y_{ijklm}$  is the  $m$ th observation of the  $l$ th family from the  $k$ th seed source in the  $j$ th block of the  $i$ th test;  $L_i$  is the fixed effect of the  $i$ th location;  $B(L)_{j(i)}$  is the random effect of the  $j$ th block within the  $i$ th location  $\sim$  iid  $(0, \sigma_{b(l)}^2)$ ;  $S_k$  is the fixed effect of the  $k$ th seed source;  $F(S)_{l(k)}$  is the random effect for the  $l$ th family nested within the  $k$ th seed source  $\sim$  iid  $(0, \sigma_{f(s)}^2)$ ;  $LS_{il}$  is the fixed term for interaction between  $i$ th location and the  $k$ th seed source;  $LF(S)_{il(k)}$  is the random interaction between  $i$ th location and  $l$ th family nested within the  $k$ th seed source  $\sim$  iid  $(0, \sigma_{lf(s)}^2)$ ;  $BS(L)_{kj(i)}$  is the random interaction between  $k$ th seed source and  $j$ th block within the  $i$ th location  $\sim$  iid  $(0, \sigma_{bs(l)}^2)$ ; and  $e_{ijklm}$  is the residual associated with  $m$ th observation of the  $l$ th family from the  $k$ th seeds source in the  $j$ th block of the  $i$ th test  $\sim$  iid  $(0, \sigma_e^2)$ .

Using the variances components, the family mean heritabilities for height, volume, forking, rust incidence, and straightness across all sites were estimated as follows:

$$h_f^2 = \frac{\sigma_{f(s)}^2}{\sigma_{f(s)}^2 + \sigma_{lf(s)}^2/t + \sigma_e^2/tn} \quad (\text{Eq. 2.7})$$

where  $h_p^2$  is the pooled family mean heritability across all sites,  $\sigma_{f(s)}^2$  is the pooled variance among families within seed source,  $\sigma_{lf(s)}^2$  is the family within seed source by environment interaction,  $\sigma_e^2$  is the error variance,  $t$  is the number test used in this study, and  $n$  is the average number of individuals for a family.

Estimation of variance components and their functions were carried out using the ASReml software, which uses restricted maximum likelihood method to estimate variances for continuous traits, and uses an approximate likelihood method called penalized quasi-likelihood to estimate variances for binary traits (Gilmour et al 2006). Variance-covariances of variance components and the Delta method were used to estimate standard errors of functions of variance components (Isik et al. 2008). The error variance for the binomial traits was fixed to  $\pi^2/3$  (Gilmour et al. 1985). Test sites with binomial traits averaging less than 0.2 and greater than 0.8 were not used to calculate heritabilities, since the variance components may become skewed outside of these limits (Lopes et al 2000).

Using the family by environment interaction and the additive genetic variance, type B correlation was calculated to examine the GxE interaction across all the sites:

$$r_{Bg} = \frac{\sigma_{f(s)}^2}{\sigma_{f(s)}^2 + \sigma_{lf(s)}^2} \quad (\text{Eq. 2.8})$$

where  $r_{Bg}$  is the type B correlation coefficient across all sites,  $\sigma_{f(s)}^2$  is the family variance, and  $\sigma_{lf(s)}^2$  is the family by location, or GxE interaction variance. The type B correlation coefficient gives a general prediction of importance for interaction terms where a value less than 0.67 suggests that family by test site (GxE) interactions could be considerable and warrants closer analysis to understand the underlying causes (Burdon 1977, Shelbourne 1972, Isik et al 2008, Komakech 2009). Traits with low type B correlations (e.g.  $r_{Bg} < 0.67$ )

were then tested in linear models with an environmental index to find the stability parameters of the genotypes across environments.

The regression of families on an environmental index, as suggested by Finlay and Wilkinson (1963), was used to assess the stability of families in the following linear regression model:

$$y = \beta_0 + \beta_1x + \varepsilon \quad (\text{Eq. 2.9})$$

where  $y$  is the vector of family means for different sites;  $\beta_0$  is the intercept;  $\beta_1$  is the coefficient for the site mean ( $x$ ); and  $\varepsilon$  is the error. The slope is a measure of the stability and response of family means to different sites. Average stability or response for a family is defined as  $\beta_1=1$ .  $\beta_1<1$  indicates that families have high stability, while  $\beta_1>1$  indicates families with low stability or high responsiveness (Finlay and Wilkinson 1963). The intercept ( $\beta_0$ ) represents the difference of families compared to the overall mean. Model significance was tested for individual families with the null hypothesis  $H_0: \beta_1=1$  and  $H_1: \beta_1\neq 1$  with the significance level set at  $\alpha=0.05$ . The model was run using the REG procedure of SAS (SAS Institute Inc. 2008). Individual family means were plotted against individual family slopes to show the relative stability of a family compared to its average performance. The individual family slopes, intercepts, and test significance are in Appendix D along with the plots of individual family means and slopes.

To determine if there were significant differences between seed sources for their response to environment, we ran a one-way analysis of variance using individual family regression parameters as the response variables and seed source as a factor in the following model:

$$y_{ij} = \mu + A_i + \varepsilon_{ij} \quad (\text{Eq. 2.10})$$

where  $y_{ij}$  the  $j$ th observation of the  $i$ th seed source;  $\mu$  is the intercept;  $A_i$  is the fixed effect of the  $i$ th seed source; and  $\varepsilon_{ij}$  is the residual associated with  $j$ th observation of the  $i$ th seed source  $\sim \text{iid}(0, \sigma_\varepsilon^2)$ . The GLM procedure of SAS software was used to run the model for Eq. 2.10 (SAS Institute Inc. 2008). Model significance was set at  $\alpha=0.05$  for the F test. Seed source means for slopes ( $\beta_1$ ) and intercepts ( $\beta_0$ ) were compared using Tukey's adjusted multiple range test.

## 2.4 Results

The individual tree heritabilities of growth traits for individual sites ranged from 0.1 to 0.6 (Table 2.4). Straightness had lower individual tree heritabilities for individual sites between 0.04 and 0.26 (Table 2.4). The family mean heritabilities for individual sites were higher than the individual tree heritabilities with height, volume, forking incidence, rust incidence, and straightness having heritabilities between 0.3 and 0.8 (Table 2.7). Blanks in the family mean heritabilities for binomial traits indicate tests with means that were too low for calculating

heritabilities. Pooled family mean heritabilities across all sites for all traits were very high with heritabilities around 0.9 (Table 2.8).

Family mean heritabilities for height and volume for each site showed a positive relationship with minimum winter temperatures, and these heritabilities increased somewhat as minimum winter temperatures increased (Table 2.7, Figures 2.2 & 2.3). Height was the only trait to show a highly significant ( $p < 0.05$ ) heritability relationship with minimum winter temperatures, though it should be noted that the model for volume was not significant ( $p < 0.1$ ) but noteworthy (Table 2.7, Figures 2.2 & 2.3). Straightness score, rust incidence, and forking incidence family mean heritabilities showed no significant relationship ( $p > 0.05$ ) with minimum winter temperatures (Table 2.7, Figure 2.4, 2.5, and 2.6).

Straightness score, rust incidence, and forking incidence had low GxE interactions as shown by their type B correlations  $r_{Bg} > 0.67$  (Table 2.8). The growth traits showed higher GxE interactions with height having a  $r_{Bg} = 0.66$  and volume having a  $r_{Bg} = 0.54$  (Table 2.8). To further evaluate GxE interaction, growth traits were tested using the Finlay and Wilkinson (1963) linear regressions to find the stability parameters of the genotypes across environments.

The slope values ( $\beta_1$ ) for height had an average stability (e.g.  $\beta_1 \sim 1$ ) for most families (Table 2.9). Only 6 families had slopes that were significantly different from  $\beta_1 = 1$  (Appendix D Table D1). In addition, there was no seed source effect ( $p = 0.284$ ) on the slopes for each family regression (Table 2.10). The main difference for height occurred with the intercept

( $\beta_0$ ) as the intercepts were significantly different ( $p=0.008$ ) among seed sources (Table 2.10). South Carolina Coastal had the highest rank and Virginia had the lowest rank (Table 2.9), indicating that the families in the South Carolina Coastal Seed source had the highest performance while the families in the Virginia seed source had the lowest (Figure 2.7).

Slope values ( $\beta_1$ ) for volume were more varied than those for height. Slope values for volume were significantly different ( $p<0.001$ ) among seed sources, and 23 families had slopes that were significantly different from  $\beta_1=1$  (Table 2.10, Appendix D Table D1). Families from the South Carolina Coastal seed source had the lowest stability (average  $\beta_1 = 1.09$ ) indicated by having the highest slopes, while the families from the Virginia seed source had the highest average stability  $\beta_1(=0.84)$  indicated by having the lowest slopes (Table 2.9). The intercept ( $\beta_0$ ) for volume was significantly different ( $p=0.011$ ) among seed sources with South Carolina Coastal having the highest intercepts and Virginia having the lowest (Tables 2.9 & 2.10). The lower stability and higher performance for volume indicated a highly positive response to site means for the families in the South Carolina seed source while higher stability and lower performance for volume indicated a lower positive response to site means for the families in the Virginia seed source (Figure 2.8).

## **2.5 Discussion**

The objective of this study was to estimate genetic and environmental components of variation, genotype by environment (GxE) interaction, and the stability parameters that relate

to GxE interactions for 140 families of first-generation plantation selection loblolly pine. The wide variation of individual-tree narrow-sense and family-mean heritabilities across sites is most likely due to the wide range of sites and their environments as these can greatly influence the genetic variation of the families and seed sources in this study (Hocker, Jr. 1956, Schimidtling 2001, Schimidtling 2007). The positive relationship of these heritabilities and minimum winter temperatures for growth traits reflects the previous chapter's results in which %CV values among seed sources were found to increase with increasing minimum winter temperatures (Tables 2.1, 2.2, 2.4, & 2.7, Figures 2.2 & 2.3). The relationship of heritability with minimum winter temperatures for height appears to be mainly caused by the increase of family variances relative to increasing minimum winter temperatures (Table 2.1). A more complex combination of the family and error variances are involved in the relationship of minimum winter temperatures with volume heritabilities (Table 2.2). These relationships are important to note because they show that testing in colder climates may limit the heritabilities found for growth traits.

The high type B genetic correlations for forking incidence, rust incidence, and straightness scores indicate GxE interaction is not critical for these quality traits and may not vary enough between sites to warrant widespread site dependent testing and breeding. The growth traits, however, do show substantial GxE interaction as their type B genetic correlations were low ( $r_{Bg} < 0.67$ ) indicating the possible need for site dependent breeding and testing. Height and volume were evaluated further with the use of linear models based on a comparison of family by site means and overall site means as outlined in Finlay and Wilkinson (1963). The Finlay

and Wilkinson (1963) linear regressions were used to define stability of traits using an environmental index, but these regressions also represent the magnitude and type of response that genotypes have to that environmental index. It is important to note that the stability parameters from the Finlay and Wilkinson (1963) linear regressions are based on environmental indices (site means) and are independent of the evaluations using minimum winter temperatures. The stability parameters are then a measure of growth response and performance defined by site means while the variation and heritability of growth traits are defined by minimum winter temperatures in this study.

The slopes ( $\beta_1$ ) for height were not significantly different than  $\beta_1=1$  (Tables 2.9 & 2.10, Figure 2.7, Appendix D Table D1), which was not a surprise as first-generation opened-pollinated loblolly pine progeny tests have shown similar trends (Li & McKeand 1989, McKeand et al. 1990). Since the stability, or response, for height is mostly  $\beta_1=1$ , differences between seed sources and their families were then defined by the intercept ( $\beta_0$ ); the South Carolina Coastal seed source ranked the highest and the Virginia seed source ranked the lowest. These effects showed that height was relatively predictable across sites as the stability was average and differences between families and seed sources were defined by their intercepts. For example, one could expect to breed superior performing offspring for height from the cross of two families with high intercept values, such as one of the families from the South Carolina Coastal or Florida & Georgia Coastal seed sources, without worrying about stability issues for different environments so long as one remembers the risks and general rules for seed movement (Schmidtling 1994, Schmidtling 2001).

Volume slope ( $\beta_1$ ) and intercept ( $\beta_0$ ) values differed significantly among seed sources with the South Carolina Coastal seed source ranking highest, and the Virginia seed source ranking the lowest for both  $\beta_1$  and  $\beta_0$  values (Tables 2.9 & 2.10, Figure 2.8, Appendix D Table D1). The higher variation of slope ( $\beta_1$ ) values makes it harder to predict the response of volume across sites for families and seed sources. While the varying stability parameters for volume make it harder to plan testing and breeding due to the potential GxE interactions, they offer the potential for selecting families for optimum responses to different environments (Li & McKeand 1989). For example, the South Carolina Coastal seed source has the highest response and performance, so it would be expected to have better than average response on good sites. This would make families from the South Carolina Coastal seed source a good choice for planting on a site with a high site index as opposed to the Virginia seed source, which has the lowest response and performance, as long as one remembers the risks of seed movement.

The results suggest that straightness, rust incidence, and forking incidence traits are reasonably predictable due to expected individual- and family-mean heritabilities and non-substantial GxE interactions ( $r_{Bg} > 0.67$ ), while height and volume are not as easily predicted due to substantial GxE interaction ( $r_{Bg} < 0.67$ ). The evaluation of GxE interaction through linear regression using environmental indices shows that height can be relatively predictable as most families and seed sources have average stability ( $\beta_1 = 1$ ), while volume has highly variable family stabilities. The benefit of the average stability of height is that testing and breeding can be done at almost any site without complications, but it means that there is little

genetic control for height response to better sites. Volume is the opposite, having high potential genetic control for response to better sites, but more complicated testing and breeding requirements due to the more variable stability parameters between seed sources and families. Further analyses with results from 15<sup>th</sup> year measurements of this study, along with other tests utilizing different environments, can better define the responsiveness of volume for families and seed sources.

## 2.6 References

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**Table 2.1.** Average minimum winter temperature ( $^{\circ}\text{C}$ ), individual site means, number of observations per family (n), number of families per site (f), and variance components for height. Standard errors follow the  $\pm$  symbol. The sites are ordered by Temp ( $^{\circ}\text{C}$ ).

<b>Temp (<math>^{\circ}\text{C}</math>)</b>	<b>Site</b>	<b>n</b>	<b>f</b>	<b>Mean (dm)</b>	<b>Family var</b>	<b>Error var</b>
-14.7	McNairy, TN	22.2	140	98.9 $\pm$ 0.18	4.22 $\pm$ 0.95	78.19 $\pm$ 2.04
-14.6	Hardin, TN	18.4	140	90.0 $\pm$ 0.22	3.29 $\pm$ 0.90	72.43 $\pm$ 2.15
-12.7	Northampton, NC	15.1	140	79.2 $\pm$ 0.23	2.89 $\pm$ 1.25	108.52 $\pm$ 3.59
-12.1	Laurens, SC	22.0	140	89.4 $\pm$ 0.15	3.27 $\pm$ 0.72	55.76 $\pm$ 1.46
-10.9	Chilton, AL	23.0	130	108.6 $\pm$ 0.22	7.66 $\pm$ 1.71	131.21 $\pm$ 3.49
-10.9	Newberry, SC	20.4	140	91.9 $\pm$ 0.22	3.94 $\pm$ 1.07	95.20 $\pm$ 2.66
-10.6	Robeson, NC	20.4	140	103.8 $\pm$ 0.21	4.86 $\pm$ 1.10	83.83 $\pm$ 2.29
-10.1	Autauga, AL	12.7	138	88.4 $\pm$ 0.19	3.38 $\pm$ 0.92	51.13 $\pm$ 1.81
-10	Williamsburg, SC	10.3	140	76.7 $\pm$ 0.31	10.11 $\pm$ 2.68	117.84 $\pm$ 4.64
-8.8	Randolph, GA	21.6	140	70.0 $\pm$ 0.19	7.00 $\pm$ 1.27	70.27 $\pm$ 1.90
-8.8	Escambia 1, AL	19.9	140	105.1 $\pm$ 0.25	15.00 $\pm$ 2.70	138.48 $\pm$ 3.93
-8.8	Escambia 2, AL	23.0	136	106.2 $\pm$ 0.17	6.44 $\pm$ 1.20	73.47 $\pm$ 1.95
-8.6	Screven, GA	22.1	140	89.3 $\pm$ 0.15	8.05 $\pm$ 1.30	55.22 $\pm$ 1.44
-7.7	Berkeley, SC	19.6	140	118.5 $\pm$ 0.18	6.38 $\pm$ 1.26	73.94 $\pm$ 2.11
-7.6	Tattnall, GA	22.3	140	122.9 $\pm$ 0.19	10.37 $\pm$ 1.70	77.15 $\pm$ 2.05
-7.6	Bradford, FL	21.9	140	83.4 $\pm$ 0.24	12.91 $\pm$ 2.33	131.38 $\pm$ 3.45
-7.6	Ware, GA	22.6	140	79.6 $\pm$ 0.25	11.07 $\pm$ 2.20	153.64 $\pm$ 4.06

**Table 2.2.** Average minimum winter temperature (°C), individual site means, and variance components for individual-tree volume. Standard errors follow the ± symbol. The sites are ordered by Temp (°C).

<b>Temp (oC)</b>	<b>Site</b>	<b>Mean (dm3)</b>	<b>Family var</b>	<b>Error var</b>
<b>-14.7</b>	McNairy, TN	81.2 ± 0.45	52.7 ± 9.6	559 ± 14.6
<b>-14.6</b>	Hardin, TN	69.2 ± 0.48	22.0 ± 5.4	390 ± 11.5
<b>-12.7</b>	Northampton, NC	58.0 ± 0.59	24.4 ± 8.8	696 ± 23.1
<b>-12.1</b>	Laurens, SC	53.4 ± 0.30	17.0 ± 3.5	244 ± 6.5
<b>-10.9</b>	Chilton, AL	78.1 ± 0.57	65.4 ± 13.1	855 ± 23.3
<b>-10.9</b>	Newberry, SC	76.3 ± 0.54	36.8 ± 8.6	663 ± 18.5
<b>-10.6</b>	Robeson, NC	81.2 ± 0.56	59.1 ± 12.0	783 ± 21.4
<b>-10.1</b>	Autauga, AL	62.0 ± 0.47	37.1 ± 7.8	312 ± 11.0
<b>-10</b>	Williamsburg, SC	36.9 ± 0.51	18.4 ± 6.1	315 ± 12.7
<b>-8.8</b>	Randolph, GA	29.0 ± 0.24	15.4 ± 2.6	117 ± 3.2
<b>-8.8</b>	Escambia 1, AL	61.4 ± 0.57	101.5 ± 16.7	686 ± 18.9
<b>-8.8</b>	Escambia 2, AL	85.7 ± 0.50	88.0 ± 14.2	585 ± 15.6
<b>-8.6</b>	Screven, GA	56.6 ± 0.36	36.7 ± 6.3	322 ± 8.4
<b>-7.7</b>	Berkeley, SC	104.1 ± 0.62	90.4 ± 16.7	864 ± 24.7
<b>-7.6</b>	Tattnall, GA	97.2 ± 0.64	155.5 ± 24.0	886 ± 23.0
<b>-7.6</b>	Bradford, FL	34.3 ± 0.33	27.6 ± 4.8	252 ± 6.8
<b>-7.6</b>	Ware, GA	27.5 ± 0.26	10.7 ± 2.3	174 ± 4.6

**Table 2.3.** Average minimum winter temperature ( $^{\circ}\text{C}$ ), individual site means, and variance components for straightness (mean values are 100 times the straightness score). Sites are ordered by Temp ( $^{\circ}\text{C}$ ). Standard errors follow the  $\pm$  symbol.

<b>Temp (<math>^{\circ}\text{C}</math>)</b>	<b>Site</b>	<b>Mean</b>	<b>Family var</b>	<b>Error var</b>
-14.7	McNairy, TN	356 $\pm$ 1.5	458 $\pm$ 93	6733 $\pm$ 175
-14.6	Hardin, TN	313 $\pm$ 1.7	373 $\pm$ 92	6764 $\pm$ 200
-12.7	Northampton, NC	350 $\pm$ 1.8	62 $\pm$ 59	6225 $\pm$ 206
-12.1	Laurens, SC	344 $\pm$ 1.5	258 $\pm$ 69	6604 $\pm$ 177
-10.9	Chilton, AL	341 $\pm$ 1.1	119 $\pm$ 35	3555 $\pm$ 94
-10.9	Newberry, SC	349 $\pm$ 1.6	277 $\pm$ 75	6766 $\pm$ 183
-10.6	Robeson, NC	349 $\pm$ 1.4	280 $\pm$ 66	5276 $\pm$ 148
-10.1	Autauga, AL	342 $\pm$ 2.0	472 $\pm$ 125	6666 $\pm$ 236
-10	Williamsburg, SC	328 $\pm$ 2.5	372 $\pm$ 144	8032 $\pm$ 324
-8.8	Randolph, GA	304 $\pm$ 2.6	478 $\pm$ 170	19411 $\pm$ 526
-8.8	Escambia 1, AL	342 $\pm$ 2.0	530 $\pm$ 130	10422 $\pm$ 288
-8.8	Escambia 2, AL	329 $\pm$ 1.8	524 $\pm$ 118	9502 $\pm$ 253
-8.6	Screven, GA	341 $\pm$ 1.1	244 $\pm$ 50	3495 $\pm$ 91
-7.7	Berkeley, SC	374 $\pm$ 2.8	837 $\pm$ 233	20172 $\pm$ 561
-7.6	Tattnall, GA	352 $\pm$ 1.4	356 $\pm$ 77	6023 $\pm$ 157
-7.6	Bradford, FL	354 $\pm$ 1.7	206 $\pm$ 72	8225 $\pm$ 216
-7.6	Ware, GA	337 $\pm$ 1.4	217 $\pm$ 57	5531 $\pm$ 146

**Table 2.4.** Average minimum winter temperature ( $^{\circ}\text{C}$ ) and individual tree heritabilities ( $h^2$ ) by site for height, volume, and straightness (STRT). Standard errors follow the  $\pm$  symbol. The sites are ordered by Temp ( $^{\circ}\text{C}$ ).

Temp ( $^{\circ}\text{C}$ )	Site	Height	Volume	STRT
-14.7	McNairy, TN	$0.21 \pm 0.05$	$0.34 \pm 0.06$	$0.25 \pm 0.05$
-14.6	Hardin, TN	$0.17 \pm 0.05$	$0.21 \pm 0.05$	$0.21 \pm 0.05$
-12.7	Northampton, NC	$0.10 \pm 0.05$	$0.14 \pm 0.05$	$0.04 \pm 0.04$
-12.1	Laurens, SC	$0.22 \pm 0.05$	$0.26 \pm 0.05$	$0.15 \pm 0.04$
-10.9	Chilton, AL	$0.22 \pm 0.05$	$0.28 \pm 0.05$	$0.13 \pm 0.04$
-10.9	Newberry, SC	$0.16 \pm 0.04$	$0.21 \pm 0.05$	$0.16 \pm 0.04$
-10.6	Robeson, NC	$0.22 \pm 0.05$	$0.28 \pm 0.05$	$0.20 \pm 0.05$
-10.1	Autauga, AL	$0.25 \pm 0.07$	$0.43 \pm 0.08$	$0.26 \pm 0.07$
-10	Williamsburg, SC	$0.32 \pm 0.08$	$0.22 \pm 0.07$	$0.18 \pm 0.07$
-8.8	Randolph, GA	$0.36 \pm 0.06$	$0.46 \pm 0.07$	$0.10 \pm 0.03$
-8.8	Escambia 1, AL	$0.39 \pm 0.07$	$0.52 \pm 0.08$	$0.19 \pm 0.05$
-8.8	Escambia 2, AL	$0.32 \pm 0.06$	$0.52 \pm 0.08$	$0.21 \pm 0.05$
-8.6	Screven, GA	$0.51 \pm 0.07$	$0.41 \pm 0.06$	$0.26 \pm 0.05$
-7.7	Berkeley, SC	$0.32 \pm 0.06$	$0.38 \pm 0.07$	$0.16 \pm 0.04$
-7.6	Tattnall, GA	$0.47 \pm 0.07$	$0.60 \pm 0.08$	$0.22 \pm 0.05$
-7.6	Bradford, FL	$0.36 \pm 0.06$	$0.39 \pm 0.06$	$0.10 \pm 0.03$
-7.6	Ware, GA	$0.27 \pm 0.05$	$0.23 \pm 0.05$	$0.15 \pm 0.04$

**Table 2.5.** Average minimum winter temperature (°C), individual site means, and variance components for rust incidence. Standard errors follow the  $\pm$  symbol. The sites are ordered by Temp (°C). Error variance is fixed at 3.29 ( $\pi^2/3$ ) and has no standard error.

Temp (°C)	Site	Mean	Family var
-14.7	McNairy, TN	0.05 $\pm$ 0.004	0.656 $\pm$ 0.202
-14.6	Hardin, TN	0.01 $\pm$ 0.002	0.000 $\pm$ 0.000
-12.7	Northampton, NC	0.84 $\pm$ 0.006	0.182 $\pm$ 0.066
-12.1	Laurens, SC	0.47 $\pm$ 0.009	0.297 $\pm$ 0.062
-10.9	Chilton, AL	0.25 $\pm$ 0.008	0.284 $\pm$ 0.069
-10.9	Newberry, SC	0.69 $\pm$ 0.008	0.178 $\pm$ 0.049
-10.6	Robeson, NC	0.48 $\pm$ 0.009	0.349 $\pm$ 0.071
-10.1	Autauga, AL	0.69 $\pm$ 0.010	0.092 $\pm$ 0.051
-10	Williamsburg, SC	0.45 $\pm$ 0.013	0.281 $\pm$ 0.087
-8.8	Randolph, GA	0.61 $\pm$ 0.009	0.389 $\pm$ 0.074
-8.8	Escambia 1, AL	0.09 $\pm$ 0.005	0.226 $\pm$ 0.110
-8.8	Escambia 2, AL	0.31 $\pm$ 0.008	0.378 $\pm$ 0.076
-8.6	Screven, GA	0.55 $\pm$ 0.009	0.411 $\pm$ 0.076
-7.7	Berkeley, SC	0.72 $\pm$ 0.008	0.475 $\pm$ 0.091
-7.6	Tattnall, GA	0.51 $\pm$ 0.009	0.432 $\pm$ 0.079
-7.6	Bradford, FL	0.62 $\pm$ 0.008	0.402 $\pm$ 0.076
-7.6	Ware, GA	0.23 $\pm$ 0.007	0.327 $\pm$ 0.076

**Table 2.6.** Average minimum winter temperature (°C), individual site means, and variance components for fork incidence. Standard errors follow the  $\pm$  symbol. The sites are ordered by Temp (°C). Error variance is fixed at 3.29 ( $\pi^2/3$ ) and has no standard error.

Temp (°C)	Site	Mean	Family var
-14.7	McNairy, TN	0.50 $\pm$ 0.009	0.107 $\pm$ 0.036
-14.6	Hardin, TN	0.35 $\pm$ 0.009	0.154 $\pm$ 0.049
-12.7	Northampton, NC	0.17 $\pm$ 0.008	0.160 $\pm$ 0.078
-12.1	Laurens, SC	0.28 $\pm$ 0.008	0.114 $\pm$ 0.042
-10.9	Chilton, AL	0.33 $\pm$ 0.009	0.113 $\pm$ 0.040
-10.9	Newberry, SC	0.46 $\pm$ 0.009	0.079 $\pm$ 0.035
-10.6	Robeson, NC	0.24 $\pm$ 0.008	0.193 $\pm$ 0.058
-10.1	Autauga, AL	0.10 $\pm$ 0.007	0.041 $\pm$ 0.108
-10	Williamsburg, SC	0.05 $\pm$ 0.006	0.000 $\pm$ 0.000
-8.8	Randolph, GA	0.39 $\pm$ 0.009	0.103 $\pm$ 0.037
-8.8	Escambia 1, AL	0.30 $\pm$ 0.008	0.234 $\pm$ 0.059
-8.8	Escambia 2, AL	0.17 $\pm$ 0.007	0.136 $\pm$ 0.055
-8.6	Screven, GA	0.17 $\pm$ 0.007	0.061 $\pm$ 0.047
-7.7	Berkeley, SC	0.12 $\pm$ 0.006	0.142 $\pm$ 0.077
-7.6	Tattnall, GA	0.21 $\pm$ 0.007	0.304 $\pm$ 0.072
-7.6	Bradford, FL	0.08 $\pm$ 0.005	0.000 $\pm$ 0.000
-7.6	Ware, GA	0.08 $\pm$ 0.005	0.088 $\pm$ 0.080

**Table 2.7.** Average minimum winter temperature ( $^{\circ}\text{C}$ ) and family mean heritabilities ( $h_f^2$ ) by site for height, volume, rust incidence, forking, and straightness (STRT). The sites are ordered by Temp ( $^{\circ}\text{C}$ ). Standard errors follow the heritabilities after the  $\pm$  symbol.

Temp ( $^{\circ}\text{C}$ )	Site	Height	Volume	STRT	Rust Incidence	Forking Incidence
-14.7	McNairy, TN	$0.55 \pm 0.06$	$0.68 \pm 0.04$	$0.60 \pm 0.05$	----	$0.42 \pm 0.08$
-14.6	Hardin, TN	$0.46 \pm 0.07$	$0.51 \pm 0.06$	$0.50 \pm 0.06$	----	$0.46 \pm 0.08$
-12.7	Northampton, NC	$0.29 \pm 0.09$	$0.35 \pm 0.08$	$0.13 \pm 0.11$	----	----
-12.1	Laurens, SC	$0.56 \pm 0.06$	$0.61 \pm 0.05$	$0.46 \pm 0.07$	$0.66 \pm 0.05$	$0.43 \pm 0.09$
-10.9	Chilton, AL	$0.57 \pm 0.06$	$0.64 \pm 0.05$	$0.43 \pm 0.07$	$0.66 \pm 0.05$	$0.44 \pm 0.09$
-10.9	Newberry, SC	$0.46 \pm 0.07$	$0.53 \pm 0.06$	$0.46 \pm 0.07$	$0.52 \pm 0.07$	$0.33 \pm 0.10$
-10.6	Robeson, NC	$0.54 \pm 0.06$	$0.61 \pm 0.05$	$0.52 \pm 0.06$	$0.68 \pm 0.04$	$0.55 \pm 0.07$
-10.1	Autauga, AL	$0.46 \pm 0.07$	$0.60 \pm 0.05$	$0.47 \pm 0.07$	$0.26 \pm 0.11$	----
-10	Williamsburg, SC	$0.47 \pm 0.07$	$0.37 \pm 0.08$	$0.32 \pm 0.09$	$0.47 \pm 0.08$	----
-8.8	Randolph, GA	$0.68 \pm 0.04$	$0.74 \pm 0.03$	$0.35 \pm 0.08$	$0.72 \pm 0.04$	$0.40 \pm 0.09$
-8.8	Escambia 1, AL	$0.68 \pm 0.04$	$0.75 \pm 0.03$	$0.50 \pm 0.06$	----	$0.59 \pm 0.06$
-8.8	Escambia 2, AL	$0.67 \pm 0.04$	$0.78 \pm 0.03$	$0.56 \pm 0.06$	$0.73 \pm 0.04$	----
-8.6	Screven, GA	$0.76 \pm 0.03$	$0.72 \pm 0.04$	$0.61 \pm 0.05$	$0.73 \pm 0.04$	----
-7.7	Berkeley, SC	$0.63 \pm 0.05$	$0.67 \pm 0.04$	$0.45 \pm 0.07$	$0.74 \pm 0.04$	----
-7.6	Tattnall, GA	$0.75 \pm 0.03$	$0.80 \pm 0.03$	$0.57 \pm 0.05$	$0.75 \pm 0.04$	$0.67 \pm 0.05$
-7.6	Bradford, FL	$0.68 \pm 0.04$	$0.71 \pm 0.04$	$0.35 \pm 0.08$	$0.73 \pm 0.04$	----
-7.6	Ware, GA	$0.62 \pm 0.05$	$0.58 \pm 0.05$	$0.47 \pm 0.07$	$0.69 \pm 0.05$	----

**Table 2.8.** Variance components (standard errors follow  $\pm$ ) for family ( $\sigma_f^2$ ), family by environment interaction ( $\sigma_{fe}^2$ ), residual ( $\sigma_e^2$ ), type B correlation coefficient ( $r_{Bg}$ ), and family mean heritabilities ( $h_f^2$ ) for height (dm), volume (dm<sup>3</sup>), rust incidence, forking, and straightness across all sites. Residual variance ( $\sigma_e^2$ ) for forking and rust incidence were determined by  $\pi^2/3$  (Gilmour et al 1985). The average number of progeny across all sites was  $n=19.8$  and the number of test sites was  $t=17$ , except for rust which had an average of  $n=21.4$ . These were used as the devisors for  $\sigma_{fe}^2$  and  $\sigma_e^2$ .

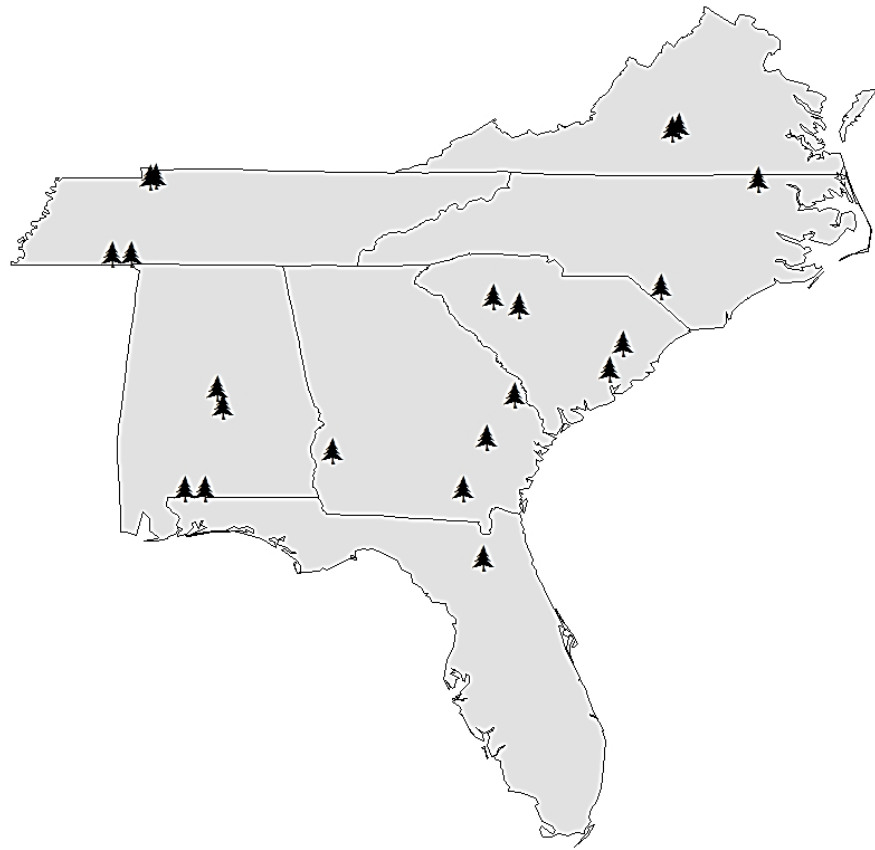
<b>Trait</b>	<b><math>\sigma_f^2 \pm SE</math></b>	<b><math>\sigma_{fe}^2 \pm SE</math></b>	<b><math>\sigma_e^2 \pm SE</math></b>	<b><math>r_{Bg} \pm SE</math></b>	<b><math>h_f^2 \pm SE</math></b>
<b>Height</b>	4.74 $\pm$ 0.62	2.45 $\pm$ 0.22	92.36 $\pm$ 0.64	0.66 $\pm$ 0.04	0.92 $\pm$ 0.01
<b>Volume</b>	28.0 $\pm$ 3.75	23.9 $\pm$ 1.56	517.2 $\pm$ 3.57	0.54 $\pm$ 0.04	0.91 $\pm$ 0.01
<b>Straightness</b>	267.9 $\pm$ 35.96	84.2 $\pm$ 15.57	8235.5 $\pm$ 55.39	0.76 $\pm$ 0.04	0.90 $\pm$ 0.01
<b>Rust Incidence</b>	0.327 $\pm$ 0.04	0.051 $\pm$ 0.01	3.29	0.86 $\pm$ 0.03	0.96 $\pm$ 0.01
<b>Forking</b>	0.108 $\pm$ 0.02	0.031 $\pm$ 0.01	3.29	0.78 $\pm$ 0.06	0.90 $\pm$ 0.01

**Table 2.9.** Average of family slopes ( $\beta_1$ ), intercepts ( $\beta_0$ ), and coefficient of determination ( $R^2$ ) by seed source. A slope of 1 is considered average stability with higher values representing a higher response and lower values representing lower response to an environmental index (site means). The intercept represents the initial response of the trait. Seed source means with same letter for a given parameter ( $\beta_0$ ,  $\beta_1$ ) are not significantly different. Standard errors follow the means after the  $\pm$  symbol.

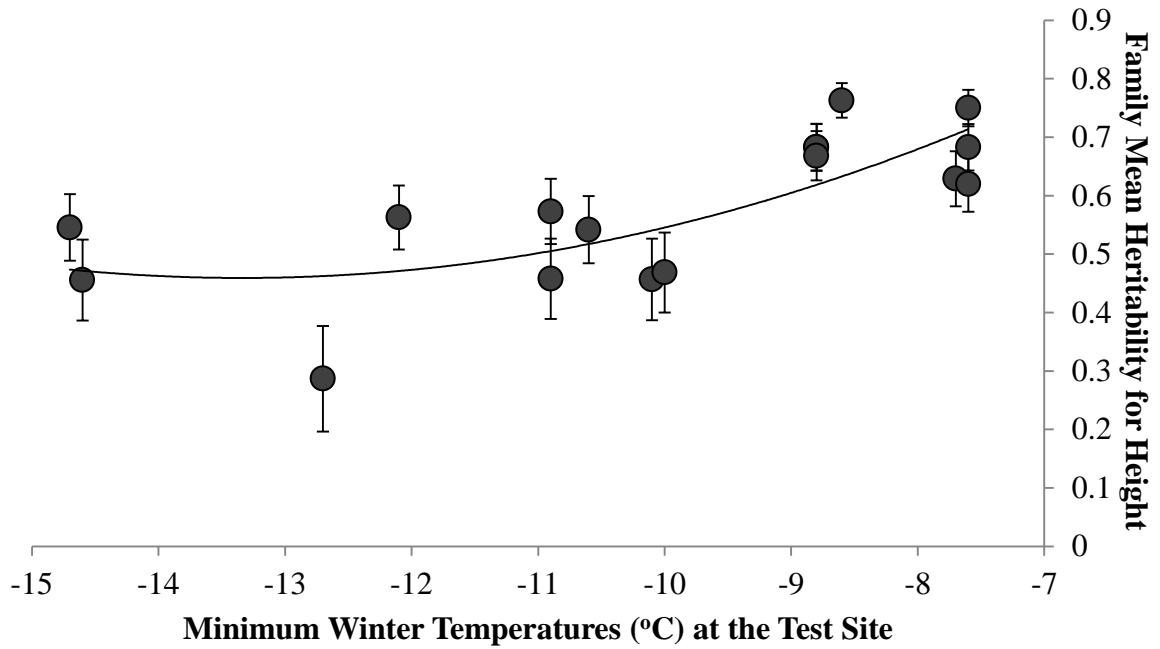
Seed Source	Height			Volume		
	$\beta_1$	$\beta_0$	$R^2$	$\beta_1$	$\beta_0$	$R^2$
VA	0.98 <sup>a</sup> $\pm 0.01$	-2.71 <sup>b</sup> $\pm 1.03$	0.93 $\pm 0.01$	0.84 <sup>c</sup> $\pm 0.02$	-1.81 <sup>ab</sup> $\pm 0.79$	0.82 $\pm 0.01$
NC-C	1.01 <sup>a</sup> $\pm 0.01$	-0.26 <sup>ab</sup> $\pm 1.11$	0.97 $\pm 0.00$	0.98 <sup>b</sup> $\pm 0.02$	0.61 <sup>ab</sup> $\pm 0.74$	0.93 $\pm 0.01$
SC-C	1.00 <sup>a</sup> $\pm 0.01$	3.63 <sup>a</sup> $\pm 1.12$	0.96 $\pm 0.00$	1.09 <sup>a</sup> $\pm 0.02$	2.29 <sup>a</sup> $\pm 1.09$	0.91 $\pm 0.01$
FL&GA-C	1.01 <sup>a</sup> $\pm 0.01$	0.69 <sup>ab</sup> $\pm 1.48$	0.97 $\pm 0.00$	1.03 <sup>ab</sup> $\pm 0.03$	1.15 <sup>ab</sup> $\pm 1.32$	0.91 $\pm 0.01$
LG	1.01 <sup>a</sup> $\pm 0.01$	-1.46 <sup>b</sup> $\pm 1.13$	0.96 $\pm 0.00$	1.00 <sup>ab</sup> $\pm 0.02$	-0.04 <sup>ab</sup> $\pm 0.68$	0.90 $\pm 0.01$
UG	1.01 <sup>a</sup> $\pm 0.01$	-1.36 <sup>ab</sup> $\pm 1.17$	0.97 $\pm 0.00$	1.06 <sup>ab</sup> $\pm 0.03$	-2.91 <sup>b</sup> $\pm 1.18$	0.93 $\pm 0.01$
PD	0.99 <sup>a</sup> $\pm 0.01$	0.67 <sup>ab</sup> $\pm 1.16$	0.96 $\pm 0.01$	0.99 <sup>b</sup> $\pm 0.03$	0.42 <sup>ab</sup> $\pm 1.25$	0.91 $\pm 0.01$

**Table 2.10.** The F-tests to compare seed sources for their response to sites (slopes of families originating from the seed source,  $\beta_1$ ) and intercept ( $\beta_0$ ) values of family means within seed sources.

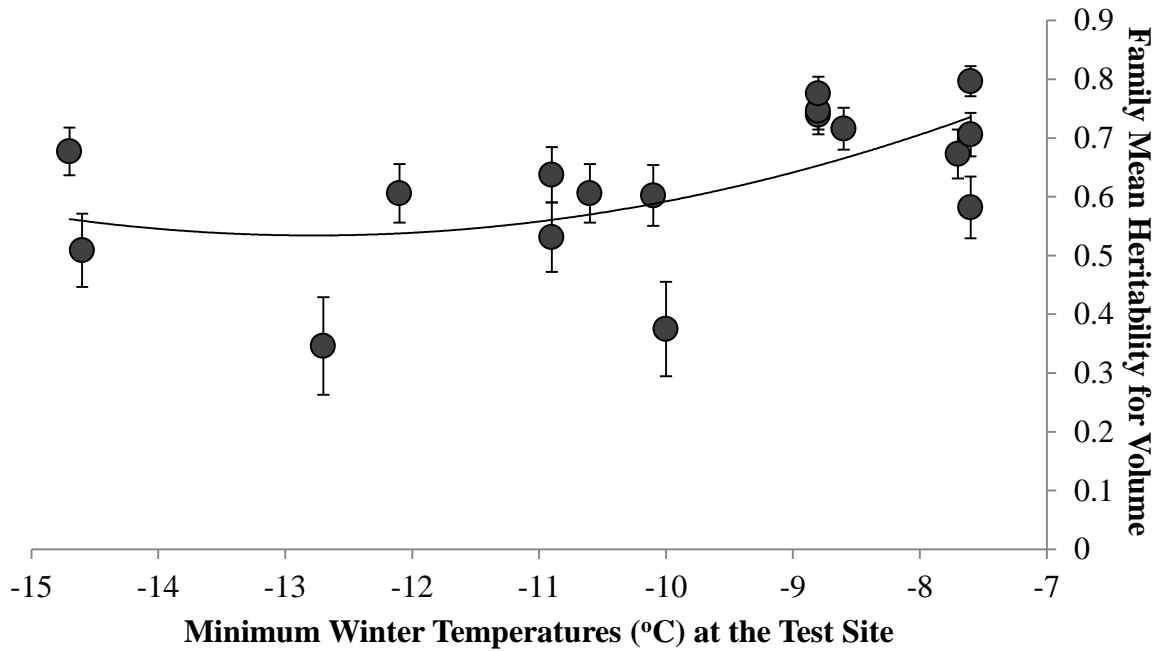
<b>Trait</b>	<b>SS df</b>	<b>Error DF</b>	<b>SS MS</b>	<b>MSE</b>	<b>F</b>	<b>Pr&gt;F</b>
Height $\beta_1$	6	133	0.003	0.003	1.25	0.284
Height $\beta_0$	6	133	84.7	27.8	3.05	0.008
Volume $\beta_1$	6	133	0.126	0.012	10.87	<0.001
Volume $\beta_0$	6	133	62.8	21.5	2.92	0.011



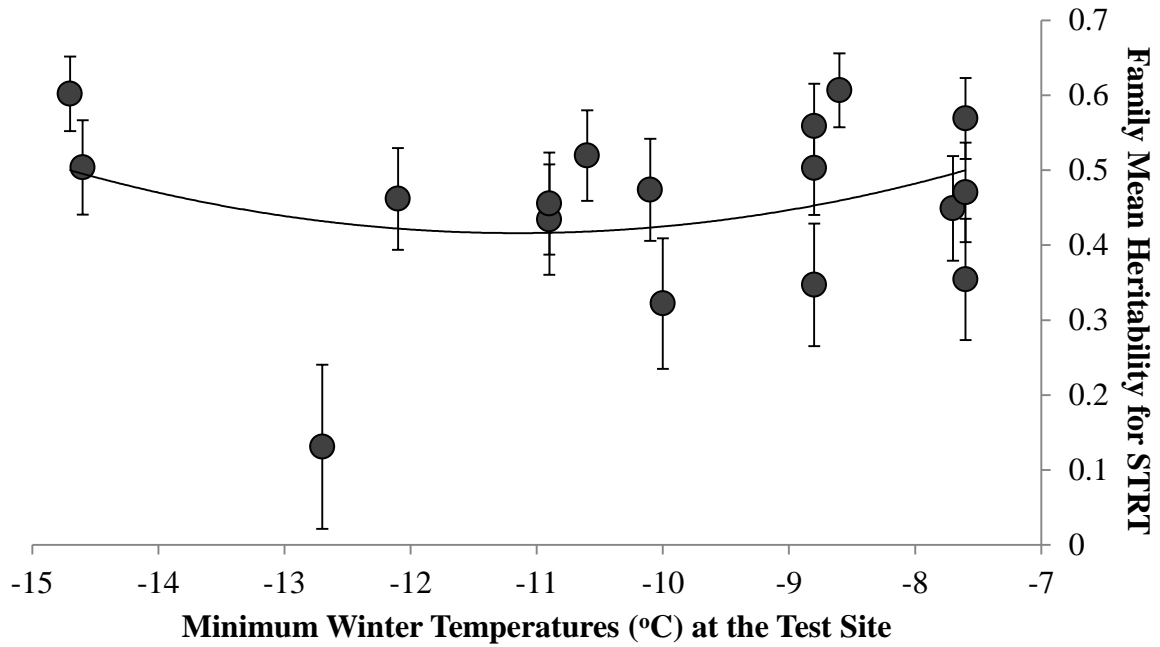
**Figure 2.1.** Test site locations for the Plantation Selection Seed Source Study (PSSSS) trials. These 21 test locations are scattered across the entirety of the loblolly range east of the Mississippi river. The tests in Virginia and Northern Tennessee were not included in this part of the study.



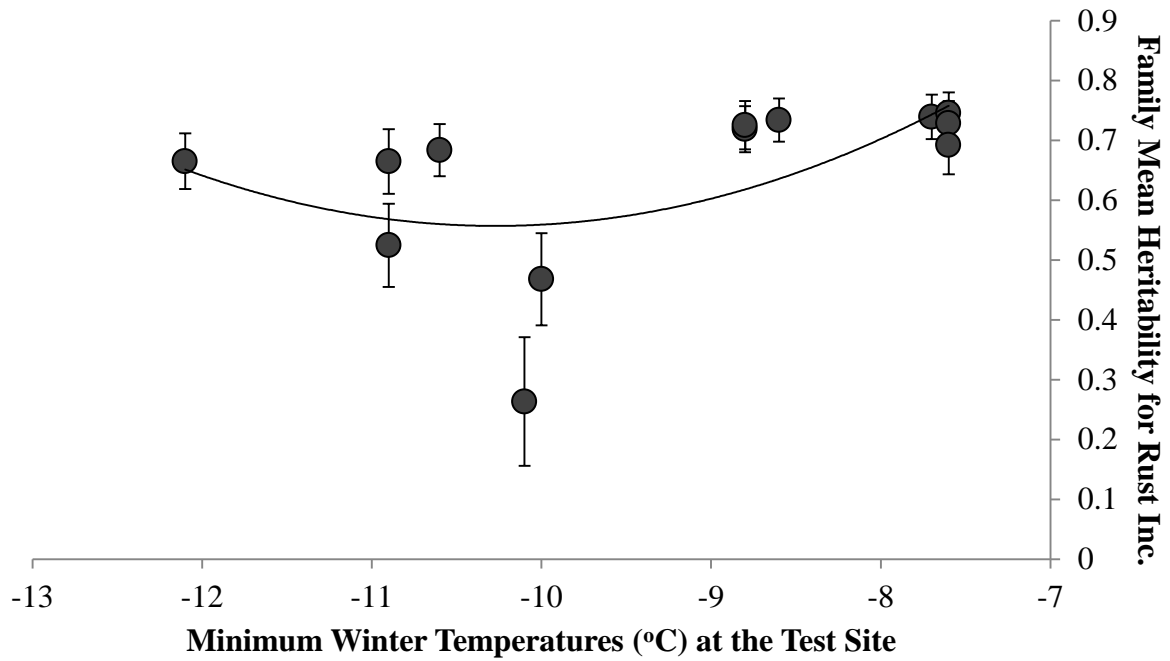
**Figure 2.2.** Family mean heritabilities ( $h_f^2$ ) by site for height with standard error bars set on a scale for minimum winter temperatures ( $^{\circ}\text{C}$ ). The quadratic model fitted for these data is  $h_f^2 = 0.206x + 0.008x^2 + 1.835$  with an  $R^2=0.57$  (where  $x$ = minimum winter temperatures). The model's F-test was significant at  $p=0.003$ .



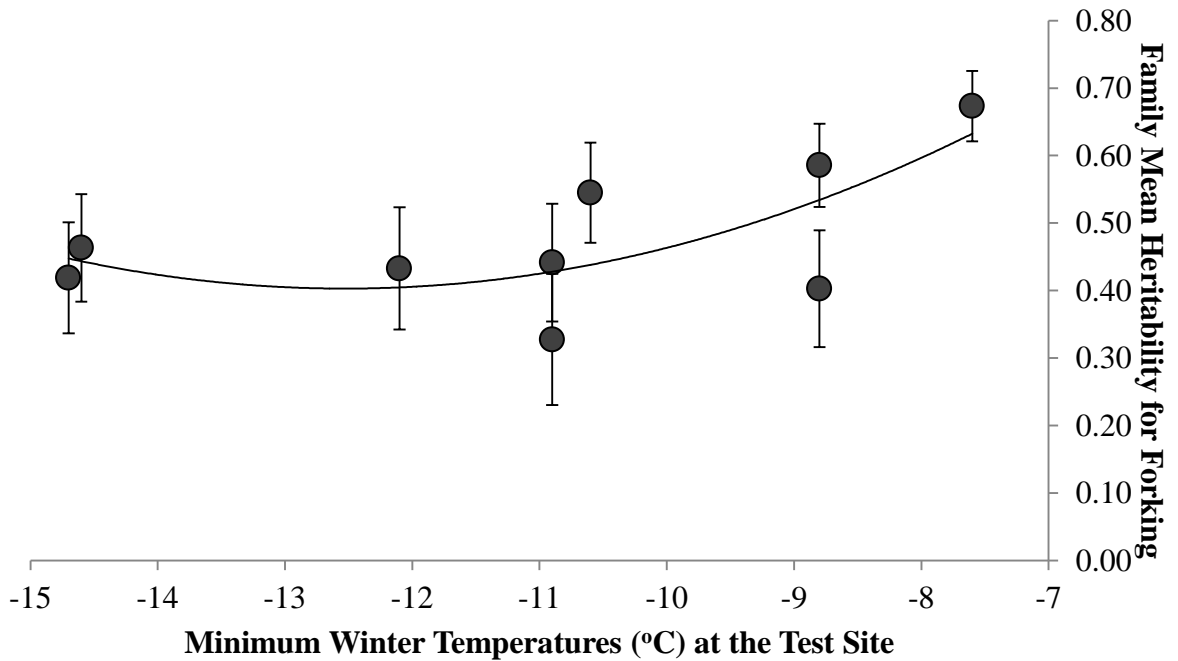
**Figure 2.3.** Family mean heritabilities ( $h_f^2$ ) by site for volume with standard error bars set on a scale for minimum winter temperatures ( $^{\circ}\text{C}$ ). The quadratic model fitted for these data was  $h_f^2 = 0.192x + 0.008x^2 + 1.761$  with an  $R^2=0.34$  (where  $x$ = minimum winter temperatures). The model's F-test was somewhat significant at  $p=0.057$ .



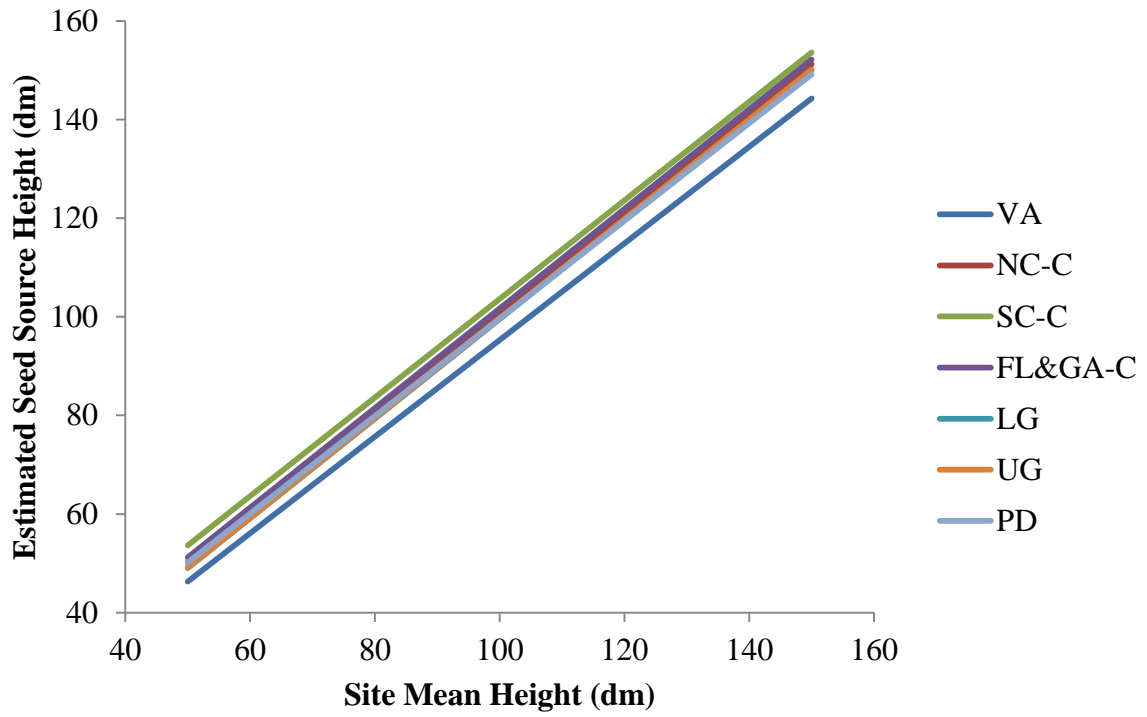
**Figure 2.4.** Family heritabilities ( $h_f^2$ ) by site for straightness score (STRT) with standard error bars set on a scale for minimum winter temperatures ( $^{\circ}\text{C}$ ). The quadratic model fitted for these data was  $h_f^2 = 0.148x + 0.007x^2 + 1.243$  with an  $R^2=0.09$  (where  $x$ = minimum winter temperatures). The model's F-test was not significant at  $p=0.533$ .



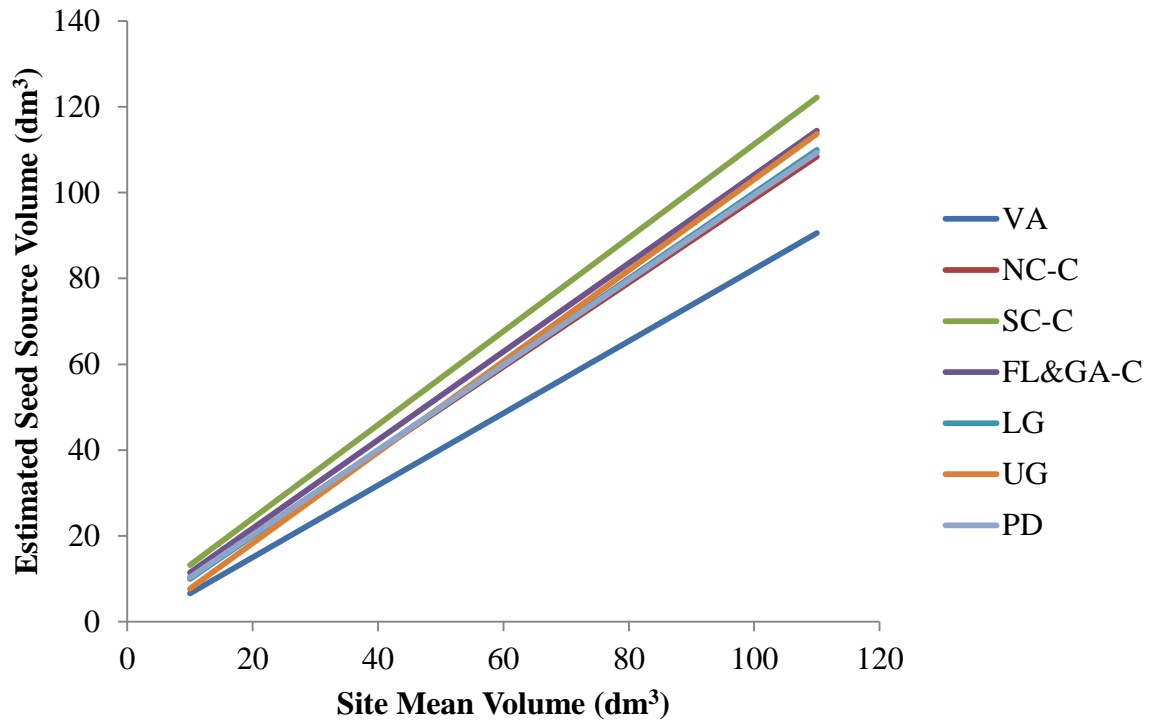
**Figure 2.5.** Family mean heritabilities ( $h_f^2$ ) by site for rust incidence set on a scale for minimum winter temperatures ( $^{\circ}\text{C}$ ). The quadratic model fitted for these data was  $h_f^2 = 0.575x + 0.028x^2 + 3.516$  with an  $R^2=0.35$  (where  $x$ = minimum winter temperatures). The model's F-test was somewhat significant at  $p=0.115$ .



**Figure 2.6.** Family mean heritabilities ( $h_f^2$ ) by site for forking incidence set on a scale for minimum winter temperatures ( $^{\circ}\text{C}$ ). The quadratic model fitted for these data was  $h_f^2 = 0.232x + 0.009x^2 + 1.86$  with an  $R^2=0.48$  (where  $x$ = minimum winter temperatures). The model's F-test was not significant at  $p=0.138$ .



**Figure 2.7.** Estimated seed source mean heights compared to site means for height. This is a model of estimated seed source mean heights using the average slope ( $\beta_1$ ) and intercept ( $\beta_0$ ) values provided in Table 2.9.



**Figure 2.8.** Estimated seed source mean volumes compared to site means for volume. This is a model of estimated seed source mean volume using the average slope ( $\beta_1$ ) and intercept ( $\beta_0$ ) values provided in Table 2.9.

## Appendices

# **Appendix A**

Chapter 1: Seed source by site means

**Table A1.** Individual site least square mean values by seed source for volume (dm<sup>3</sup>). Seed sources are sorted by overall rank going highest rank from left to right (highest means in bold). Standard errors range from 0.6 to 1.6.

Min. Temp. (°C)	Site	Seed sources						
		SC	FL&GA	UG	NC	LG	PD	VA
-16.4	Stewart 1, TN	---	---	<b>42.0</b>	40.3	---	39.3	41.5
-16.4	Stewart 2, TN	---	---	<b>42.0</b>	39.3	---	39.0	40.2
-15.4	Appomattox 1,	---	---	<b>50.0</b>	46.3	---	48.1	46.0
-15.4	Appomattox 2,	---	---	58.2	57.2	---	<b>61.2</b>	55.1
-14.7	Mcnairy, TN	83.2	79.2	<b>84.3</b>	83.6	80.3	83.0	75.3
-14.6	Hardin, TN	69.8	69.7	<b>73.3</b>	70.4	67.9	68.9	66.1
-12.7	Northampton, NC	<b>59.5</b>	56.1	59.1	56.0	57.8	58.6	59.1
-12.1	Laurens, SC	<b>56.3</b>	56.1	54.4	53.9	54.2	52.6	46.4
-10.9	Chilton, AL	<b>88.3</b>	81.3	76.0	79.9	77.6	79.9	65.0
-10.9	Newberry, SC	<b>82.2</b>	77.7	79.1	75.4	75.4	78.1	66.5
-10.6	Robeson, NC	<b>87.4</b>	82.4	86.6	81.9	77.7	79.5	72.6
-10.1	Autauga, AL	<b>72.4</b>	66.1	63.9	56.3	65.1	61.7	50.4
-10	Williamsburg, SC	<b>43.7</b>	39.9	34.1	38.3	35.0	37.0	29.4
-8.8	Randolph, GA	<b>34.7</b>	31.2	28.8	29.6	28.8	28.3	20.0
-8.8	Escambia, AL	<b>75.1</b>	67.0	60.5	66.1	61.6	62.2	37.0
-8.8	Escambia, AL	<b>100.0</b>	91.1	87.1	84.0	83.8	89.3	64.8
-8.6	Screven, GA	<b>65.0</b>	62.8	58.0	55.4	60.0	52.7	42.6
-7.7	Berkeley, SC	<b>118.5</b>	109.5	106.0	102.8	103.3	100.0	88.0
-7.6	Tattnall, GA	<b>115.6</b>	110.4	99.0	93.1	102.3	93.8	64.5
-7.6	Bradford, FL	<b>43.1</b>	40.0	32.6	32.5	37.1	33.3	20.6
-7.6	Ware, GA	<b>33.5</b>	30.7	25.5	27.3	25.4	28.1	21.8

**Table A2.** Individual site least square mean values by seed source for height (m). Seed sources are sorted by overall rank going highest rank from left to right (highest means in bold). Standard errors range from 0.04 to 0.08.

Min. Temp. (°C)	Site	Seed sources						
		SC	FL&GA	NC	UG	PD	LG	VA
-16.4	Stewart 1, TN	---	---	<b>7.1</b>	<b>7.1</b>	6.9	---	<b>7.1</b>
-16.4	Stewart 2, TN	---	---	7.0	<b>7.1</b>	6.9	---	7.0
-15.4	Appomattox 1, VA	---	---	<b>8.3</b>	<b>8.3</b>	8.2	---	8.1
-15.4	Appomattox 2, VA	---	---	9.0	9.0	<b>9.1</b>	---	8.9
-14.7	Mcnairy, TN	10.0	9.8	<b>10.1</b>	9.9	10.0	9.8	9.8
-14.6	Hardin, TN	9.0	9.0	<b>9.1</b>	9.0	9.0	8.9	8.9
-12.7	Northampton, NC	<b>8.1</b>	7.8	7.8	8.0	7.9	7.8	8.0
-12.1	Laurens, SC	<b>9.1</b>	9.0	9.0	9.0	8.9	8.9	8.7
-10.9	Chilton, AL	<b>11.2</b>	10.9	11.0	10.8	10.9	10.7	10.6
-10.9	Newberry, SC	<b>9.4</b>	9.3	9.3	9.2	9.3	9.1	8.9
-10.6	Robeson, NC	<b>10.5</b>	10.4	<b>10.5</b>	<b>10.5</b>	10.2	10.3	10.1
-10.1	Autauga, AL	<b>9.2</b>	8.9	8.7	8.9	8.8	8.9	8.8
-10	Williamsburg, SC	<b>8.1</b>	7.9	7.8	7.5	7.7	7.6	7.2
-8.8	Randolph, GA	<b>7.4</b>	7.2	7.1	7.0	7.0	7.0	6.3
-8.8	Escambia, AL	<b>11.1</b>	10.8	10.8	10.5	10.5	10.6	9.4
-8.8	Escambia, AL	<b>11.0</b>	10.8	10.7	10.6	10.7	10.6	10.1
-8.6	Screven, GA	<b>9.3</b>	9.2	9.0	9.0	8.7	9.1	8.3
-7.7	Berkeley, SC	<b>12.2</b>	12.0	11.9	11.8	11.7	11.8	11.5
-7.6	Tattnall, GA	<b>12.8</b>	12.6	12.3	12.3	12.1	12.4	11.5
-7.6	Bradford, FL	<b>9.0</b>	8.7	8.3	8.2	8.2	8.5	7.4
-7.6	Ware, GA	<b>8.6</b>	8.2	8.0	7.7	7.9	7.9	7.4

**Table A3.** Individual site least square mean values by seed source for straightness. Values in bold indicate seed sources having the lowest mean for each site (seed sources are sorted by overall rank going highest rank from left to right). Standard errors range from 0.03 to 0.07.

Min. Temp. (°C)	Site	Seed sources						
		VA	NC	LG	SC	PD	FL&GA	UG
-16.4	Stewart 1, TN	<b>2.18</b>	2.26	---	---	2.24	---	2.45
-16.4	Stewart 2, TN	<b>2.14</b>	2.26	---	---	2.18	---	2.22
-15.4	Appomattox 1, VA	<b>2.03</b>	2.04	---	---	2.05	---	2.05
-15.4	Appomattox 2, VA	<b>3.09</b>	3.37	---	---	3.40	---	3.44
-14.7	Mcnairy, TN	<b>3.37</b>	3.57	3.57	3.63	3.51	3.68	3.61
-14.6	Hardin, TN	<b>3.01</b>	3.10	3.14	3.18	3.14	3.18	3.24
-12.7	Northampton, NC	<b>3.33</b>	3.47	3.48	3.63	3.48	3.59	3.49
-12.1	Laurens, SC	<b>3.34</b>	3.49	3.36	3.52	3.42	3.44	3.56
-10.9	Chilton, AL	<b>3.35</b>	3.44	3.38	3.43	<b>3.35</b>	3.48	3.45
-10.9	Newberry, SC	<b>3.44</b>	3.39	3.45	3.57	3.45	3.57	3.58
-10.6	Robeson, NC	<b>3.35</b>	3.42	3.49	3.64	3.42	3.62	3.49
-10.1	Autauga, AL	<b>3.26</b>	3.30	3.35	3.47	3.49	3.50	3.50
-10	Williamsburg, SC	<b>3.06</b>	3.30	3.30	3.38	3.17	3.34	3.42
-8.8	Randolph, GA	<b>2.92</b>	3.03	3.04	3.15	2.93	3.01	3.16
-8.8	Escambia, AL	3.45	3.32	3.33	<b>3.31</b>	3.38	3.56	3.64
-8.8	Escambia, AL	<b>3.03</b>	3.29	3.21	3.41	3.35	3.37	3.35
-8.6	Screven, GA	<b>3.32</b>	3.40	3.42	3.40	3.41	3.46	3.44
-7.7	Berkeley, SC	<b>3.41</b>	3.75	3.78	3.75	3.66	3.88	3.94
-7.6	Tattnall, GA	<b>3.42</b>	3.50	3.50	3.53	3.51	3.60	3.61
-7.6	Bradford, FL	3.54	3.50	<b>3.42</b>	3.51	3.52	3.61	3.66
-7.6	Ware, GA	3.36	3.30	3.36	<b>3.23</b>	3.42	3.37	3.57

**Table A4.** Individual site least square mean values by seed source for fusiform rust incidence. The sites are ordered by minimum winter temperatures. The values in bold indicate seed sources that have the lowest mean for each site. Cold tolerance sites in Virginia and Tennessee were not included because there was no rust incidence on those sites. Standard errors range from 0.00 to 0.02.

Min. Temp. (°C)	Site	Seed sources						
		VA	NC	LG	SC	PD	FL&GA	UG
-14.7	Mcnairy, TN	<b>0.04</b>	0.06	<b>0.04</b>	<b>0.04</b>	<b>0.04</b>	0.06	<b>0.04</b>
-14.6	Hardin, TN	0.01	0.01	<b>0.00</b>	0.01	<b>0.00</b>	0.01	0.01
-12.7	Northampton, NC	0.88	0.88	0.84	<b>0.77</b>	0.84	0.85	0.83
-12.1	Laurens, SC	0.48	0.47	0.49	<b>0.39</b>	0.41	0.53	0.50
-10.9	Chilton, AL	0.27	0.29	<b>0.22</b>	0.23	0.24	0.26	0.23
-10.9	Newberry, SC	<b>0.65</b>	0.71	<b>0.65</b>	0.66	0.69	0.78	0.66
-10.6	Robeson, NC	0.48	0.49	0.43	<b>0.41</b>	0.50	0.57	0.52
-10.1	Autauga, AL	0.68	0.76	0.65	<b>0.64</b>	0.65	0.76	0.68
-10	Williamsburg, SC	0.44	0.47	<b>0.34</b>	0.41	0.46	0.57	0.45
-8.8	Randolph, GA	0.62	0.70	<b>0.54</b>	0.57	0.62	0.63	0.59
-8.8	Escambia, AL	0.09	0.08	<b>0.06</b>	0.07	0.09	0.12	0.12
-8.8	Escambia, AL	0.36	0.30	<b>0.23</b>	0.25	0.27	0.38	0.35
-8.6	Screven, GA	0.52	0.62	<b>0.47</b>	0.49	0.57	0.62	0.58
-7.7	Berkeley, SC	0.70	0.75	0.66	<b>0.64</b>	0.72	0.79	0.75
-7.6	Tattnall, GA	0.56	0.54	<b>0.43</b>	<b>0.43</b>	0.50	0.60	0.48
-7.6	Bradford, FL	0.60	0.69	<b>0.56</b>	0.60	0.62	0.69	0.61
-7.6	Ware, GA	0.25	0.21	0.20	<b>0.19</b>	0.24	0.27	0.24

**Table A5.** Individual site least square mean values by seed source for forking incidence. The values in bold indicate seed sources that have the lowest mean for each site. Cold tolerance sites in Virginia and Tennessee were not included because there was no measurement of forking on those sites. The sites are ordered by minimum winter temperatures. Standard errors ranged from 0.01 to 0.02.

Temp. (°C)	Site	Seed sources						
		VA	NC	LG	SC	PD	FL&GA	UG
-14.7	Mcnairy, TN	<b>0.46</b>	0.49	0.52	0.49	0.54	0.49	0.48
-14.6	Hardin, TN	<b>0.28</b>	0.35	0.34	0.37	0.38	0.34	0.38
-12.7	Northampton, NC	<b>0.11</b>	0.17	0.20	0.17	0.22	0.19	0.16
-12.1	Laurens, SC	<b>0.25</b>	0.26	0.34	0.26	0.30	0.27	0.29
-10.9	Chilton, AL	<b>0.26</b>	0.32	0.35	0.38	0.34	0.33	0.33
-10.9	Newberry, SC	0.45	<b>0.42</b>	0.47	0.51	0.47	0.44	0.43
-10.6	Robeson, NC	<b>0.19</b>	0.23	0.29	0.25	0.24	0.21	0.25
-10.1	Autauga, AL	<b>0.07</b>	0.11	0.16	0.09	0.13	0.08	0.08
-10	Williamsburg, SC	<b>0.02</b>	0.08	0.05	0.07	0.04	0.04	0.06
-8.8	Randolph, GA	<b>0.37</b>	0.37	0.39	0.37	0.39	0.44	0.38
-8.8	Escambia, AL	0.30	<b>0.26</b>	0.30	0.30	0.35	0.32	0.29
-8.8	Escambia, AL	<b>0.14</b>	0.17	0.17	0.19	0.22	0.15	0.17
-8.6	Screven, GA	<b>0.13</b>	0.18	0.16	0.17	0.21	0.14	0.17
-7.7	Berkeley, SC	<b>0.11</b>	0.13	0.12	<b>0.11</b>	0.15	0.12	0.08
-7.6	Tattnall, GA	<b>0.15</b>	0.22	0.21	0.20	0.24	0.21	0.23
-7.6	Bradford, FL	0.10	<b>0.07</b>	0.08	0.09	0.09	<b>0.07</b>	0.08
-7.6	Ware, GA	<b>0.06</b>	0.10	<b>0.06</b>	0.08	0.09	0.09	0.10

# **Appendix B**

## Statistical Examples

**Example 1.1.** Check for unbiased variance estimators for Shukla's stability variances for height from Chapter 1. The unbiased variance estimators for height ( $\hat{\sigma}_{LS(k)}^2$ ) can be found in Table 1.4 and the location by seed source variance for height ( $\bar{\sigma}_{LS}^2 = \sigma_{Is}^2 = 0.028$ ) can be confirmed in Table 1.3. The variable t is the number of seed sources  $\sigma_{Is}^2$  was split into for Shukla's analysis.

$$\bar{\sigma}_{LS}^2 = \frac{1}{t} \times \sum_{k=0}^t \hat{\sigma}_{LS(k)}^2 = \frac{1}{7} \times (0.119 + 0.004 + 0.035 + 0.018 + 0.012 + 0.005 + 0.005) = 0.028$$

## **Appendix C**

General Site Description, Silvicultural Prescriptions, & Other Pertinent Information

All soil series descriptions are summaries derived from the database of Official Soil Series, which is maintained by the Natural Resources Conservation Service of the United States Department of Agriculture. Most of the locations listed for the sites are county centers since exact coordinates were not listed on establishment reports for most test sites.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Official Soil Series Descriptions. Available online at <http://soils.usda.gov/technical/classification/osd/index.html>. Accessed 04/27/2011.

**Appomattox County 1&2, VA** (Minimum Winter Temperature -15.4 °C)

These tests were planted on May 7-8, 1996 by Westvaco on the Fleshman Tract in Appomattox County, VA. The approximate location of the planting is 37° 22' 2" N / 78° 49' 5" W. Each test contains 50-55 pollen-mixed crosses (excluding the South Carolina Coastal, Florida & Georgia Coastal, and Lower Gulf seed sources). Trees were planted in a randomized complete block design with a single cross represented in each of 24 blocks. The trees were planted on a 9'x9' spacing with 2 buffer rows on each side of the test.

Before planting, the site was occupied by a 29 year old loblolly pine stand that was harvested in the summer of 1995. Chopping and burning in the fall of 1995 was used to clear the site for planting. A broadcast spray of 4 oz of Arsenal® with 2oz of Oust® per acre on May 5, 1996 was used to control herbaceous competition before planting. On May 20, 1996, hand-held sprayers were used to treat trees with application of a 4% solution of Dursban® 4E in water to control Pales weevil damage. Hardwood competition was controlled using backpack sprayers that held a 0.5% Arsenal® with 0.25% Timbersurf® 90 solution in water. Trees were planted by hand.

The soil series and estimated site index were not listed for this site. The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Northampton County, NC** (Minimum Winter Temperature -12.7 °C)

This test was planted on May 3, 1994 by Champion International Corp. on the Daniels Tract in Northampton County, NC. The approximate location of the planting is 36° 26' 28" N / 77° 28' 10" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 9'x9' spacing.

Before planting, the site was an old agricultural field. Subsoiling was applied to the site before planting. A site preparation spray of 96 oz Round-up®, 7.5 oz Arsenal®, and 4.5 oz Oust® per acre was used to control competition before planting. Trees were planted by hand.

The site index at a base age of 25 for the site was 63 feet. The soil series for the site was Bethera Silt Loam in the soil class for fine, mixed, semiactive, thermic Typic Paleaquults. The Bethera series is a deep, poorly drained, clayey soil with slow permeability and extreme to moderate acidity. Drainage is typically so poor in these soils that the water table is at or near surface level a quarter to half of the year. This soil series is typically found in the terraces and flood plains of the Coastal Plain with < 2% slopes. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/B/BETHERA.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/B/BETHERA.html)). The base material is clayey marine or fluvial deposits.

The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Robeson County, NC** (Minimum Winter Temperature -10.6 °C)

This test was planted on November 2, 1994 by Federal Paper Board on the Maynor Tract in Robeson County, NC. The approximate location of the planting is 34° 39' 30" N / 79° 6' 23" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 6'x10' spacing.

Before planting, the site was an old agricultural field. Disking and subsoiling was applied to the site before planting. A site preparation spray, September 1994, of 32 oz Round-up®, 3 oz Arsenal®, and 3 oz Oust® per acre was used to control competition before planting. Trees were planted by hand.

The site index at a base age of 25 for the site was 60 feet (SI of 90 feet at base age 50). The soil series for the site was Pantego in the soil class for fine-loamy, siliceous, semiactive, thermic Umbric Paleaquults. The Pantego series is a very deep, very poorly drained, loamy soil with moderate permeability and extreme to strong acidity. Drainage is typically so poor in these soils that the water table is at or near surface during the wet season. This soil series is typically found in the depressions of the Coastal Plain and Coastal Flatwoods with < 2% slopes. The base material is loamy, medium-sized sediment deposits. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at

[https://soilseries.sc.egov.usda.gov/OSD\\_Docs/P/PANTEGO.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/P/PANTEGO.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Williamsburg County, SC** (Minimum Winter Temperature -10.0 °C)

This test was planted on April 17, 1996 by International Paper on the Whites Bay/Cedar Swamp Rd. Tract in Williamsburg County, SC. The approximate location of the planting is 33° 37' 57" N / 79° 44' 25" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 7'xBed spacing (spacing of the bed was not specified).

Before planting, the site was harvested and was prepared using chopping and bedding. In May 1996, 32 oz of Velpar® and 2 oz of Oust® per acre were used to control competition after planting. Trees were planted by hand.

The site index at a base age of 25 for the site was 62 feet. The soil series for the site was Stallings in the soil class for coarse-loamy, siliceous, semiactive, thermic Aeric Paleaquults. The Stallings series is a deep, somewhat poorly drained, loamy sand soil with moderately rapid permeability and extreme to strong acidity. This soil series is typically found in the interstream areas of the Coastal Plain with 0-3% slopes. The base material is coarse Coastal Plain sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/S/STALLINGS.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/S/STALLINGS.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Berkeley County, SC** (Minimum Winter Temperature -7.7 °C)

This test was planted on November 9, 1993 by Westvaco on the Powell Bay Tract in Berkeley County, SC. The approximate location of the planting is 33° 7' 37" N / 79° 58' 50" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 9'x9' spacing.

Before planting, the site was an old agricultural field and was prepared using mowing and subsoiling. On August 26, 1993, 21 oz of Round-up®, 3 oz of Oust®, and 8 oz Arsenal® Oust®, Dursban® per acre was used to control competition before planting. On March 30 and May 11, 1994, Dursban® 4E was used to control for aphids. Post-planting competition was controlled using 3 oz of Oust® per acre. Trees were planted by hand.

The site index at a base age of 25 for the site was 70 feet. The soil series for the site was Goldsboro in the soil class for fine-loamy, siliceous, subactive, thermic Aquic Paleudults. The Goldsboro series is a very deep, moderately well-drained, loamy sand soil with moderate permeability and extreme to strong acidity. This soil series is typically found in the terraces and upland areas of the Coastal Plain with 0-10% slopes. The base material is fluvial and marine sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/G/GOLDSBORO.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/G/GOLDSBORO.html)).

The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Screven County, GA** (Minimum Winter Temperature -8.6 °C)

This test was planted on December 8, 1994 by Georgia Pacific on the Gainer-McRae Tract in Berkeley County, SC. The approximate location of the planting is 32° 44' 44" N / 81° 37' 55" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 8'x10' spacing.

Before planting, the site was an old agricultural field and was prepared using mowing and subsoiling. On May 1, 1995, 5 oz of Velpar® and 1 oz of Oust® per acre was used to control competition after planting. Starting in April 1995, 15 oz of Asana® XL per acre was used to control pine tip moth on the 10<sup>th</sup> day of each month. Trees were planted by hand.

The site index at a base age of 25 for the site was 55 feet. The soil series for the site was Bonifay sand in the soil class for loamy, siliceous, subactive, thermic Grossarenic Plinthic Paleudults. The Bonifay series is a very deep, well drained, loamy sand soil with very strong to moderate acidity and permeability varying between layers with the upper part of the pedon having rapid drainage and decreasing drainage the deeper you go. This soil series is typically found in the higher ridges of the Coastal Plain with 0-12% slopes. The base material is sandy and loamy marine sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/B/BONIFAY](https://soilseries.sc.egov.usda.gov/OSD_Docs/B/BONIFAY))

.html). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Tattnall County, GA** (Minimum Winter Temperature -7.6 °C)

This test was planted on July 6, 1994 by Union Camp on the Old Tattnall Seed Orchard Tract in Tattnall County, GA. The approximate location of the planting is 32° 3' 30" N/ 81° 59' 15" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 6'x12' spacing.

Before planting, the site was a seed orchard and was prepared using chopping, burning, harrowing, and bedding. Trees were planted by hand.

The estimated site index was not recorded for this site. The soil series for the site was Leefield loamy sand in the soil class for loamy, siliceous, subactive, thermic Arenic Plinthaquic Paleudults. The Leefield series is a very deep, somewhat poorly drained, loamy sand soil with very strong to strong acidity and permeability varying between layers with the upper part of the pedon having rapid drainage and lower part having slow drainage. This soil series is typically found in the higher ridges of the Coastal Plain with 0-12% slopes. The base material is sandy and loamy marine sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/L/LEEFIELD.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/L/LEEFIELD.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Randolph County, GA** (Minimum Winter Temperature -8.8 °C)

This test was planted on April 19, 1995 by Mead Coated Paper Board on the Holeman-Lee Tract in Randolph County, GA. The approximate location of the planting is 31° 45' 50" N / 84° 44' 43" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 7'x7' spacing.

Before planting, the site was an old agricultural field and was prepared using disking and subsoiling. Pre-planting competition control was done on March 14, 1995 using 2 oz of Oust® per acre. Tip moth was controlled on April 20, 1995 using 7 grams of Furadan® 15G per tree. Trees were planted by hand.

The site index at a base age of 25 for the site was between 65 and 70 feet. The soil series for the site was Americus loamy sand in the soil class for sandy, siliceous, thermic Rhodic Paleudults, but some notes suggested that the site might also contain Red Bay soil series. The Americus series is a very deep, somewhat excessively drained, loamy sand soil with very strong to strong acidity, moderately rapid to rapid permeability, and low available water. This soil series is typically found in the uplands of the Coastal Plain with 0-25% slopes. The base material is sandy sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/A/](https://soilseries.sc.egov.usda.gov/OSD_Docs/A/))

AMERICUS. html). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Bradford County, FL** (Minimum Winter Temperature -7.6 °C)

This test was planted on October 30 through December 7, 1995 by Rayonier on the Smith and Rowe Lease Tract in Bradford County, FL. The approximate location of the planting is 29° 55' 43" N / 82° 8' 32" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 11'x5.5' spacing.

Before planting, the site was harvested in October 1993 and was prepared by spot raking with windrows outside of the planting area and double-bedding of the test site. Fertilization occurred in the fall of 1996 with the application of 200 lbs per acre of diammonium phosphate (DAP). Post-planting competition control was done in the spring of 1996 using 6 oz of Arsenal® per acre. Tip moth was controlled in April 1996 using Asana®. Trees were planted by hand.

The site index at a base age of 25 for the site was 70 feet. The soil series for the site was Seagate fine sand in the soil class for sandy-loamy, siliceous, active, thermic Typic Haplohumods. The Seagate series is a very deep, somewhat poorly to moderately well-drained, fine sand soil with extreme to moderate acidity, moderately rapid permeability, and deep, persistent free water. This soil series is typically found in the marine terraces and flatwoods of the lower Coastal Plain with 0-3% slopes. The base material is sandy and loamy marine sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation

Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/S/SEAGATE.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/S/SEAGATE.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Ware County, GA** (Minimum Winter Temperature -7.6 °C)

This test was planted on December 15 and 16, 1994 by the Georgia Forestry Commission in the Dixon State Forest within Ware County, GA. The approximate location of the planting is 29° 55' 43" N / 82° 8' 32" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 12'x6' spacing.

Before planting, the site was harvested and was prepared using burning, chopping, and double-bedding. Trees were planted by hand.

The estimated site index was not recorded for this site. The soil series for the site was Pelham loamy sand in the soil class for loamy, siliceous, subactive, thermic Arenic Paleaquults. The Pelham series is a very deep, poorly drained, loamy sand soil with extreme to strong acidity, moderate permeability, and ponding of water above ground level. This soil series is typically found in the toe slopes, drainage-ways, depressions, and broad flats of the Coastal Plain with 0-5% slopes. The base material is unconsolidated sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/P/PELHAM.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/P/PELHAM.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Escambia County 1, AL** (Minimum Winter Temperature -8.8 °C)

This test was planted on May 20 and 21, 1997 by Jefferson Smurfit Corp. on the Brewton Seed Orchard Tract in Escambia County, AL. The approximate location of the planting is 31° 6' 14" N / 87° 13' 58" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 6'x9' spacing.

Before planting, the site was an old field before planting and was prepared by disking the test site. Pre-planting competition control was done with 2oz of Oust® per acre on April 3, 1997 and 4 oz of Oust® per acre on May 1, 1997. Trees were planted by hand.

The site index at a base age of 25 for the site was 40 feet. The soil series for the site was Greenville fine sandy loam in the soil class for fine, kaolinitic, thermic Rhodic Kandiudults. The Greenville series is a very deep, well-drained, fine sandy loam soil with very strong to moderate acidity and moderate permeability. This soil series is typically found in the uplands of the Coastal Plain with 0-18% slopes. The base material is clayey marine sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/G/GREENVILLE.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/G/GREENVILLE.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Escambia County 2, AL** (Minimum Winter Temperature -8.8 °C)

This test was planted on June 7, 1994 by Scott Paper Company on the Jack Springs Tract in Escambia County, AL. The approximate location of the planting is 31° 6' 14" N / 87° 13' 58" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 8'x10' spacing.

Before planting, the site was a sycamore plantation. The previous stand was harvested and the site was prepared by disking and energizing. Pre-planting competition control was done with 96 oz of Atrazine® and 2 oz of Oust® per acre. Trees were planted by hand.

The site index at a base age of 25 for the site was 65 feet. The soil series for the site was Poarch fine sandy loam in the soil class for coarse-loamy, siliceous, semiactive, thermic Plinthic Paleudults. The Poarch series is a deep, well to moderately well-drained, fine sandy loam soil with very strong to strong acidity and moderate to slow permeability. This soil series is typically found in the uplands of the Coastal Plain with 0-8% slopes. The base material is unconsolidated sandy and loamy marine sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/P/POARCH.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/P/POARCH.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Autauga County, AL** (Minimum Winter Temperature -10.1 °C)

This test was planted on December 6, 1996 by Alabama Forestry Commission in the Miller Nursery of Autauga County, AL. The approximate location of the planting is 32° 31' 23" N / 86° 34' 37" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. Tree spacing was not recorded for this site.

Before planting, the site was an old field and was prepared by disking. No further treatments were listed. Trees were planted by hand.

The site index at a base age of 25 for the site was 60 feet (SI of 90 feet at base age 50). The soil series for the site was Lucedale loam in the soil class for fine-loamy, siliceous, subactive, thermic Rhodic Paleudults. The Lucedale series is a deep, well-drained, loam soil with strong to slight acidity and moderate permeability. This soil series is typically found in the uplands of the southern Coastal Plain with 0-2% slopes. The base material is loamy sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/L/LUCEDALE.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/L/LUCEDALE.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

## **Sumter County, AL\***

This test was planted on January 1, 1999 by Gulf States and Fort James on the Tract in Sumter County, AL. The approximate location of the planting is 32° 33' 31" N / 88° 12' 56" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 8'x10' spacing.

Before planting, the site was harvested and the site was prepared by burning and bedding. Pre-planting competition control was done with oz of Arsenal® and oz of Oust® per acre. Post-planting competition control was done with an unlisted amount of Arsenal® and Escort®. Post-planting competition control was done with an unlisted amount of Velpar® and Oust®. Trees were planted by hand.

The site index at a base age of 25 for the site was 70 feet. The soil series for the site was Cahaba sandy loam in the soil class for fine-loamy, siliceous, semiactive, thermic Typic Hapludults. The Cahaba series is a deep, well-drained, sandy loam soil with very strong to moderate acidity and moderate permeability. This soil series is typically found in the stream terraces of the Coastal Plain with 0-8% slopes. The base material is sandy and loamy alluvial sediments. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/C/CAHABA.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/C/CAHABA.html)). The

planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

(\*This site was not used in this study because it only had 4 year measurement data. It is included because the block plot portion of this study may be used in the future and require this information.)

**McNairy County, TN** (Minimum Winter Temperature -14.7 °C)

This test was planted on June 4 through 6, 1996 by Champion International Corp. on the Kirby Tract in McNairy County, TN. The approximate location of the planting is 35° 10' 47" N / 88° 33' 2" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 8'x10' spacing.

Before planting, the site was an old field and was prepared by subsoiling. Pre-planting competition control was done with 16 oz of Accord® and 4 oz of Oust® per acre. Trees were planted by hand.

The site index at a base age of 25 for the site was 75 feet. The soil series for the site was not listed, but the description was for a soil having coarse-loamy, siliceous, acid, Thermic Aquic Udifluvents. The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Chilton County, AL** (Minimum Winter Temperature -10.9°C)

This test was planted on May 3, 1996 by International Paper on the Highway 82 Tract in Chilton County, AL. The approximate location of the planting is 32° 51' 9" N / 86° 41' 23" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 7'x9' spacing.

Before planting, the site was harvested and was prepared by shearing, raking, stumping, and bedding. No other treatments are listed for this test site. Trees were planted by hand.

The estimated site index was not recorded for this site. The soil series for the site was Falaya silt loam in the soil class for coarse-silty, mixed, active, acid, thermic Aeric Fluvaquents. The Falaya series is a very deep, somewhat poorly drained, silt loam soil with very strong to strong acidity, moderate permeability, and high water table during rain events. Flooding and standing water is also typical for the sites where this soil occurs. This soil series is typically found in the flood plains of the Southern Mississippi Valley Silty Uplands with 0 to 2% slopes. The base material is silty alluvial materials from loess. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/F/FALAYA.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/F/FALAYA.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Hardin County, TN** (Minimum Winter Temperature -14.6 °C)

This test was planted in January 1995 by the Tenneco Packaging-Counce Woodlands on the Hookers Bend Tract in Hardin County, TN. The approximate location of the planting is 35° 12' 26" N / 88° 12' 29" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 9'x9' spacing.

Before planting, the site was an old field and was prepared using subsoiling. Post-planting competition control was done with 2 oz of Oust® per acre. Trees were planted by hand.

The site index at a base age of 25 for the site was 70 feet. The soil series for the site was Taft silt loam in the soil class for fine-silty, siliceous, semiactive, thermic Glossaquic Fragiudults. The Taft series is a very deep, somewhat poorly drained, silt loam soil with extreme to strong acidity, slow permeability, and occurrence of subsoil fragipan. This soil series is typically found in the upland flats, depressions, and stream terraces with 0 to 2% slopes. The base materials consist of a top mantle of alluvium or loess with underlying residuals from limestone or shale. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/T/TAFT.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/T/TAFT.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Newberry County, SC** (Minimum Winter Temperature -10.9 °C)

This test was planted in June 21, 1995 by Champion International Corp. on the Thompson-Ridgley Tract in Newberry County, SC. The approximate location of the planting is 34° 15' 55" N / 81° 35' 18" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 9'x9' spacing.

Before planting, the site was an old field and was prepared using subsoiling. Post-planting competition control was done with 2 oz of Arsenal® and 1 oz of Oust® per acre on August 2, 1995. Pine tip moth was controlled using 4 oz of Pounce® per acre on August 2, 1995. Trees were planted by hand.

The site index at a base age of 25 for the site was 60 feet (SI of 90 feet at base age 50). The soil series for the site was Congaree silt loam in the soil class for fine-loamy, mixed, active, nonacid, thermic Oxyaquic Udifluvents. The Congaree series is a deep, well to moderately well-drained, loam soil with strong acidity to neutral pH and moderate permeability. This soil series is typically found in floodplains or bottoms of slopes with 0 to 4% slopes. The base materials consist of loamy alluvium 2 to 6 feet deep. The areas where these soils occur are prone to winter and spring flooding. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/C/](https://soilseries.sc.egov.usda.gov/OSD_Docs/C/)

CONGAREE.html). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

**Laurens County, SC** (Minimum Winter Temperature -12.1 °C)

This test was planted in May 12 through 16, 1995 by Bowater Carolina on the CDW 1185 RT Hollingsworth Rd Tract in Laurens County, SC. The approximate location of the planting is 34° 29' 12" N / 82° 0' 35" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 8'x8' spacing.

Before planting, the site was harvested and was prepared using a KG blade and disking. Pre-planting competition control was done with 2 oz of Oust® per acre on May 1, 1995. Trees were planted by hand.

The site index at a base age of 25 for the site was 57 feet. The soil series for the site was Cataula sandy loam in the soil class for fine, kaolinitic, thermic Oxyaquic Kanhapludults. The Cataula series is a very deep, moderately well-drained, loam soil with strong to slight acidity and slow permeability. This soil series is typically found in between streams and upper slopes of the Piedmont with 2 to 25% slopes. The base materials consist of eroded igneous and metamorphic rocks. The description of this soil series was derived from the Official Soil Series Description archive run by the Soil Survey Staff of the Natural Resources Conservation Service. See the first page for the archive site or last few pages for the specific soil series descriptions (found at [https://soilseries.sc.egov.usda.gov/OSD\\_Docs/C/CATAULA.html](https://soilseries.sc.egov.usda.gov/OSD_Docs/C/CATAULA.html)). The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

## **Floyd County, GA\***

This test was planted in January 19, 2000 by Temple-Inland Forest on an unlisted tract in Floyd County, GA. The approximate location of the planting is 34° 15' 17" N / 85° 11' 54" W. The test contains 140 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each block. The trees were planted on a 6'x10' spacing.

Before planting, the site was harvested and was prepared using disking and subsoiling. Competition control was done with an unlisted amount of Oust® per acre on at an unknown date. Fertilization occurred at an unknown date with the application of 200 lbs per acre of diammonium phosphate (DAP). Pine tip moth was controlled using an unlisted amount of Pounce® per acre at unknown date. Trees were planted by hand.

The site index at a base age of 25 for the site was 57 feet. The soil series and description was not listed. The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

(\*This site was not used in this study because it only had 4 year measurement data. It is included because the block plot portion of this study may be used in the future and require this information.)

**Stewart County 1&2, TN** (Minimum Winter Temperature -16.4 °C)

These tests were planted on May 7-8, 1996 by Westvaco on the Tract Eightenn in Stewart County, TN. The approximate location of the planting is 36° 28' 50" N / 87° 48' 53" W. Each test contains 50 pollen-mixed crosses. Trees were planted in a randomized complete block design with a single cross represented in each of 24 blocks. The trees were planted on a 9'x9' spacing with 2 buffer rows on each side of the test.

Before planting, the site was occupied by an upland hardwood stand that was harvested in the winter of 1994 and 1995. The site was sheared, raked into windrows, and disked following harvest. Hardwood competition was controlled using backpack sprayers that held a 1% Arsenal®, 2% Accord®, and 1% Entry II® surfactant solution in water on September 24 to 30, 1996. Trees were planted by hand.

The soil series and site index were not listed for this site. The planting design and location maps can be found in the establishment report archives of the NCSU Tree Improvement Program.

## Appendix C References

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# **Appendix D**

## Chapter 2: Individual Family Linear Models

**Table D1.** Finlay and Wilkinson (1963) regression models for height and volume for each family within seed source. A family's slope is not significantly different for the test  $H_0: \beta_1=1$  if  $p>0.05$  (significant values in bold;  $\beta_1=1$ , average stability;  $\beta_1>1$ , low stability;  $\beta_1<1$ , high stability; and  $\beta_0$  difference from overall mean). Standard errors follow the  $\pm$  symbol.

Seed Source	Family	Height				Volume			
		$\beta_1$	$\beta_0$	$R^2$	Pr>F	$\beta_1$	$\beta_0$	$R^2$	Pr>F
VA	TIP1625340	0.99	-2.31	0.95	0.905	0.87	-1.52	0.88	0.136
VA	TIP11242661	0.98	-5.04	0.88	0.847	0.81	-2.94	0.76	0.133
VA	TIP1479572	1.04	-7.83	0.95	0.521	0.91	-3.51	0.83	0.423
VA	TIP190436	0.95	0.37	0.95	0.354	0.83	-2.85	0.88	<b>0.045</b>
VA	TIP1343859	1.01	0.33	0.98	0.771	1.01	-3.84	0.95	0.931
VA	TIP1251216	1.04	-7.39	0.92	0.572	0.94	-4.60	0.85	0.553
VA	TIP179389	1.00	-3.13	0.93	0.978	0.85	-2.81	0.84	0.147
VA	TIP1160767	0.89	5.20	0.87	0.243	0.84	0.22	0.71	0.276
VA	TIP1220681	0.94	2.42	0.90	0.455	0.84	-0.02	0.79	0.163
VA	TIP1453620	0.99	-4.51	0.90	0.869	0.96	-8.76	0.78	0.775
VA	TIP188307	1.00	-6.83	0.94	0.994	0.79	-1.63	0.84	<b>0.035</b>
VA	TIP1105210	0.94	2.68	0.92	0.418	0.76	7.11	0.72	0.075
VA	TIP1497589	0.91	5.40	0.95	0.130	0.78	4.57	0.77	0.063
VA	TIP1232739	0.99	-3.71	0.96	0.865	0.92	-5.35	0.89	0.351
VA	TIP11036368	0.92	0.04	0.93	0.259	0.73	-0.06	0.81	<b>0.012</b>
VA	TIP1520371	0.97	-3.54	0.94	0.700	0.79	1.43	0.85	<b>0.021</b>
VA	TIP1247793	1.03	-6.32	0.96	0.547	0.88	-3.84	0.84	0.244
VA	TIP1515862	1.02	-10.17	0.90	0.808	0.75	-4.85	0.82	<b>0.016</b>
VA	TIP1410320	1.02	-9.26	0.96	0.749	0.73	-0.90	0.87	<b>0.003</b>
VA	TIP11115345	0.97	-0.57	0.85	0.775	0.84	-1.96	0.69	0.308

**Table D1.** Continued.

Seed Source	Family	Height				Volume			
		$\beta_1$	$\beta_0$	$R^2$	Pr>F	$\beta_1$	$\beta_0$	$R^2$	Pr>F
NC-C	TIP1429158	0.95	2.31	0.97	0.233	0.82	2.42	0.95	<b>0.002</b>
NC-C	TIP185013	0.98	2.16	0.99	0.586	0.94	1.60	0.95	0.254
NC-C	TIP1113647	0.93	6.39	0.98	0.079	0.88	3.87	0.92	0.103
NC-C	TIP191224	0.97	3.11	0.96	0.526	0.96	1.44	0.89	0.664
NC-C	TIP1867475	1.08	-2.04	0.95	0.236	1.18	0.33	0.85	0.181
NC-C	TIP1100828	1.08	-4.51	0.98	0.078	1.12	-1.84	0.94	0.116
NC-C	TIP1117239	1.02	-1.54	0.98	0.501	1.07	-2.56	0.96	0.232
NC-C	TIP1250548	1.01	-2.15	0.97	0.798	0.92	3.59	0.91	0.317
NC-C	TIP1265473	0.94	8.47	0.97	0.188	0.88	6.05	0.92	0.103
NC-C	TIP1154291	1.03	-1.14	0.99	0.307	1.01	-0.20	0.97	0.903
NC-C	TIP1322436	0.92	7.72	0.97	0.082	0.86	4.71	0.91	0.072
NC-C	TIP1568481	1.02	-0.90	0.97	0.718	1.12	-4.02	0.94	0.113
NC-C	TIP1159535	1.08	-9.32	0.93	0.314	1.04	-6.42	0.87	0.705
NC-C	TIP1202544	1.03	-4.02	0.96	0.591	0.97	-2.60	0.91	0.722
NC-C	TIP1479524	0.97	5.87	0.98	0.372	1.01	4.71	0.95	0.931
NC-C	TIP11152103	0.98	-0.54	0.98	0.618	0.84	0.37	0.95	<b>0.008</b>
NC-C	TIP1694746	1.04	-0.43	0.95	0.495	1.09	3.05	0.88	0.392
NC-C	TIP1955942	1.01	-0.20	0.97	0.791	1.00	1.24	0.94	0.976
NC-C	TIP1305914	1.07	-7.29	0.98	0.120	0.94	-3.43	0.94	0.358
NC-C	TIP1483577	1.07	-7.17	0.98	0.079	0.99	-0.16	0.98	0.737

**Table D1.** Continued.

Seed Source	Family	Height				Volume			
		$\beta_1$	$\beta_0$	$R^2$	Pr>F	$\beta_1$	$\beta_0$	$R^2$	Pr>F
SC-C	TIP187077	1.00	3.66	0.96	0.942	1.13	-1.05	0.93	0.144
SC-C	TIP1287581	1.02	-1.06	0.99	0.547	1.11	-1.70	0.93	0.174
SC-C	TIP1421716	1.04	-1.27	0.97	0.410	1.12	-0.17	0.90	0.206
SC-C	TIP1347009	1.03	1.08	0.97	0.464	1.07	0.39	0.91	0.431
SC-C	TIP1343723	1.05	-0.50	0.95	0.481	1.10	0.42	0.89	0.315
SC-C	TIP1982790	0.90	14.51	0.94	0.127	0.94	12.41	0.82	0.615
SC-C	TIP1110138	0.98	5.79	0.96	0.670	0.98	6.08	0.91	0.833
SC-C	TIP1321291	0.94	11.22	0.94	0.290	0.97	8.93	0.88	0.750
SC-C	TIP1509321	0.97	6.80	0.97	0.438	1.12	3.85	0.94	0.134
SC-C	TIP1702651	0.94	11.31	0.94	0.333	1.05	7.22	0.93	0.558
SC-C	TIP163568	1.06	-4.64	0.99	0.073	1.27	-7.95	0.95	<b>0.003</b>
SC-C	TIP169970	1.00	0.10	0.97	0.953	0.99	3.87	0.90	0.891
SC-C	TIP1174016	1.04	-0.50	0.96	0.513	1.27	-0.05	0.85	0.079
SC-C	TIP1171211	0.96	6.57	0.96	0.492	1.03	4.91	0.91	0.777
SC-C	TIP1202550	1.03	-2.14	0.97	0.587	1.08	-2.88	0.90	0.399
SC-C	TIP1463621	0.99	2.98	0.97	0.814	1.11	0.26	0.94	0.171
SC-C	TIP1562077	1.01	5.55	0.95	0.938	1.15	5.70	0.85	0.300
SC-C	TIP1730876	0.98	6.45	0.95	0.737	0.97	7.92	0.90	0.756
SC-C	TIP1663917	1.02	1.99	0.98	0.586	1.18	-2.80	0.96	<b>0.013</b>
SC-C	TIP1452683	0.99	4.71	0.95	0.892	1.12	0.53	0.90	0.229

**Table D1.** Continued.

Seed Source	Family	Height				Volume			
		$\beta_1$	$\beta_0$	$R^2$	Pr>F	$\beta_1$	$\beta_0$	$R^2$	Pr>F
FL&GA	TIP11367795	0.94	5.42	0.91	0.403	0.9	4.19	0.88	0.231
FL&GA	TIP1497029	0.95	5.71	0.97	0.235	0.91	6.6	0.94	0.165
FL&GA	TIP1120639	0.99	0.98	0.98	0.788	0.89	7.81	0.93	0.099
FL&GA	TIP1860872	0.98	1.24	0.97	0.583	0.84	3.91	0.95	<b>0.008</b>
FL&GA	TIP1749053	0.99	2.73	0.97	0.798	1.04	6.39	0.92	0.666
FL&GA	TIP181356	1.06	-3.1	0.99	0.087	1.23	-5.62	0.93	<b>0.018</b>
FL&GA	TIP178908	0.94	10.58	0.93	0.334	0.93	9.77	0.85	0.530
FL&GA	TIP1152470	1.03	-2.77	0.96	0.565	0.97	-0.31	0.9	0.739
FL&GA	TIP1789107	1.02	0.05	0.98	0.542	1.00	1.73	0.93	0.988
FL&GA	TIP1317337	1.04	-2.4	0.98	0.314	1.09	-2.3	0.95	0.213
FL&GA	TIP1346095	1.02	-4.94	0.99	0.367	0.99	0.89	0.96	0.849
FL&GA	TIP1475490	0.88	10.96	0.97	<b>0.011</b>	0.89	7.7	0.92	0.122
FL&GA	TIP1647667	0.96	6.26	0.98	0.331	1.12	0.24	0.96	<b>0.070</b>
FL&GA	TIP1806541	1.01	-1.75	0.98	0.717	1.07	2.06	0.96	0.276
FL&GA	TIP1255910	0.95	7.83	0.93	0.427	0.94	5.93	0.9	0.459
FL&GA	TIP1104353	0.98	6.56	0.96	0.730	1.06	3.84	0.88	0.532
FL&GA	TIP1163615	1.07	-5.6	0.96	0.228	1.18	-5.89	0.89	0.112
FL&GA	TIP1267628	1.03	0.72	0.97	0.559	1.11	-3.8	0.87	0.332
FL&GA	TIP1143098	1.16	-14.62	0.96	<b>0.021</b>	1.29	-12.62	0.81	0.086
FL&GA	TIP1295707	1.11	-10.14	0.99	<b>0.005</b>	1.19	-7.55	0.95	<b>0.014</b>

**Table D1.** Continued.

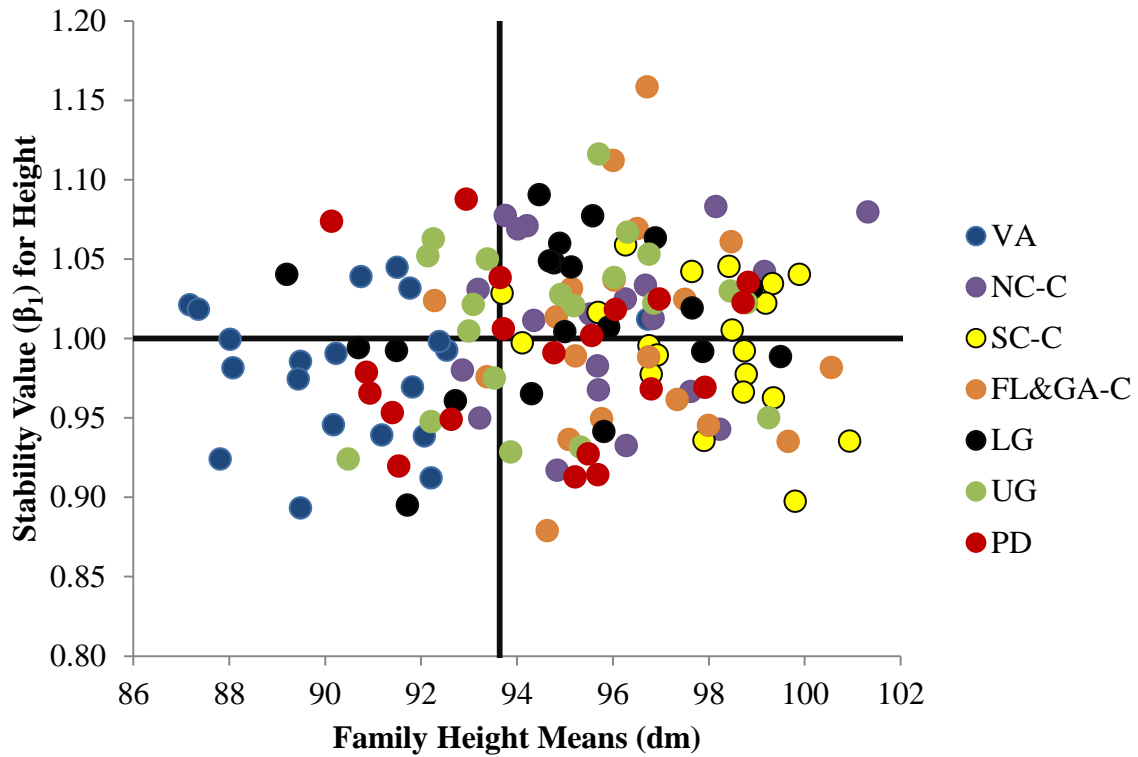
Seed Source	Family	Height				Volume			
		$\beta_1$	$\beta_0$	$R^2$	Pr>F	$\beta_1$	$\beta_0$	$R^2$	Pr>F
LG	TIP1682577	1.06	-6.35	0.97	0.208	1.00	-4.50	0.93	0.998
LG	TIP1238004	0.99	3.84	0.96	0.881	1.04	4.41	0.91	0.615
LG	TIP1769095	0.96	0.89	0.97	0.373	0.88	2.26	0.93	0.093
LG	TIP11357773	1.05	-4.74	0.97	0.319	1.12	-5.47	0.89	0.254
LG	TIP1633765	1.02	1.22	0.93	0.798	1.11	2.28	0.87	0.340
LG	TIP1906517	1.04	-9.53	0.95	0.518	0.85	-1.73	0.87	0.104
LG	TIP1440845	1.05	-4.84	0.97	0.362	1.04	-3.41	0.95	0.508
LG	TIP1190338	1.00	1.28	0.98	0.915	1.09	0.34	0.91	0.388
LG	TIP1190168	0.90	6.59	0.93	0.114	0.84	1.91	0.87	0.077
LG	TIP1506084	0.94	6.15	0.98	0.153	0.98	2.49	0.92	0.763
LG	TIP1590185	1.08	-7.53	0.96	0.210	0.98	0.66	0.88	0.807
LG	TIP1388650	0.97	2.60	0.94	0.601	0.92	4.26	0.89	0.387
LG	TIP1493302	0.99	-3.67	0.97	0.896	0.79	0.59	0.87	<b>0.019</b>
LG	TIP1251699	1.01	0.03	0.97	0.872	1.00	1.15	0.92	0.976
LG	TIP1110567	0.99	-2.87	0.96	0.881	0.94	-4.47	0.90	0.472
LG	TIP1351988	1.03	0.54	0.96	0.585	1.11	-0.29	0.90	0.253
LG	TIP1252129	1.05	-4.75	0.98	0.275	1.14	-2.12	0.89	0.198
LG	TIP1522696	1.06	-4.76	0.98	0.151	1.03	1.32	0.94	0.683
LG	TIP1563667	1.09	-9.30	0.97	0.086	1.03	-3.73	0.91	0.693
LG	TIP1294219	0.99	5.94	0.95	0.842	1.12	3.32	0.93	0.142

**Table D1.** Continued.

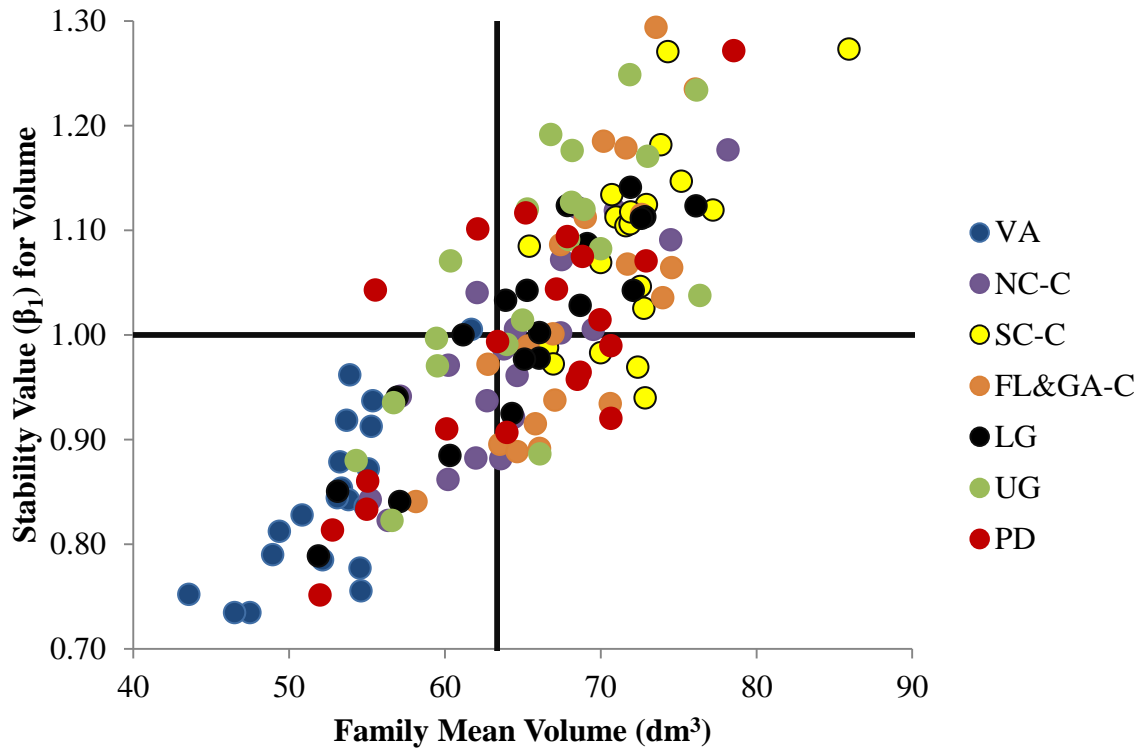
Seed Source	Family	Height				Volume			
		$\beta_1$	$\beta_0$	$R^2$	Pr>F	$\beta_1$	$\beta_0$	$R^2$	Pr>F
UG	TIP164068	1.07	-5.32	0.96	0.262	1.25	-9.72	0.94	<b>0.009</b>
UG	TIP182370	0.95	3.27	0.95	0.380	0.99	1.72	0.95	0.888
UG	TIP1130414	1.00	-2.29	0.98	0.910	0.82	4.20	0.93	<b>0.017</b>
UG	TIP1685362	1.04	-2.74	0.97	0.441	1.18	-8.66	0.93	<b>0.050</b>
UG	TIP11779639	0.93	4.98	0.97	0.104	0.89	8.01	0.92	0.115
UG	TIP178461	1.03	0.71	0.94	0.653	1.17	-2.24	0.92	0.072
UG	TIP1131229	1.05	-4.74	0.98	0.220	1.09	-5.87	0.93	0.265
UG	TIP1233515	0.93	7.87	0.97	0.149	1.08	1.45	0.92	0.378
UG	TIP1330398	1.02	-2.15	0.96	0.708	1.12	-3.60	0.95	0.101
UG	TIP1521273	0.95	7.00	0.98	0.182	1.04	6.30	0.94	0.589
UG	TIP11053654	1.05	-7.34	0.97	0.296	1.00	-5.90	0.94	0.963
UG	TIP1459390	0.98	1.97	0.96	0.656	0.97	-1.57	0.91	0.724
UG	TIP1591899	1.06	-9.06	0.97	0.227	1.13	-5.61	0.93	0.135
UG	TIP1325364	0.92	2.65	0.94	0.221	0.88	-2.53	0.87	0.200
UG	TIP1172692	1.02	1.63	0.97	0.610	1.23	-4.22	0.94	<b>0.009</b>
UG	TIP1259985	1.02	-0.09	0.97	0.663	1.12	-3.59	0.94	0.125
UG	TIP1696289	1.05	-7.87	0.97	0.279	0.94	-4.19	0.95	0.244
UG	TIP1822282	1.12	-10.66	0.97	<b>0.043</b>	1.19	-11.47	0.93	<b>0.045</b>
UG	TIP11022007	1.02	-1.71	0.99	0.510	1.01	-1.00	0.95	0.820
UG	TIP11062415	1.03	-3.35	0.97	0.555	1.07	-9.73	0.92	0.389

**Table D1.** Continued.

Seed Source	Family	Height				Volume			
		$\beta_1$	$\beta_0$	$R^2$	Pr>F	$\beta_1$	$\beta_0$	$R^2$	Pr>F
PD	TIP1285180	0.93	6.73	0.96	0.168	0.91	4.29	0.92	0.203
PD	TIP1778102	0.97	0.63	0.96	0.542	0.83	3.28	0.93	<b>0.022</b>
PD	TIP1898651	0.92	3.37	0.91	0.327	0.86	-0.50	0.82	0.229
PD	TIP1359762	0.99	1.74	0.99	0.737	1.08	-0.67	0.97	0.201
PD	TIP1433004	1.02	-0.68	0.98	0.648	0.96	6.02	0.95	0.464
PD	TIP11869793	0.91	8.59	0.98	<b>0.019</b>	0.99	6.63	0.94	0.880
PD	TIP151372	0.95	0.66	0.97	0.286	0.75	3.46	0.91	<b>0.001</b>
PD	TIP1223294	1.09	-11.20	0.98	<b>0.039</b>	1.10	-10.47	0.93	0.206
PD	TIP1132323	0.97	4.53	0.90	0.725	0.96	4.74	0.74	0.817
PD	TIP1280144	1.02	2.41	0.98	0.573	1.07	4.47	0.93	0.394
PD	TIP1521248	1.01	-2.44	0.97	0.899	0.99	-1.72	0.92	0.935
PD	TIP11210491	1.04	-4.95	0.98	0.384	1.12	-7.49	0.88	0.291
PD	TIP11332589	1.02	-0.75	0.97	0.616	1.04	-0.84	0.94	0.546
PD	TIP1188249	1.00	-0.50	0.97	0.964	1.09	-4.34	0.93	0.244
PD	TIP1323970	0.97	5.47	0.95	0.626	0.92	10.19	0.85	0.471
PD	TIP1181672	0.95	2.08	0.97	0.266	0.91	0.74	0.95	0.103
PD	TIP1125980	1.07	-8.86	0.94	0.352	1.04	-9.45	0.85	0.729
PD	TIP1808466	0.91	9.31	0.96	0.105	1.01	5.41	0.92	0.854
PD	TIP1407979	0.98	-2.60	0.97	0.621	0.81	-0.64	0.94	<b>0.003</b>
PD	TIP1221234	1.04	-0.06	0.97	0.447	1.27	-4.79	0.96	<b>0.001</b>



**Figure D1.** Stability values for different families for heights compared to family means for height. The chart is divided into four quadrants by the average response slope ( $\beta_1=1$ ) and the overall height mean (93.6 dm). The responses represented by each quadrant are as follows: the top left represents high responsiveness and low yield; the bottom left represents low responsiveness and low yield; the top right represents high responsiveness and high yield; and bottom right represents low responsiveness and high yield. The correlation between the stability value and height was  $r=0.13$ .



**Figure D2.** Stability values for different families for volumes compared to family means for volume. The chart is divided into four quadrants by the average response slope ( $\beta_1=1$ ) and the overall volume mean ( $63.4 \text{ dm}^3$ ). The responses represented by each quadrant are as follows: the top left represents high responsiveness and low yield; the bottom left represents low responsiveness and low yield; the top right represents high responsiveness and high yield; and bottom right represents low responsiveness and high yield. The correlation between the stability value and volume was  $r=0.83$ .