GROWTH AND STEM FORM QUALITY OF CLONAL *PINUS TAEDA* FOLLOWING FERTILIZATION IN THE VIRGINIA PIEDMONT

Jeremy P. Stovall, Colleen A. Carlson, John R. Seiler, and Thomas R. Fox[1]

Abstract—Clonal forestry offers the opportunity to increase yields, enhance uniformity, and improve wood characteristics. Intensive silvicultural practices, including fertilization, will be required to capture the full growth potential of clonal plantations. However, variation in nutrient use efficiency that exists among clones could affect growth responses. Our research objective was to determine the range of growth response and stem form quality due to fertilization in clones of *Pinus taeda*. A split-plot experimental design was used, with the whole plots being 2 levels of fertilization (with or without) and the split-plot factor being 25 clones. Whole-plot treatments were blocked and replicated four times. Trees were planted in May 2003, with fertilizer applied in May 2004 and May 2006. Five years after planting, a repeated measures analysis showed fertilizer by time and clone by time interactions significantly affected volume. Although there were no fertilizer by clone interactions in this trial across all 25 clones, the response to fertilizer varied, with 40 percent of the clones showing a volume improvement at 3.5 years of <3 percent while 20 percent showed improvement >15 percent. Our results suggest that a screening technique for clonal response to silvicultural treatments such as fertilization may be necessary given the wide range of fertilizer responses found among clones in this field trial and the large numbers of clones being developed by forest industry.

INTRODUCTION

Two fundamental properties influence tree growth in plantations: (1) genetics, or the ability of a plant to acquire and use resources and (2) the environment, or the availability of resources. Both properties may be manipulated to alter growth rates. Genetics may be constrained by deploying clones with high-growth rates and favorable stem form, while resource availability may be increased through fertilization. Currently clones of loblolly pine (*Pinus taeda*) propagated through both rooted cuttings and somatic embryogenesis are being deployed in increasing numbers throughout the Southeast (Frampton and others 2000, MacKay and others 2006). Fertilization is already a common practice, with approximately 0.5 million ha fertilized annually as of 2004, primarily with both nitrogen and phosphorus (Fox and others 2007). However, it is conceivable that clone by fertilizer interactions could arise, altering growth rates in response to fertilization differently for different clones. The purpose of this research is to determine (1) if the magnitude of potential clone by fertilizer interactions is substantial enough to be a problem and (2) if these interactions are common enough to be a problem. This could be a pressing issue for both landowners who purchase and plant clonally propagated loblolly pine, and for companies that are producing and testing these clones.

We know from the literature that there are few genetics by environment interactions in open-pollinated loblolly pine (McKeand and others 2006), with the notable exception of some genotype by silviculture interactions (Roth and others 2007). In other words, a higher performing family will always be better than a lower performing family, on any uniform site, or under any uniform silvicultural system. Traditional tree breeding utilizes population means to determine whether interactions occur. However, clonal screening is a process that seeks and chooses only a small handful of spectacularly high-performing outliers. Most clonal screening programs are currently planting a large number of clones across a number of sites but are only selecting the best few after no more than 6 years. Clonal screening results in the intentional selection and planting of unusual individuals from the tail end of the population distribution across large acreages. There is a great deal of stochasticity in finding these few elite genotypes, because outliers are by definition infrequent and unusual. Evidence pertaining to clone by environment interactions is currently based only on a small number of field trials which have thus far yielded inconsistent results (McKeand and others 2006).

As of this year several tens of thousands of acres have already been planted with clonal loblolly pine, primarily as single clone blocks. This trend is likely to increase in the next decade, as clonal forestry offers the opportunity to dramatically increase financial returns by increasing timber and pulp yields and plantation uniformity (Dougherty 2007). Clonal screening seeks not only to maximize yields but also to find ideotypes with other favorable characteristics such as straight stems, infrequent forking, flat branch angles, and low incidence of diseases, such as fusiform rust (Nelson and Johnsen 2008). Clones cost about 10 times more than open-pollinated trees, and thus, landowners will demand high performance for their high initial investment (Dougherty 2007). Clonal screening trials are already very large and expensive due to the number of clones being tested and as a result are typically grown under a uniform silvicultural regime. These trials are not testing for clone by fertilizer interactions. Thus, if clone by fertilizer interactions do occur frequently in loblolly pine, it will be necessary to incorporate a screening process for this into clonal screening programs.

Our alternate hypotheses are thus—that we will find significant clone by fertilizer interactions for (1) stem-volume growth, (2) growth efficiency, and (3) stem form. We are

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[1] Graduate Assistant, Research Associate, Shelton H. Short Professor of Forestry, and Associate Professor, Virginia Tech, Department of Forestry, Blacksburg, VA, respectively.

interested in economic traits for obvious reasons. However, we are also interested in some physiological traits so that if clone by fertilizer interactions for volume growth occur, we can determine the processes causing this interaction to better determine appropriate screening methods.

METHODS

Study Site

Our study was located at the Reynolds Homestead Forest Resources Research Center (36°40' N, 80°10' W) in the upper Piedmont of Patrick County, VA. Annual precipitation is 1308 mm, while mean annual maximum and minimum temperatures are 18.5 °C and 7.0 °C, respectively. Average July high temperature is 29.3 °C, and average January low temperature is –4.0 °C (World Climate 2008). Topography consists of gently sloping hills ranging in elevation from 320 to 340 m. Past intensive agricultural land use has resulted in a truncated Ap horizon, with clayey B horizons mixed with the A. Mapped soil series include Lloyd clay loam (fine, kaolinitic, thermic Rhodic Kanhapludults), Louisa loam (loamy, micaceous, thermic, shallow Ruptic-Ultic Dystrudepts), and Hiwassee loam (very-fine, kaolinitic, thermic Rhodic Kanhapludults). Site and study design descriptions can also be found in Tyree and others (2008) and King and others (2008).

Study Design

A split-plot experimental design was installed with the whole plots being two levels of fertilization (with or without) and the split-plot factor being 25 clones. Whole-plot treatments were blocked and replicated four times. One ramet (experimental unit) of each clone was planted in each plot. Ramets were rooted cuttings planted on May 19, 2003, at a 3.0- by 2.5-m spacing. Clonal material donated by the Forest Biology Research Cooperative (University of Florida, Gainesville) was from the Loblolly Pine Lower Gulf Elite Breeding Population, which includes both Atlantic coastal and Florida provenances. A border row of open-pollinated seedlings was planted around each plot. Trenches were dug and lined with plastic between plots to contain the fertilizer treatment. Site preparation prior to planting included application of glyphosphate (Roundup®) for weed control. The site was subsequently ripped and the planting rows were shallowly cultivated. After planting, complete weed control was maintained for the first 2 years. Fertilizer was applied by hand-banded application on May 4, 2004, and May 4, 2006. Each application consisted of 224 kg/ha of diammonium phosphate and 184 kg/ha of ammonium nitrate, yielding 112 kg/ha of elemental nitrogen and 53 kg/ha of elemental phosphorous.

Measurements

The trial has been measured annually since planting for height, diameter, crown width, and a variety of stem-quality metrics, such as sinuosity. Stem volume was calculated based on Burkhart (1977). Crown volume was calculated as a cone ($0.33 \pi r^2 h$) where radius was crown radius for a representative whorl at breast height and height was crown height. Stem sinuosity was scored in classes as follows: 1 for a straight stem, 2 for evident sinuosity that was not severe, 3 for severe sinuosity that could affect stem quality, and 4 for extremely severe sinuosity that would affect stem quality. Trees were categorized as either forked or not forked. Branch angle for the average of all branches on a representative whorl near breast height was scored in classes as follows: 1 for zero to 15 degrees from horizontal, 2 for 15 to 30 degrees, 3 for 30 to 45 degrees, and 4 for >45 degrees.

Statistics

Data presented in this paper are all from winter 2007 to 2008, and thus are for the first five growing seasons. Analyses were done in SAS 9.2 (SAS Institute Inc., Cary, NC) using PROC MIXED and PROC GLIMMIX with appropriate split-plot error structures (block and block * fertilizer were random effects). Continuous data were modeled with a normal distribution, score data with a Poisson distribution, and presence-absence data with a binary distribution. Regression of stem volume vs. crown volume was performed with PROC REG.

RESULTS AND DISCUSSION

Stem Volume

Both fertilizer and clone significantly affected stem-volume growth after five growing seasons in this trial. However, the clone by fertilizer interaction was not significant, as is summarized in table 1. Despite this lack of significance, it is clear from figure 1A that stem-volume response to fertilization does vary by clone. Figure 1B depicts only the four best performing clones from this trial based on fertilized stem volume. Hypothetically, were this to have been a fertilized clonal screening trial, these would be the clones selected and placed into production. It is evident from figure 1B though, that a landowner planting these clones on a marginal site, but not fertilizing them, would see markedly reduced stem-volume growth for clones B3 (63 percent of fertilized stem volume) and C2 (68 percent). On the other hand clones D2

Table 1—*P*-values from mixed models of a loblolly pine clone by fertilizer split-plot design on the Virginia Piedmont

Effect	Stem volume	Growth efficiency	Sinuosity	Forking	Branch angle
Fertilizer	0.053	0.072	0.092	0.423	0.991
Clone	<0.001	0.460	0.015	0.340	0.722
Clone * fertilizer	0.179	0.371	0.989	0.882	0.999

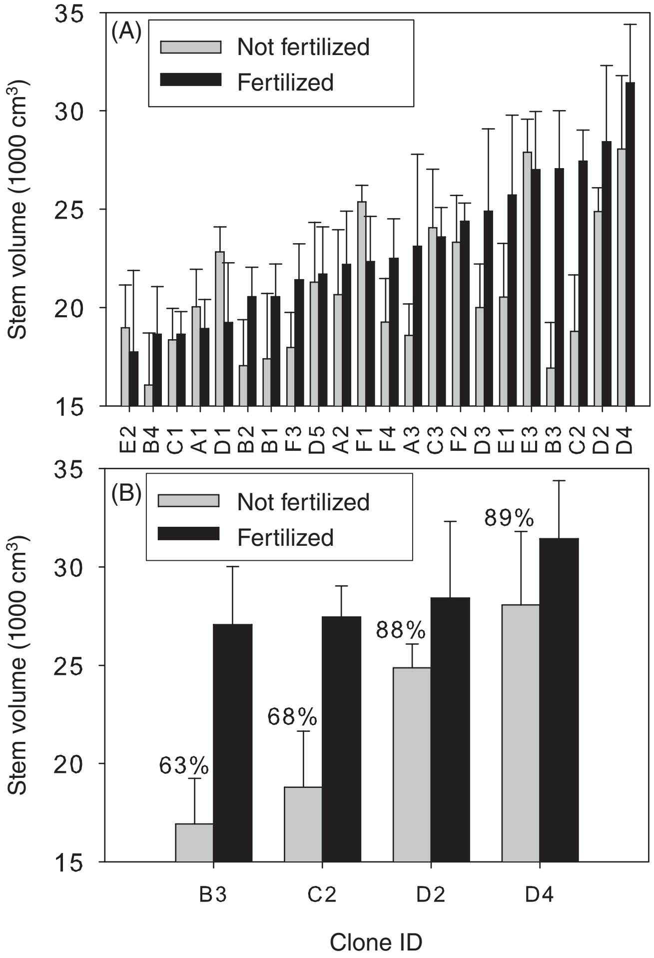

Figure 1—Volume response for the first five growing seasons of clonal loblolly pine to fertilization in the Virginia Piedmont. Panel A shows all 22 clones from the full trial, while panel B shows only the 4 best growers under fertilization. Clones identified with the same letter are full sibling to one another. Percentage values in panel B are for the volume of the unfertilized treatment relative to the fertilized treatment for each clone.

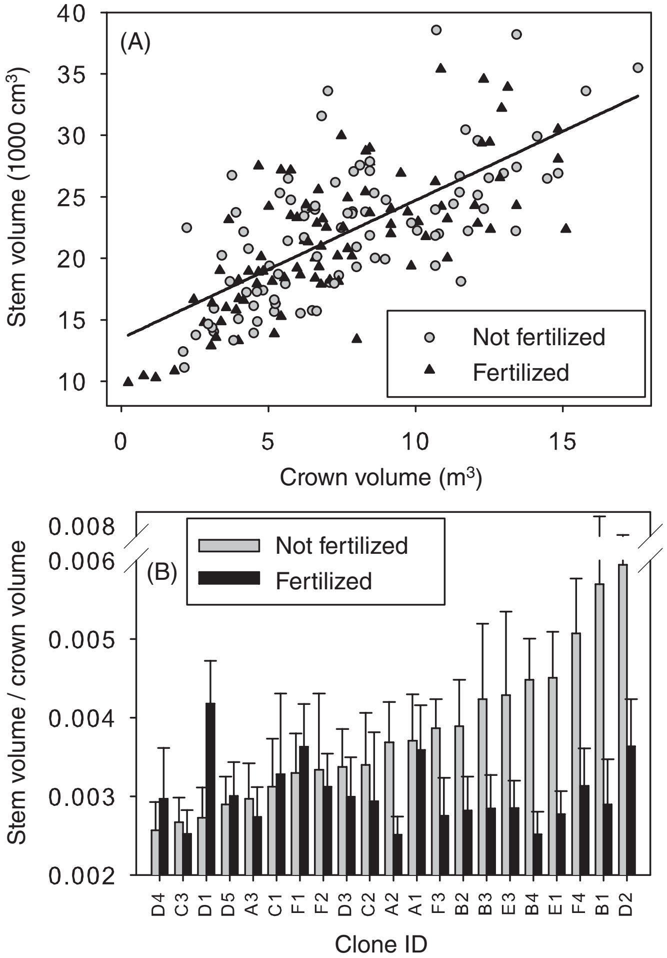

Figure 2—Growth efficiency response for the first five growing seasons of clonal loblolly pine to fertilization in the Virginia Piedmont. The regression in panel A is statistically significant ($P < 0.001$, $R^2 = 0.487$), indicating that greater leaf area is consistent with greater stem growth. Panel B depicts units of stem volume per units of crown volume, which can be interpreted as a metric of growth efficiency. Greater growth efficiency corresponds to a larger bar.

and D4 show only a moderate reduction in stem-volume growth when unfertilized (88 to 89 percent of fertilized stem-volume growth). While there is no statistically significant clone by fertilizer interaction among even these four clones ($P = 0.330$), it is evident that there would be a practically significant interaction to landowners planting, but not fertilizing, these specific genotypes.

Growth Efficiency

For the purposes of this paper we are defining growth efficiency as units of stem volume produced per units of crown volume. This metric may also be considered as a crown ideotype, indicating how large a crown is necessary to produce a given unit of wood. Crown volume is being used as an approximate surrogate for leaf area. Figure 2A shows that trees with greater crown volume (and thus leaf area) tend to have larger stem volumes as well. Greater leaf area corresponds to greater photosynthetic capacity. More carbon can be fixed, which can then be allocated to the stem. The wide variance in stem volumes produced at any given crown volume, as seen in figure 2A, may be due to differences between clones in carbon allocation patterns, although this dataset is not currently sufficient to support this hypothesis. While neither clone nor clone by fertilizer effects were significant (table 1) fertilizer did significantly reduce growth efficiency, as is seen in figure 2B. This most likely corresponds to greater production of needles as a result of fertilization leading to increased self-shading. As with stem volume, while the clone by fertilizer interaction is not statistically significant, there is a great deal of variability in growth efficiency response to fertilization between the different clones. Again, while there is not a statistically significant interaction, a range of crown ideotypes exist and depend on the specific clone selected, and whether or not fertilizer is applied as part of the silvicultural regime.

Stem Form

Sinuosity—Severe (class 3 or 4) sinuosity was present in 19.7 percent of trees after five growing seasons. Both fertilizer and clone significantly affected stem sinuosity (table 1). As expected, fertilization increases growth rates, which generally leads to an increased incidence and severity of stem sinuosity. However, while the clone by fertilizer interaction was not statistically significant, figure 3A shows clear variability in sinuosity severity in response to fertilization between clones. Some clones are never sinuous whether fertilized or unfertilized, others are highly sinuous regardless of fertilization, and yet others are sinuous only when fertilized. It should be noted that only class 4 sinuosity is likely to be evident in sawtimber-sized logs, and that lesser classes will not likely affect marketability at rotation age.

Forking—Forking affected 18.1 percent of trees by the fifth-growing season. Even relatively minor forks that may have only a minimal effect on wood quality at rotation age were included in this data. Neither the two main effects nor the interaction significantly affected the frequency of stem forking. However, as with sinuosity there do appear to be differences between clone-specific fertilizer responses with respect to forking (fig. 3B). Some clones do not appear to fork, while others fork frequently. Still others do not fork until fertilized and then show an increase in the frequency of forking.

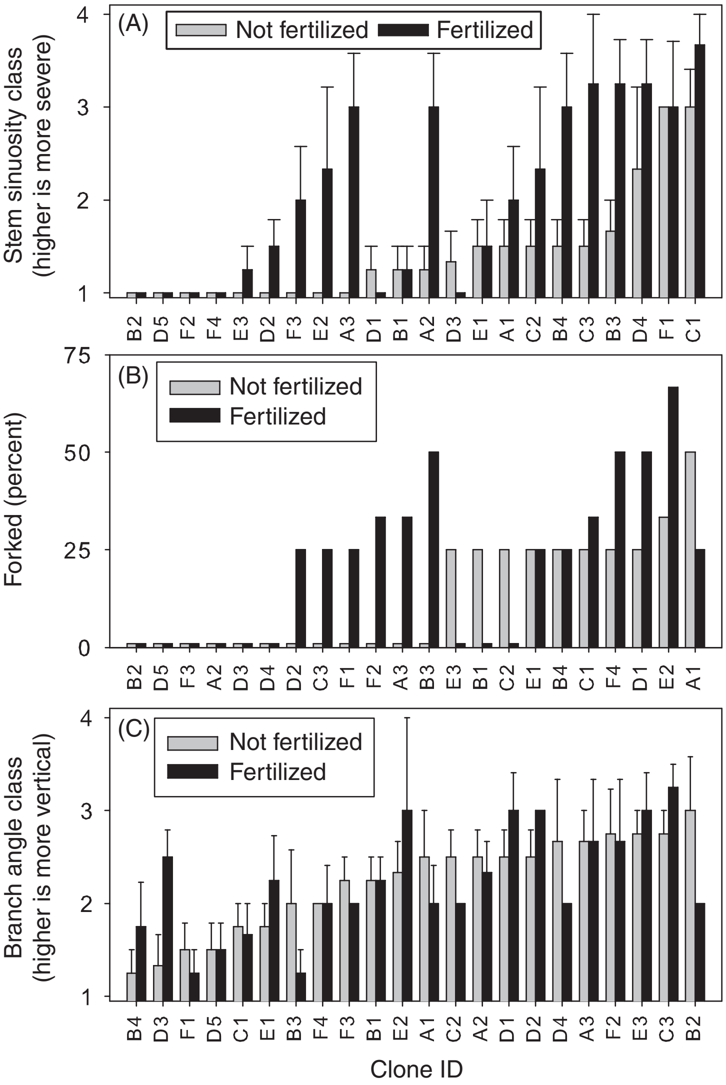

Figure 3—Stem quality response for the first five growing seasons of clonal loblolly pine to fertilization in the Virginia Piedmont. Clones identified with the same letter are full sibling to one another. Percentage values in panel B represent the proportion of ramets that forked for each clone by fertilizer treatment.

Practically speaking, a clone that is discarded from a fertilized screening program for forking may show a low incidence of forking on marginal, unfertilized sites, and may be an appropriate selection for these sites under this silvicultural regime.

Branch Angle—Steeper branch angles cause larger knots in the main stem, reducing wood quality. Branch angle was not significantly affected by fertilizer or clone effects, or their interaction. While there is some variability between clones that is apparent in figure 3C, the magnitude of these effects is less than those previously presented, and may not be of practical concern.

Nonsignificant *P*-Values and Clonal Screening

While the *P*-values for clone by fertilizer interactions depicted in table 1 were not statistically significant for any variables measured, there may still be a practical concern for clonal screening programs. Figure 4 shows that, even within this small field trial, statistically significant clone by fertilizer interactions for stem volume do exist for some randomly selected groups of clones. Figure 4 was generated by randomly selecting different subsets of clones from the full trial and calculating the *P*-value for the clone by fertilizer interaction. It reveals that about 33 percent of the groups randomly selected showed significant clone by fertilizer interactions ($P < 0.100$). Because clonal screening programs choose a very small number of clones to put into production from extremely large clonal trials, an overall lack of significant clone by fertilizer interaction does not necessarily indicate that there will be no significant interaction among the small group selected.

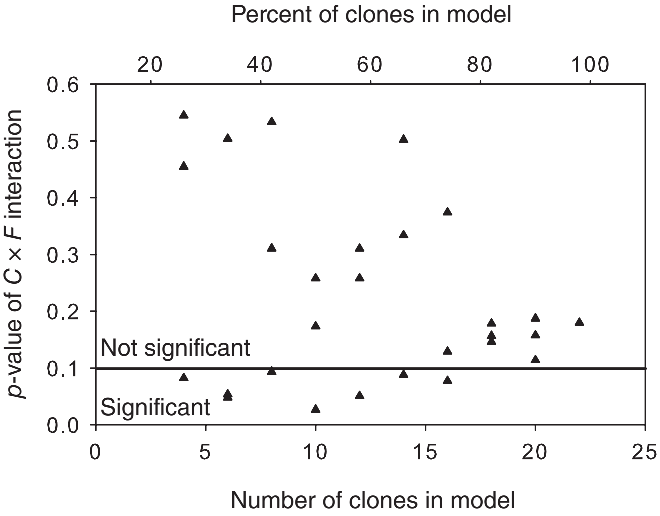

Figure 4—*P*-values of the clone by fertilizer interaction for stem volume for different groups of clones from the full trial. The *P*-value of all 22 clones is the furthest point to the right, while all points to the left were randomly selected groups of clones from the full trial. Approximately 33 percent of randomly selected groups of clones showed a statistically significant ($P < 0.100$) interaction, as denoted by the horizontal line.

CONCLUSION

Clonal forestry offers the opportunity to select specific individuals that possess a number of different favorable characteristics and plant them across large acreages. However, the results presented in this paper indicate that many important traits may vary between clones, particularly with respect to fertilizer response. Clones screened under a uniform silvicultural system may show different stem volume, growth efficiency, and stem form responses when grown under a different silvicultural system. While clone by fertilizer interactions were not statistically significant for any of these traits based on this trial, graphical evidence and the arguments presented above support that they may nonetheless be of practical concern to both companies producing and testing clones, and landowners who are buying and planting clones.

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