WILL CROWN IDEOTYPE HELP DETERMINE OPTIMUM VARIETAL SILVICULTURE?

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Abstract—Recent advances in somatic embryogenesis permit large numbers of clonal loblolly pine (*Pinus taeda* L.) to be produced and deployed. Clones may have greater growth (mean annual increment exceeding 30 cubic meters per hectare per year), greater stand uniformity and may be more susceptible to genotype by environment interactions when they are deployed in intensively managed plantations. Consequently, large numbers of clones will need testing under a range of silvicultural treatments to effectively and efficiently identify those that are best for deployment. Crown ideotypes are described by their crown dimensions, where the crop ideotype has tall (long live crown length) and narrow (short branch length) crowns and the competition ideotype has short (short live crown) and wide (long branch length) crowns. We tested the hypothesis that the response to silvicultural input was not related to crown dimension in a study in the Virginia Piedmont where six genetic entries (four clones, one mass control pollinated family and one open pollinated family) were planted at three initial stocking levels (617, 1235, and 1852 stems per hectare) and two levels of silvicultural input (low, i.e., similar to typical operations, and high, where nutrient limitations were eliminated). After three years of growth, significant silviculture and genetic entry effects were observed for diameter, height, live crown length, crown width, crown volume and stem volume increment, where silviculture increased these variables for all genetic entries although the increase due to silviculture was not consistent across genetic entry (genetic entry by silviculture interaction). The stem volume growth response to silvicultural treatment decreased with increasing crown volume. Crown ideotype may be useful in determining the response of clonal material to silvicultural input. However, it is important to know the conditions under which the ideotype is determined to be able to successfully use this method to predict the response to silvicultural input.

INTRODUCTION

Clonal forestry holds great promise to increase forest plantation productivity in the near term (Wright and Dougherty 2007). Clonal forestry relies on vegetative propagation to mass-produce identical copies of selected individual trees that possess improved genetic potential (Gleed and others 1995). Although the technology to mass-produce loblolly pine (*Pinus taeda* L.) clones is still developing, recent advances in somatic embryogenesis now permit large numbers of clonal loblolly pine to be produced and deployed. Based on results from clonal plantations in other parts of the world, it may be possible to increase loblolly pine productivity up to 50 percent (mean annual increment exceeding 30 cubic meters per hectare per year) by deploying appropriate clones to specific soil types, and then implementing integrated, intensive silvicultural regimes. Clonal plantations typically have greater stand uniformity but only when resource limitations are eliminated. In addition, genotype by environment interactions may be more common when clones are deployed in intensively managed plantations (Sierra-Lucero and others 2003). Consequently, the deployment of elite genotypes as clonal material requires a better understanding of how these genotypes respond to silvicultural manipulations (Li and others 1991). At the same time, a clonal forestry program should include an ongoing process of testing large numbers of candidate clones to determine if they are suitable for forest plantation deployment (Gleed and others 1995). These conditions create a situation where large numbers of clones need to be tested under a range of silvicultural treatments to be effectively and efficiently evaluated to identify those that are best for deployment.

One possibility for screening clones and how they respond to silvicultural treatment is to utilize the ideotype concept (Dickmann 1985). An ideotype has a consistent set of properties or characteristics that tend to respond to management practices in a uniform and consistent manner. In forestry, the ideotype is usually defined by crown characteristics such as

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branch size, branch angle, number of branches and tendency to self-prune (Martin and others 2001). Trees with a crop ideotype tend to have narrow crowns and small branches and grow well without excessively competing for site resources with other similar trees. In contrast, the competition ideotype has a large crown and aggressively expands its crown to exploit site resources to the detriment of its neighbors. The appropriate ideotype to plant in a specific stand depends on management objectives. For example, a stand with narrow crown trees may be desired in highly stocked plantations where biomass production is the management objective. In contrast, a stand with wide, large crown trees may be desired in a plantation managed at low stocking for sawtimber production. If crown ideotype can be used to classify clone response to silvicultural input, it may be possible to predict the growth responses of newly developed clones to silviculture treatments with minimal additional empirical testing.

With this background, our interest was to examine how the concept of crown ideotype could be used to predict response to silvicultural treatment. Crown ideotypes are described by their crown dimension, where the crop ideotype has tall (long live crown length) and narrow (short branch length) crowns and the competition ideotype has short (short live crown) and wide (long branch length) crowns. Consequently, we tested the hypothesis that response to silvicultural input was not related to crown dimension.

METHODS

We installed a block plot study using a split-split plot design with four replications (Gomez and Gomez 1984) at a site located at the Reynolds Homestead Research Center in the Virginia Piedmont in 2009 (Vickers and others 2012). The main plot treatment was silvicultural level (low and high). The split plot treatment was genetic entry (1 open pollinated family, 1 control mass pollinated family and 4 clones). The split-split plot treatment was initial stocking (617, 1235 and 1852 trees per hectare). This design resulted in 36 plots in each of the four blocks, yielding a total of 144 plots.

The entire site (all treatments) was chemically prepared using an aerial application of 0.29 liters per hectare of Accord XRT II, 0.29 liters per hectare of Milestone VM Plus, 1.46 liters per hectare of Chopper and 1.46 liters per hectare of DLZ oil in the summer of 2008, followed by broadcast burning in November 2008. The silvicultural treatments were designed to follow typical operational treatments (low) and a treatment where no nutrient limitations would be experienced by the trees (high). Low silviculture plots received banded herbaceous weed control during the first growing season. High silviculture plots received broadcast herbaceous weed control during the first two years. Directed sprays of herbicide were used to eliminate all hardwood competition in these plots. High silviculture plots also received tip moth control (soil-injected fipronil applied at 1.5 ml per tree) at planting and were fertilized with 112 and 12 kg per hectare of elemental nitrogen and phosphorus, respectively, at the beginning of the second year after planting. All fertilizer applications were banded on the row.

The genetic entries were one open-pollinated family, one control mass pollinated family and four clones. The clones represent a range in crown ideotypes; two with moderately wide crowns and two with broad crowns.

Initial stocking was designed for three product types, i.e., sawtimber (617 trees per hectare), pulp and sawtimber (1235 trees per hectare), and biomass or pulpwood (1852 trees per hectare). The between-row spacing for all stocking levels was 3.65 meters for all three planting densities. The distance between the trees within the row was 4.42, 2.21, and 1.48 meters, for the 617, 1235 and 1852 trees per hectare treatments, respectively. Individual plots in three blocks had 81 trees in a 9 row by 9 planting spot configuration and one block had 63 trees per plot in a 7 row by 9 planting spot configuration. The internal 25 trees (5 rows x 5 spots) were used as measurement trees for this analysis.

Trees were planted in February 2009 as containerized seedlings for the clonal material and as bare root plants for the open pollinated and mass control pollinated families.

Height, diameter at breast height (1.3 m), height to live crown (height of the lowest branch with live foliage) and crown width (average of the on row and the across row distance from drip line to drip line) were measured annually in the dormant season (December- January). Individual tree volume was calculated using an equation derived from an over-bark volume equation for unthinned trees (Tasissa and others 1997) as:

$$V = (0.21949+(0.00238 * ((D*0.3937008) * (D*0.3937008) * (H*3.28084))))*0.02831685 \quad [1]$$

where V is individual tree volume in cubic meters per tree, D is diameter at breast height in centimeters and H is height in meters. The volume increment in year three was the volume at the end of year three minus the volume at the end of year two. The response to silviculture was calculated as the difference between the three-year volume increment in the high and low silvicultural plots for corresponding combinations of block, genetic entry and stocking. Live crown length was calculated as height minus height to live crown. Crown volume was calculated as the volume of a cone:

$$CRV = 3.14 * (CW/2) * (CW/2) * LCL \qquad [2]$$

where CRV is crown volume in cubic meters per tree, CW is crown width in meters, and LCL is live crown length in meters.

PROC MIXED (SAS-Institute 2002) was used to examine treatment effects after three years for diameter, height, live crown length, crown width, crown volume and stem volume increment. Block was considered a random effect. PROC MIXED was also used to examine the relationship between crown dimensions (live crown length, crown width and crown volume) of the low silvicultural treatments and the volume response to silvicultural treatment. Tukey-Kramer means tests were used to determine treatment differences for volume response to silviculture after three years. All statistical tests were evaluated with alpha equal to 0.05.

RESULTS

Significant clone and silviculture differences were observed for diameter, height, live crown length, crown width, crown volume and volume increment (table 1). Stocking did not have a significant effect on any of the measured variables. Averaged across all genetic entries, high silviculture increased diameter (1 cm, 31 percent), height (0.3 m, 11 percent), live crown length (0.4 m, 14 percent), crown width (0.5 m, 43 percent), crown volume (1.6 cubic meters per tree, 146 percent) and stem volume increment (1145 cubic centimeters per tree per year, 95 percent) compared with low silviculture (table 2). Significant clone by silviculture interactions were observed for diameter, height, live crown length, and crown volume. All genetic entries responded positively to silviculture, whereas Clone 4 had a significantly greater stem volume response to silviculture compared with the other genetic entries (table 2). There were no differences in stem volume response to silviculture among the other genetic entries.

Stem volume incremental response to silviculture decreased with increasing crown volume across all genetic entries (fig. 1). Genetic entry did not affect the slope of the stem volume increment response to silviculture and crown volume relationship but it did affect the intercept. The intercept for Clone 4 was greater than the intercept observed for all other genetic entries.

DISCUSSION

Stem volume growth response to silviculture was related to crown volume. Crown volume is calculated from crown dimensions (live crown length and crown radius); consequently, we rejected our hypothesis that response to silviculture was not related to crown dimension. Interestingly, growth response to silviculture decreased with increasing crown volume. At this stage of stand development, crown volume is likely a surrogate for leaf area index and there is considerable evidence in the literature that leaf area and light interception drive growth (Cannell 1989; Landsberg and Sands 2011). If that is the case, this observation is in keeping with work in the literature where response to silvicultural treatment was reduced with increasing initial leaf area (Fox and others 2007). If trees in the low silviculture plots already had a large crown, it was likely that they had access to a relatively greater amount of resources that enabled them to produce a bigger crown and more leaf area. These trees would then have less response to additional resources from additional silvicultural inputs. It is important to note that large crowns do not always indicate more leaf area. Tyree and others (2009) unexpectedly found that a crop ideotype clone responded to silvicultural input (fertilization) by increasing the amount of foliage per unit crown, which led to a greater growth response to fertilizer than a competition ideotype clone.

In our analysis, crown ideotype was treated as a continuous variable. The continuous relationship we derived may be more useful than thinking of crown ideotype as a categorical variable because selected clones did not necessarily exhibit their expected ideotype. Data from the clone selection process indicated that Clone 1 and 2 were moderate crown ideotypes and Clones 3 and 4 were broad (competition) ideotypes. Our observations in the low silvicultural treatments suggest that Clone 1 and 3 are more moderate ideotypes and Clones 2 and 4 are broad ideotypes. However, the response to silviculture treatment for all genetic entries was to increase crown dimension in height (greater live crown length) and crown width. Consequently, if ideotype is used as a tool for determining the best silvicultural treatments for a specific clone, it will be important to know the conditions under which the ideotype is determined. However, if crown dimensions are used to determine 'ideotype,' the measured dimensions may act as a surrogate for resource availability up to the current stage of stand development. The potential response of the clone to additional silvicultural input would then be similar to the data in Figure 1 with less response expected for larger initial crowns.

For the genetic entries in this study, there was no crown volume by genetic entry interaction (no genetic entry effect on slope) in Figure 1. There were differences in the intercept that were related to genetic entry where Clone 4 grew better than all the other entries across the range in crown volume. In this analysis, there was no genotype by environment interaction in that all the clones responded positively to an improved

Table 1—Main and interaction effects significance levels (p values) for crown dimensional measurements at the end of the third growing season and stem volume increment for the third year for six genetic entries of loblolly pine planted in the piedmont of Virginia at three stocking levels (618, 1235, 1853 stems per hectare) and two silvicultural levels (low and high)

Effect	Diameter	Height	Live crown length	Crown width	Crown volume	Stem volume increment
Clone (C)	0.000	0.000	0.000	0.000	0.000	0.000
Stocking (D)	0.345	0.987	0.926	0.124	0.090	0.205
Silviculture (S)	0.000	0.000	0.000	0.000	0.000	0.000
C*D	0.983	0.981	0.953	0.999	0.999	0.975
C*S	0.036	0.022	0.047	0.345	0.030	0.248
D*S	0.111	0.137	0.175	0.118	0.086	0.236
C*D*S	0.982	0.915	0.934	0.990	0.997	0.996

Table 2—Genetic entry and silviculture treatment means for for crown dimensional measurements at the end of the third growing season and stem volume increment for the third year for six genetic entries of loblolly pine planted in the piedmont of Virginia at three stocking levels (618, 1235, 1853 stems per hectare) and two silvicultural levels (low and high). Means are across stocking level because stocking was not a significant effect

Genetic entry	Diameter	Height	Live crown length	Crown width	Crown volume	Stem Volume increment
	(cm)	*(m)*	*(m)*	*(m)*	*(m^3 tree^{-1})*	*(cm^3 tree^{-1} yr^{-1})*
Low Silviculture						
Clone 1	3.5	3.0	2.8	1.1	1.1	1560
Clone 2	3.7	3.1	2.7	1.2	1.2	1554
Clone 3	3.1	2.9	2.7	1.1	1.0	1118
Clone 4	3.4	3.0	2.7	1.4	1.5	1291
Mass control pollinated	2.8	2.7	2.5	1.1	0.9	939
Open pollinated	2.5	2.5	2.3	1.2	1.0	769
High Silviculture						
Clone 1	4.3	3.4	3.1	1.5	2.3	2521
Clone 2	4.4	3.2	3.0	1.7	2.6	2551
Clone 3	4.5	3.4	3.2	1.7	2.8	2423
Clone 4	4.8	3.6	3.3	2.0	3.9	2869
Mass control pollinated	3.7	3.0	2.8	1.6	2.2	2044
Open pollinated	3.1	2.7	2.5	1.6	2.3	1692

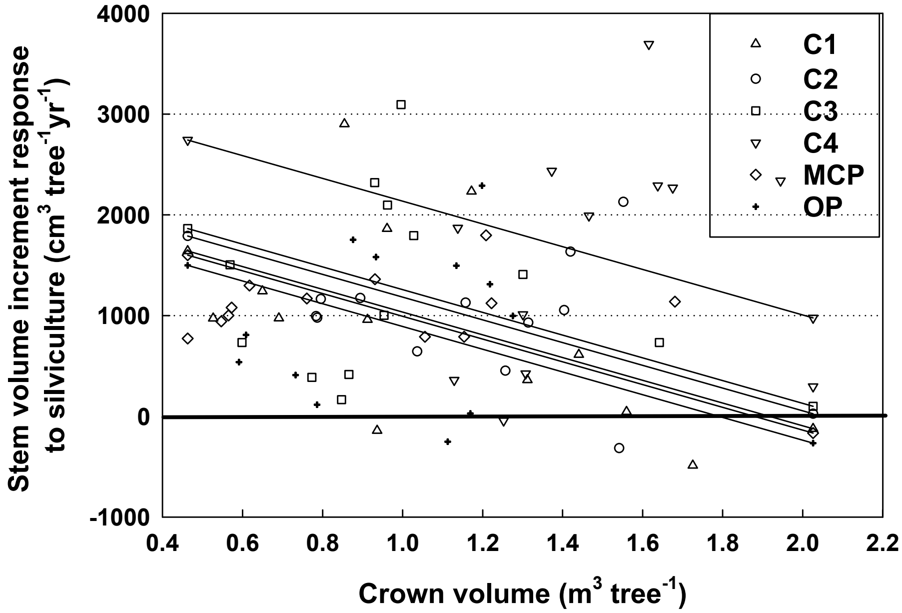

Figure 1—Stem volume incremental response to silviculture (high silviculture minus low silviculture treatments at the end of the third year of growth) versus crown volume of low silviculture trees at end of the third growing season for six genetic entries (Clones 1-4 (C1-C4), and mass control pollinated (MCP) and open pollinated (OP) families) planted in the Virginia Piedmont at three stocking levels. There was no crown volume by genetic entry interaction (no genetic effect on the slope of the relationship), but there was a significant genetic effect on the intercept, where Clone 4 had a greater intercept than all of the other genetic entries.

environment (high silviculture) although the degree of response differed by clone. However, when examining a larger population of genetic entries, this may not be the case because genotype by environment interactions have been observed with clonal material (Sierra-Lucero and others 2003).

At this point in stand development, there appeared to be relatively little above ground competition for resources (light) because even in the most densely stocked treatments the branches of adjacent trees did not overlap. This largely explains the lack of a stocking effect for any of the data reported here. However, this is not likely to be the case in the future in the 1235 and 1852 trees per hectare treatments. Anecdotal observations already indicate that branches are overlapping in these treatments. Crown closure may have a large effect on further development. Previous work indicated that the total amount of foliage (leaf area) reached an asymptote for a given level of silvicultural input when the canopy closed (Albaugh and others 2006). Crowns no longer expand outward and can only expand up. Consequently, any use of ideotype for understanding silvicultural treatment responses need to be completed before branches of adjacent trees touch.

Crown ideotype may be useful in determining the response of clonal material to silvicultural input. However, there may be some limitations noted here that may influence the utility of this method. These include: tree leaf area may not be related to crown size in all clones; information about the conditions under which ideotype is determined is required; few clones were tested here and other clones may exhibit genotype by environment interactions that were not observed here; and determination as to how the clones will respond to silvicultural input should be completed prior to crown closure. Two studies with similar designs have been installed in North Carolina and Brazil with the same genetic material and study design, which will permit additional testing to determine the robustness of the relationships developed here under a wider range in environmental conditions.

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