CONTRIBUTION OF SILVICULTURE TO LOBLOLLY PINE GROWTH AND YIELD IN THE SOUTHEASTERN UNITED STATES: A META-ANALYSIS

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Abstract—There has been an increase in loblolly pine production driven by forest management practices like intensive silviculture and improved genetics. Some reported yield gains have been modeled using meta-regression mixed effects models accounting for the potential contribution of the four factors related to forest growth: age, site quality (environment), establishment culture and management, and stand intrinsic characteristics (genetics and initial planting density). The aim of this research was to describe a methodology that allows for the derivation of response equations from yield models for diameter at breast height, stand average height, basal area, and total volume in the Southeastern United States. When compared to low-level silviculture, moderate and intensive silviculture show volume gains at age 20 of 221 and 314 m^3/ha, respectively. Likewise, moderate and intensive management consistently performed better over time as compared to low management for all response variables. These management response curves and their associated mathematical expressions can be used to perform financial marginal analyses to improve forest land decision making.

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) is the most commercially important forest species in Southeastern United States. The timber production in this region has been enhanced using genetically improved seedlings and a wide range of silvicultural treatments such as mechanical site preparation, vegetation control, fertilization, and irrigation (Allen and others 2005). These intensive forest management practices together with other key factors like initial planting density, stand age, and environmental conditions result in the expression of forest yield (Clutter and others 1983). Hence, volume gains resulting from intensive management practices can be analyzed by isolating the effect of age, environment, and density using growth and yield models. However, most of the existing models account only for one of the forest growth factors, either management, genetics, or environment. Thus, most of the research on the effect of intensive silviculture on loblolly pine growth and yield is locally restricted and/or density- and genetic composition-dependent. Therefore, those conclusions cannot be easily generalized.

An ideal response generalization would require a large experimental base, covering a wide range of ages, environmental conditions, management practices, and genotypes. The amount of resources involved in such an experimental base may make this kind of research technically challenging and economically unfeasible. In other research areas (like medicine), scientists have overcome the problem of not having a large experimental base with conclusions drawn out of a large collection of independent studies using meta-analysis. Meta-analysis is a statistical technique utilized to compile information for the purpose of integrating the findings as a rigorous alternative to the traditional narrative discussion (Schwarzer and others 2015).

There is a meta-analysis on forest yield of loblolly pine in the Southeastern United States that accounts for all growth factors (Restrepo and Bullock, in preparation),[1] i.e., effect of age, environment (through physiographic region), genetics, density, and management as explanatory variables for diameter at breast height (DBH), average height (Ht), basal area (BA), and total volume (V). Therefore, those yield models (see footnote 1) can be used to derive silvicultural responses isolating the effect of the remaining factors, which is the purpose of this paper.

[1] Restrepo, H.I.; Bullock, B.P. Manuscript in preparation. Growth and yield of loblolly pine in the Southeastern U.S.: a meta-analysis. On file with: Héctor I. Restrepo, Ph.D. Student, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602.

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METHODS

Four-Factor Forest Yield Models

The mean, standard deviation, and number of observations of the response for DBH, Ht, BA, and V were extracted from 22 studies selected out of 500 studies in the Southeastern United States (see footnote 1) in a meta-analysis framework. Included studies constitute a representative sample size of loblolly pine yield (table 1) over a wide range of environmental conditions from 44 counties located in 10 States across the Southeastern United States (fig. 1). The model is termed a four-factor model because it considers covariates from the four factors of forest growth:

- *Age*: age of the stand in years
- *Genetics*: genetically improved categories of loblolly pine [unimproved or unknown (UU), half-sibling (HS), full-sibling (FS), and clone (C)]
- *Mgmt*: management intensity [low (L), moderate (M), and high (H) in quantity and frequency of inputs and applications]
- *Region:* physiographic regions [Upper Coastal Plain and Piedmont together (UCPP), Upper Coastal Plain (UCP), Piedmont (P), and Lower Coastal Plain (LCP)]
- *Density*: surviving density in stems/ha

Forest yield models correspond to the log-transformed Schumacher model (Schumacher 1939) estimated using linear mixed effects models (see footnote 1) (app. A):

$$y_i = \theta + u_i + \in_i$$
$$\in_i \sim N(0,\sigma_i^2); u_i \sim N(0,\tau^2); Cov(\in_i, u_i) = 0 \quad (1)$$

where

θ = the fixed effects term

u_i = the random effects term assumed normally distributed with zero mean and variance τ^2

$\in_i$ = the error term assumed normally distributed with zero mean and variance σ_i^2 and independent to random effects

An estimator for θ is:

$$\hat{\theta}_{jkl} = \hat{a}_0 + \hat{a}_{1j}(Genetics) + \hat{a}_{2k}(Mgmt) + \hat{a}_{3l}(Region) + \hat{a}_4(Density)$$
$$+\frac{1}{Age}\left[\hat{\beta}_0 + \hat{\beta}_{1j}(Genetics) + \hat{\beta}_{2k}(Mgmt) + \hat{\beta}_{3l}(Region) + \hat{\beta}_4(Density)\right] \quad (2)$$

where

$\hat{\theta}_{jkl}$ = an estimator of the fixed effects of DBH, Ht, BA, or V in logarithmic units of the genetics *j* (HS=1, FS=2, C=3) with management regime *k* (M=1, H=2) in the physiographic region *l* (UCP=1, P=2, LCP=3)

α (asymptote) = parameter estimate

β (slope) = parameter estimate

Yield model for V did not consider the effect of *Genetics*(FS) and *Genetics*(C) due to the lack of observations of those levels of genetics.

Table 1—Number of observations (combination of treatments), number of measurement plots, and total area of measurements of the selected studies in the meta-analysis of loblolly pine growth and yield in the Southeastern United States (Restrepo and Bullock, in preparation; see footnote 1)

Response variable	No. treatments	No. plots	Area (ha)
DBH	105	1288	79
Ht	97	1344	81
BA	176	1476	70
V	128	1492	259

Source: Restrepo, H.I.; Bullock, B.P. Manuscript in preparation. Growth and yield of loblolly pine in the Southeastern U.S.: a meta-analysis. On file with: Héctor I. Restrepo, Ph.D. Student, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602.

DBH = diameter at breast height; Ht = total height; BA = basal area; V = volume.

Silvicultural Responses

Responses for DBH, Ht, BA, and V associated with moderate and high levels of management were derived from the yield model with respect to the low level of management:

$$\frac{\partial \hat{\theta}_{jkl}}{\partial Mgmt(M)} = \left(\hat{a}_{21} + \frac{\hat{\beta}_{21}}{Age} \right) \hat{\theta}$$
$$\frac{\partial \hat{\theta}_{jkl}}{\partial Mgmt(H)} = \left(\hat{a}_{22} + \frac{\hat{\beta}_{22}}{Age} \right) \hat{\theta} \qquad (3)$$

These partial derivatives with respect to the low level of management were fixed to HS and UCPP levels of genetics and physiographic region, respectively, and the surviving density based on an arbitrary planting density of 1,500 trees/ha was estimated using the following equation (PMRC 2002):

$$\widehat{Density} = 2.5 + (2.5 - 1500)(1 + 0.68\,Age)^{1.46}(1 + Age)^{-135} \exp\left[-5.9x10^{-4}\,Age^{2}\right] \qquad (4)$$

RESULTS AND DISCUSSION

Responses for DBH, BA, Ht, and V were consistently ranked over time from *Mgmt*(M) to *Mgmt*(H) (fig. 2). Thus, at age 20 *Mgmt*(M) added 3.6 cm, 3.3 m, 16 m^2/ha, and 221 m^3/ha of DBH, Ht, BA, and V, respectively, with respect to *Mgmt*(L); whereas, at the same age, *Mgmt*(H) added 8.3 cm, 4.5 m, 27 m^2/ha, and 314 m^3/ha to the corresponding variables with respect to *Mgmt*(L). Basal area response curves are flat up to age 5 when response curves started exhibiting a linear-looking trend up to age 20. Partial derivatives of the yield models with respect to *Mgmt*(M) and *Mgmt*(H) are presented in appendix B.

Overall, these responses are consistent with the expected management outcomes. In general, the higher the inputs and the frequency of the applications, the higher the resulting stand growth and yield (Albaugh and others 2004, Aspinwall and others 2011, Borders and others 2004, Roth and others 2007). Moreover, *Mgmt*(M) and *Mgmt*(H) are additive terms to a basic yield curve [*Mgmt*(L)], in a similar way that Pienaar and Rheney (1995) modeled silvicultural treatments.

High levels of inputs in quantity and frequency may adjust to asymptotic response curves, whereas low levels of management exhibit parabolic-looking curves (Snowdon 2002). Thus, there is a possibility that high-order terms of *Mgmt* or interactions such as *Mgmt* x *Genetics* and/or *Mgmt* x *Region* were missing in the yield models. The use of first-order terms in the model, as a way to simplify the number of inputs, may cause the management response curves for moderate management to not exhibit a parabolic form and rather attain a peak and then decrease. Despite this mathematical limitation, these management responses give insight into the size of the effect of the three simple levels of management considered here. Hence, economic tradeoffs of operational and intensive forest management can be analyzed. Likewise, since yield models account for the effect of genetics, environment, and density, the model and their derived responses can be also utilized to analyze the effect of a combination of factors.

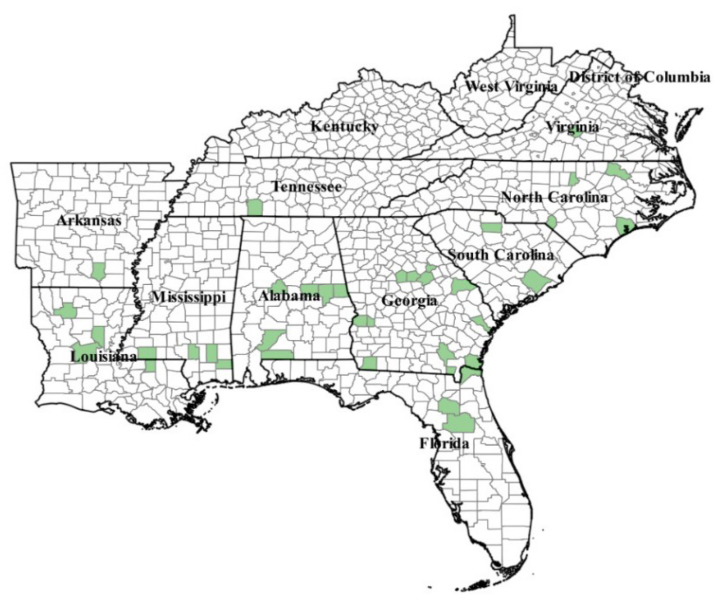

Figure 1—Southeastern U.S. counties in which studies have been conducted that were considered in this research.

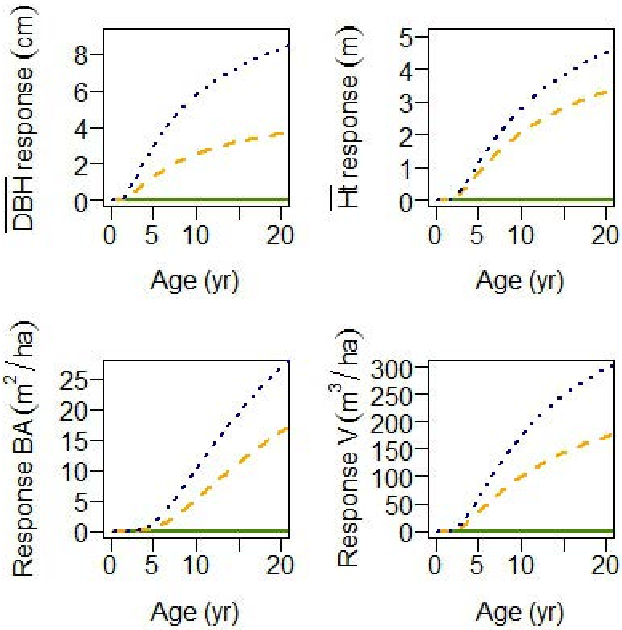

Figure 2—Loblolly pine silvicultural responses relative to low level of management [*Mgmt*(L)] in the Southeastern United States for diameter at breast height (DBH), total height (Ht), basal area (BA), and volume (V) keeping the genetics fixed as half-siblings planted and the physiographic region as Upper Coastal Plain – Piedmont. Dashed line represents the response of moderate management [*Mgmt*(M)], and dotted line represents the response of high management [*Mgmt*(H)].

CONCLUSIONS

Forest growth factors have successfully explained loblolly pine yield (see footnote 1). In those models, moderate and high levels of management were statistically different (superior) to the low level of management. Using this information, partial derivatives were taken to analyze silvicultural response equations. Volume at age 20 for moderate and high levels of management can be as much as 221 and 314 m^3/ha higher, respectively, as compared to the low level of management. Hence, yield models that consider the four factors of growth can be used to derive silvicultural responses isolating the effect of genetics, environment, and density. The same framework can be applied to determine a potential volume increase associated with genetically improved seedlings and differences in yield associated to the environment (physiographic region). This model could be used to perform a financial marginal analysis, characterizing the cost associated with the levels of management regimes and determining the profitability associated with each level.

LITERATURE CITED

Albaugh, T.J.; Allen, H.L.; Dougherty, P.M.; Johnsen, K.H. 2004. Long term growth responses of loblolly pine to optimal nutrient and water resource availability. Forest Ecology and Management. 192(1): 3–19.

Allen, H.L.; Fox, T.R.; Campbell, R.G. 2005. What is ahead for intensive pine plantation silviculture in the South? Southern Journal of Applied Forestry. 29(2): 62–69.

Aspinwall, M.J.; King, J.S.; McKeand, S.E.; Bullock, B.P. 2011. Genetic effects on stand-level uniformity and above- and belowground dry mass production in juvenile loblolly pine. Forest Ecology and Management. 262(4): 609–619.

Borders, B.E.; Will, R.E.; Markewitz, D. [and others]. 2004. Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the lower coastal plain of Georgia. Forest Ecology and Management. 192(1): 21–37.

Clutter, J.L.; Fortson, J.C.; Pienaar, L.V. [and others]. 1983. Timber management: a quantitative approach. New York: John Wiley & Sons, Inc. 321 pp.

Pienaar, L.V.; Rheney, J.W. 1995. Modeling stand level growth and yield response to silvicultural treatments. Forest Science. 41(3): 629–638.

PMRC. 2002. A generalized methodology for developing flexible whole stand survival models. Athens, GA: University of Georgia, Warnell School of Forestry and Natural Resources.

Roth, B.E.; Jokela, E.J.; Martin, T.A. [and others]. 2007. Genotype x environment interactions in selected loblolly and slash pine plantations in the Southeastern United States. Forest Ecology and Management. 238(1–3): 175–188.

Schumacher, F.X. 1939. A new growth curve and its application to timber yield studies. Journal of Forestry. 37: 819–820.

Schwarzer, G.: Carpenter, J.R.; Rücker, G. 2015. Meta-analysis with R. Toronto: Springer. 221 p.

Snowdon, P. 2002. Modeling type 1 and type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments. Forest Ecology and Management. 163: 229–244.

APPENDIX A

Summary of loblolly pine yield models for the Southeastern United States using meta-regression (Restrepo and Bullock, in preparation; see footnote 1)

Source	Estimates (log) and significance level[a]							
	DBH		Ht		BA		V	
Intercept	3.67	***	3.46	***	3.48	***	5.67	***
Genetics(HS)					0.29	***		
Genetics(FS)	0.22	***	0.19	***	0.42	***		
Genetics(C)	0.21	**	0.28	*				
Mgmt(M)	0.15	***	0.16	**	0.39	***	0.67	***
Mgmt(H)	0.29	***	0.21	***	0.49	***	0.82	***
Region(UCP)					0.72	***		
Region(LCP)	-0.20	***	-0.71	***				
Density	$-3x10^{-4}$	***	$-1.6x10^{-4}$	***	$-1.7x10^{-4}$	*		
1/*Age*	-7.36	***	-9.62	***	-11.53	***	-10.73	***
Genetics(HS):1/*Age*								
Mgmt(H):1/*Age*					1.31	***		
Region(UCP):1/*Age*					-11.52	***		
Region(LCP):1/*Age*	1.70	***	4.83	***				
Density:1/*Age*	$6.4x10^{-4}$	***	$4.8x10^{-4}$	*	$1.1x10^{-3}$	***		

[a] Significance codes: *** = *p*-value <0.0001; ** = *p*-value <0.001; * = *p*-value <0.01; . = *p*-value <0.05; blank = *p*-value <0.1.

Source: Restrepo, H.I.; Bullock, B.P. Manuscript in preparation. Growth and yield of loblolly pine in the Southeastern U.S.: a meta-analysis. On file with: Héctor I. Restrepo, Ph.D. Student, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602.

APPENDIX B

Partial derivatives of the models are:

$$\frac{\partial DBH}{\partial Mgmt(M)} = 0.15\exp\left[3.67 + 0.15 - 3x10^{-4}\,Density + \frac{1}{Age}(-7.36 + 6.4x10^{-4}\,Density)\right]$$

$$\frac{\partial DBH}{\partial Mgmt(H)} = 0.29\exp\left[3.67 + 0.29 - 3x10^{-4}\,Density + \frac{1}{Age}(-7.36 + 6.4x10^{-4}\,Density)\right]$$

$$\frac{\partial Ht}{\partial Mgmt(M)} = 0.16\exp\left[3.46 + 0.16 - 1.6x10^{-4}\,Density + \frac{1}{Age}(-9.62 + 4.8x10^{-4}\,Density)\right]$$

$$\frac{\partial Ht}{\partial Mgmt(H)} = 0.21\exp\left[3.46 + 0.21 - 1.6x10^{-4}\,Density + \frac{1}{Age}(-9.62 + 4.8x10^{-4}\,Density)\right]$$

$$\frac{\partial BA}{\partial Mgmt(M)} = 0.39\exp\left[3.48 + 0.29 + 0.39 + 0.72 - 1.7x10^{-4}\,Density + \frac{1}{Age}(-11.53 - 11.52 + 1.1x10^{-3}\,Density)\right]$$

$$\frac{\partial BA}{\partial Mgmt(H)} = \left(0.49 + \frac{1.31}{Age}\right)\exp\left[3.48 + 0.29 + 0.49 + 0.72 - 1.7x10^{-4}\,Density + \frac{1}{Age}(-11.53 + 1.31 - 11.52 + 1.1x10^{-3}\,Density)\right]$$

$$\frac{\partial V}{\partial Mgmt(M)} = 0.67\exp\left[5.67 + 0.67 + \frac{1}{Age}(-10.73)\right]$$

$$\frac{\partial V}{\partial Mgmt(H)} = 0.82\exp\left[5.67 + 0.82 + \frac{1}{Age}(-10.73)\right]$$