EMPIRICAL ALLOMETRIC MODELS TO ESTIMATE TOTAL NEEDLE BIOMASS FOR LOBLOLLY PINE

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Abstract-Empirical geometric models based on the cone surface formula were adapted and used to estimate total dry needle biomass (TNB) and live branch basal area (LBBA). The results suggest that the empirical geometric equations produced good fit and stable parameters while estimating TNB and LBBA. The data used include trees form a spacing study of 12 years old and a set of fully measured trees on the coastal plain of North and South Carolina of ages 10 to 25.

INTRODUCTION

One of the most important factors contributing to the development of a stand is the amount of leaf biomass. Although its contribution to total tree biomass is only 4 to 6 percent, leaf biomass is responsible for most of the transpiration-respiration processes and total carbon uptake in the tree (Zhang, 1997). Leaf biomass has proven to be very sensitive to climatic patterns and silvicultural treatments, thus quantification of leaf biomass may be important for explaining productivity of forest stands.

Accurate estimation of leaf biomass may not only improve estimation of the potential growth rate but can be used to characterize other stand conditions. For example leaf area is useful as an index of productivity and vigor that explains a potential source of variability in stand response to silvicultural treatments. O'Hara (1989) states that thinned stands have higher transpiration/respiration rates and require greater sapwood area to supply a given amount of leaf biomass. In this case, the reduction in the number of trees makes more water and nutrients available producing more conductive tissue that remains healthy for more time. This is also true for stands growing on good quality sites.

Leaf biomass and leaf area may become an important input to a new generation of growth and yield models that are more site specific than today's models. It is anticipated that since leaf biomass is sensitive to environmental and silvicultural factors, models that use it to project growth will also be more sensitive to these factors. The most wide spread approach for estimating leaf area and needle biomass is based on allometric relationships. The basic allometric relationship between leaf biomass and stem size (diameter or stem area) is based on the pipe model theory proposed by Shinozaki and others(l964). Based on this work, Waring and others(1981) suggested that the amount of foliage is proportional to the amount of conductive tissue present on the stem, which for conifers is the sapwood. In geometric terms leaf biomass should be related not only to the transversal area but the geometry of the crown.

Several of these studies show that, in general, these allometric relationships are not completely linear or are only linear for a given age class. Most of the equations developed to estimate biomass are linear in logarithmic units or intrinsically non-linear. Baldwin (1989) presented equations to compare the fit of leaf biomass from DBH and the sapwood area (cm^2) at breast height and live crown height, finding that DBH was the best independent variable to estimate needle and branch biomass for loblolly pine. Long and Smith (1988) and Long and Smith (1989) developed non-linear models for *Pinus contorta* and *Abies lasiocarpa* that include crown size observations, making the equations more tree specific and sensitive to stand density. McCrady and Jokela (1998) used the pipe model theory and assume that leaf biomass is proportional to total tree volume suggesting that the amount of leaf area/leaf biomass is strongly related with the geometry of the tree biomass.

The main objective of this study is to develop site/tree specific allometric needle biomass prediction equations such that the total tree dry needle biomass (TNB) prediction equations are sensitive to stand density and stand structure. The new models should improve leaf area estimation and provide a means of differentiating total stand biomass growth for stands that have similar size stem dimensions but different amounts of leaf biomass.

MATERIALS AND METHODS

The research was conducted in a loblolly pine spacing study established at the B.F Grant Memorial Forest near Eatonton, Georgia (Pienaar and others, 1997). The study was planted with genetically improved seedlings in March 1983 at a 6 by 6 ft spacing (1.81 by 1.81 m). In July 1983, 24 one fifth-acre treatment plots each with a one-tenth acre interior measurement plot (0.08 ha) were installed with planting densities of 100, 200, 400 600, 800 and 1000 trees per acre (247, 494, 988, 1483, 1977 and 2471 tress per hectare, respectively). The experimental plots were completely randomized with four replications of each density. The study is located on an old agricultural field

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Calculated Total Needle Biomass and Live Branch Basal Area for the B.F. Grant Spacing study

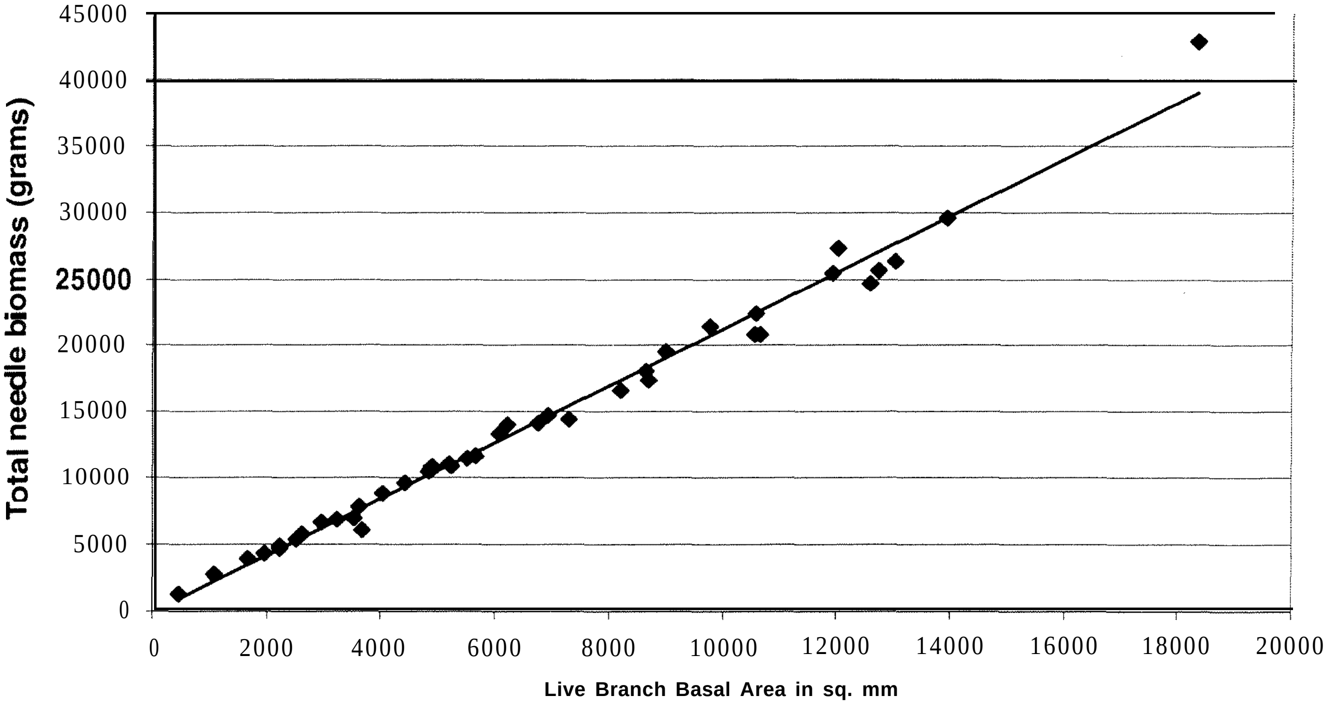

Figure 1— Total Dry Needle Biomass (TNB) vs Live Branch Basal Area (LBBA) for the B. F. Grant spacing study.

Observed Total Needle Biomass and Live Branch Basal Area for 28 tree form the Coastal plain of South and North Carolina (Brister database)

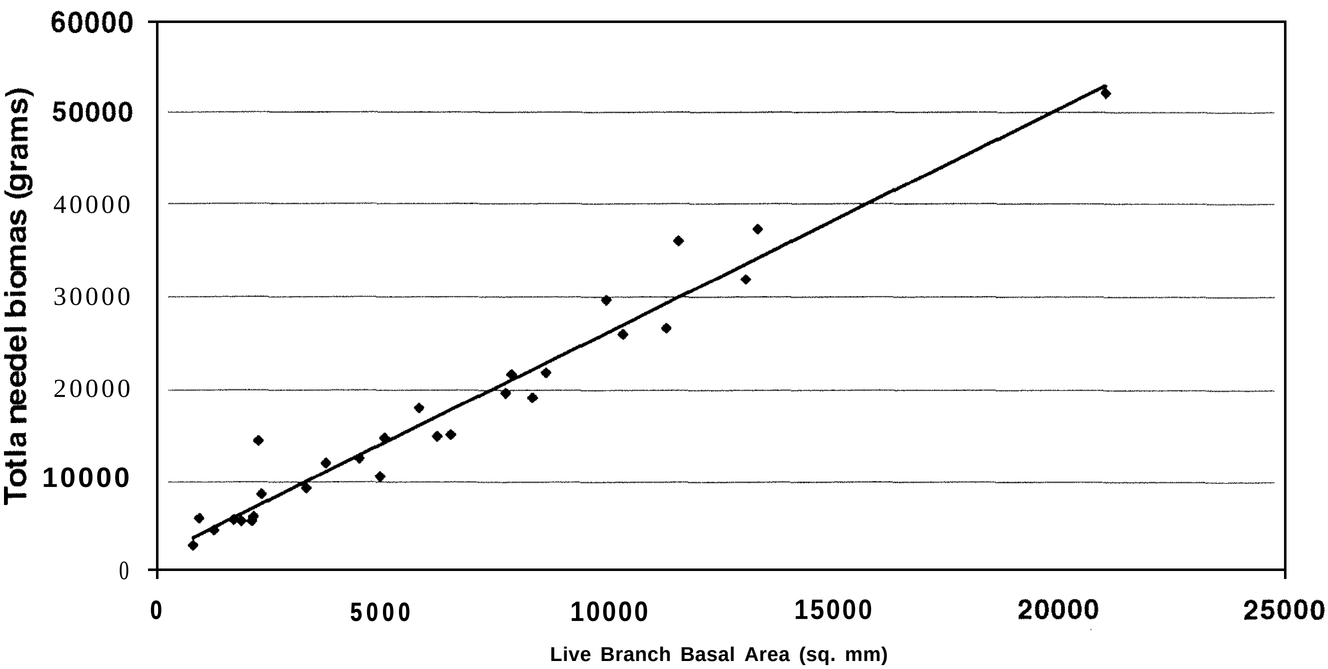

Figure 2— Total Dry Needle Biomass (TNB) vs Live Branch Basal Area (LBBA) for the Brister database on the Coastal plain of North and South Carolina.

which had been previously planted with soybeans. Herbicide was first applied in May 1984 and in 1985, wildlings of both loblolly pine and sweetgum *(Liquidambar styraciflua)* were mechanically removed in 1985. As a result all the plots have been growing essentially free of competing vegetation throughout the life of the study.

In July 1997 felled trees from the first thinning of the B. F. Grant spacing study were sampled to produce needle biomass estimators. Trees from all plots, except the 247 trees/ha plots, were cut to reach a residual target number of trees. The thinning was primarily from below, however good spatial distribution of residual stems was also a criterion for tree selection. Forty-three trees were selected and sampled using the methodology described by Xu (1997) to develop a two-level allometric estimation procedure: equations based on branch measurements were used to estimate dry needle branch biomass and in turn other equations were used to estimate total tree dry needle biomass. Sample trees came from four crown classes: dominant (12), co-dominant (21), intermediate (8) and suppressed (2). The selected trees were free of deformities and fusiform rust.

The variables measured for each tree include diameter at breast height (D) in cm, total height from the stump in m, stump height in m, and live crown height in m. The crown also was carefully measured and divided in five equal length sections along the stem. One branch was randomly taken in each section and the parts of the branch with foliage were collected, identified for tree and section number and bagged for further laboratory analysis. For each sample, branch length (m) and basal branch diameter (mm), at approximately 20 mm from the base of the branch, were obtained with a measuring tape and a digital caliper, respectively. The branch height (BH) and basal branch diameter (BBD) for every live branch was also recorded.

In the laboratory, the foliage of each sample branch was separated from the branch fragment, identified, and dried at 70" C until reaching a constant weight. The needle weight was then measured with a balance to the nearest gram. An additional database from a similar study on loblolly pine was provided by Professor Graham H. Brister and used to test the models by estimate LBBA and TNB per tree.

RELATIONSHIP BETWEEN TOTAL NEEDLE BIOMASS AND LIVE BRANCH BASAL AREA

In an attempt to increase the precision of estimation for total dry needle biomass for the entire tree the relationship between the total dry needle biomass (TNB) and the total live branch basal area in mm^2 (LBBA) was analyzed. Graphical analysis shows (figure 1) that this relationship is very strongly linear and stable for the trees in this study. This behavior is logical since branch needle biomass was estimated with a linear equation that uses the branch diameter squared (De los Santos, 1998). To verify this relationship a database generated by Brister in 1977 for 28 loblolly pine trees was used (figure 2). All trees in this database were located in the coastal plain of North and South Carolina and total needle biomass was obtained by removing and weighing all needles in each branch. Clearly the relationship between LBBA and the observed TNB is very similar to the relationship observed for the 43 trees in the B. F. Grant spacing study. A similar relationship was found by Whitehead *(1990)* in *Pinus radiata* for branch basal area and leaf area clustered on "branch complexes" but was never aggregated to estimate the total leaf area per tree. This relationship seems less appropriate for shade intolerant trees growing at wide spacing and/or old stands that have changed the excurrent growing pattern from the young-middle ages to a more sympodic pattern. In these old age trees the crown expands more longitudinally than vertically, the branches become more massive and ultimately accumulate heartwood.

Regression analysis (table 1) with both databases shows a strong and stable correlation between these two characteristics. The slope of the regression line can be interpreted as the amount of needle biomass sustained by each unit of conductive tissue surface area attached to the stem. The differences in the slope can be attributed in part to the process of allometric estimation versus measured biomass and by differences in site quality and management at each site. Trees in the B. F. Grant spacing study sustain more needle biomass than the sites in the coastal plain which is most likely due not only to differences in nutrient availability but to the amount and types of competing vegetation.

GEOMETRIC MODELS

Since LBBA and TNB are linearly and highly correlated it may be useful to focus on prediction of LBBA using geometric based models. Thus the hypothesis is that LBBA should be proportional to the stem surface area occupied by live crown. The main assumption is that the estimation based on tree characteristics will be more precise for LBBA than for the TNB.

The basic form for the cone surface was modified to be used as empirical models. Since the diameter at the base of the live crown was not obtained, diameter at breast height (D) and crown length (L) are used in these model forms. The constant p was replaced by a scale parameter in the formulations. These structures were motivated by the description that Steill (1964) cited by Seymour and Smith, (1987) used for crown volume for *Pinus resinosa.* He found a very good correlation between foliage weight and crown volume estimated with a paraboloid formula.

The models derived are:

Cone formulation 1

$$B = a\left(\frac{D}{2}\right) * \sqrt{\left(\frac{D}{4}\right)^{b} + L^{c}} \tag{1}$$

Cone formulation 2

$$B = a\left(\frac{D}{2}\right) * \left[\left(\frac{D}{4}\right)^{b} + L^{2}\right]^{d} \tag{2}$$

Where:

a, b, c and d are the parameters to be estimated,
B = LBBA or some other biomass crown component as needle biomass, all else is as defined above.

Table I-Analysis of Variance for Total dry needle biomass (TNB) vs Live Branch Basal Area (LBBA) vs. for B.F. Grant spacing study data and North and South Carolina coastal plain (Brister Data) $TNB_i = \alpha + \beta(LBBA_i) + e_i$

B.F. Grant Database

Source	df	SSE	MSE	F Value	Prob > F
		Analysis of Variance			
Regression	1	691369020.8	691369020.8	3049.81	.0000001
Residual	40	9067698.453	226692.4613		
Total	41	700436719.3			

R-square = 0.98705

	Coefficients	Standard Error	t stat	P-value
Intercept	120.8546	139.7541	0.8647	0.392324
Slope	0.4638	0.0084	55.2251	0.00001

Brister Database

Source	df	SSE	MSE	F Value	Prob > F
		Analysis of Variance			
Regression	1	544452712	544452712	497.139	.0000001
Residual	24	26284127.89	1095171.995		
Total	25	570736839.8			

R-square = 0.95394

	Coefficients	Standard Error	t stat	P-value
Intercept	-436.412	382.2230	-1.14177	0.264812
Slope	0.391966	0.01758	22.2966	.0000001

Table 2— Fit statistics and parameter estimates for cone formulation 1 on the B.F. Grant spacing study data

	DF Model	DF Error	SSE	MSE	Root MSE	R-square
TNB	3	40	8348	208.6878	14.44603	0.9278
LBBA	3	40	35465	886.6308	29.77635	0.9304

	Parameter	Estimate	Standard Error	Aprox T ratio	Aprox Prob > |T|
TNB	*a*	15.73783	4.52413	3.48	0.0012
	b	3.456465	0.32257	10.72	0.0001
	c	4.219977	0.3263	12.93	0.0001
LBBA	*a*	30.31826	8.39138	3.61	0.0008
	b	3.61632	0.29436	12.29	0.0001
	c	4.230212	0.33276	12.71	0.0001

Table 3— Fit statistics and parameter estimates for cone formulation 2 on the B.F. Grant spacing study data

	DF Model	DF Error	SSE	MSE	Root MSE	R-square
TNB	3	40	8441	211.0289	14.52683	0.927
LBBA	3	40	35908	897.6995	29.96163	0.9295

	Parameter	Estimate	Standard Error	Aprox T ratio	Aprox Prob > |T|
TNB	*a*	12.82514	4.35711	2.94	0.0054
	b	2.450571	0.09015	9.47	0.0001
	c	0.854042	0.24696	9.92	0.0001
LBBA	*a*	23.91818	7.70821	3.1	0.0035
	b	2.278922	0.08229	11	0.0001
	c	0.905521	0.23598	9.66	0.0001

Table 4— Fit statistics and parameter estimates for cone formulation 1 on the Brister Data for the coastal plain of North and South Carolina

	DF Model	DF Error	SSE	MSE	Root MSE	R-square
TNB	3	25	62661312	2506453	1583.2	0.8989
LBBA	3	25	2.61 E+08	10431197	3229.7	0.9307

	Parameter	Estimate	Standard Error	Aprox T ratio	Aprox Prob >ITI
TNB	*a*	60.92423	21.79016	2.8	0.0098
	b	2.4915	0.36447	6.84	0.0001
	c	2.238613	0.49897	4.49	0.0001
LBBA	*a*	253.6395	66.22154	3.83	0.0008
	b	1.989328	0.29422	6.76	0.0001
	c	1.942278	0.31365	6.19	0.0001

As density changes it seems logical that tree crown volume changes, adapting its form to the conditions of stand density and competition. Cone formulation 1 above implies that the cone is modified not only by the scale parameter but by changing the form of the arc defined by $(D/4)^b+L^c$. In cone formulation 2 parameter d generalizes the form of the relationship onto a more flexible structure.

The geometric formulations were used to estimate both LBBA and TNB with good results (table 2 and 3) on the spacing study trees. For both formulations the parameters are stable with an acceptable fit. As hypothesized the r-square for LBBA is higher than for the TNB. To correct for effect of heteroscedasticity the following weight function was used

$$(3)\quad W=\frac{1}{D^2L}$$

MODEL TEST FOR GEOMETRIC MODELS

To test the previous equations 28 trees measured by Brister were fitted with geometric equations to predict TNB and LBBA (table 3 and 4). It is also interesting to notice that estimation of LBBA is better than for TNB as foreseen for this kind of data (total foliage sampled per tree). Note however that the cone formulations show stability on the parameters for both TNB and LBBA fit. In this case no effect

Table 5— Fit statistics and parameter estimates for cone formulation 2 on the Brister Data for the coastal plain of North and South Carolina

	DF Model	DF Error	SSE	MSE	Root MSE	R-square
TNB	3	25	62471770	2498871	1580.8	0.8992
LBBA	3	25	2.61 E+08	10430419	3229.6	0.9307

	Parameter	Estimate	Standard Error	Aprox T ratio	Aprox Prob >ITI
TNB	*a*	55.99056	22.82834	2.45	0.0215
	b	1.708317	0.09752	6.48	0.0001
	c	0.632363	0.41849	4.08	0.0004
LBBA	*a*	255.5783	78.06633	3.27	0.0031
	b	1.957699	0.07653	6.48	0.0001
	c	0.495678	0.32397	6.04	0.0001

of heteroscedastisity is shown in the residual analysis, so the estimates of the model are the regular least squares.

Theoretically the models generated shall produce similar results on the same data range. However validation is needed to better qualify the model behavior at more operative levels using a wider more realistic range of variability.

CONCLUSIONS

The inherent hypothesis of the geometric models suggest that a better knowledge of the surface stem geometry at the crown level may produce better estimates of the TNB, crown biomass and LBBA at tree and stand level. The models generated show stability on their parameters and a predictive ability among the best for loblolly pine at the tree level. These structures should produce reliable and more site specific estimates of photosynthetic tissue.

REFERENCES

Baldwin Jr.; **V.** C. 1989. Is sapwood a better predictor of loblolly pine crown biomass than bole diameter? Biomass 20: 177-185.

Long **J. M.; F. W.** Smith. 1988. Leaf area-sapwood area relations of lodgepole pine as influenced by stand density and site index. Canadian Journal of Forestry Reseach. 18: 247-250.

Long J. M.; **F. W.** Smith. 1989. Estimating leaf area of Abies lasiocarpa across ranges of stand density and site quality. Canadian Journal of Forest Research. 19: 930-932.

McCrady, R. L.; E. J. Jokela. 1998. Canopy dynamics, light interception, and radiation use efficiency of selected loblolly pine families. Forest Science. 44(l): 64-72.

O'Hara, K. L. 1989. Stand growth efficiency in a Douglas fir Thinning trial. Forestry. 62(4): 409-418.

Pienaar, L. V.; B. D. Shiver; W. M. Harrison. 1997. Growth potential of loblolly pine plantations in the Georgia Piedmont: A spacing study example. PMRC Tech. Rep. 1997-l. Plantation Management Research Coop., University of Georgia. Athens, GA. 15 p.

Seymour, R.; D. M. Smith. 1987. A new stocking guide formulation applied to eastern White pine. Forest Science. 33:469-484.

Shinozaki, K.; K. Yoda; K Hozumi· T. Kira. 1964. A quantitative analysis of plant form • The pipe model theory. I. Basic Analyses. Japanese Journal of Ecology. 14: 133-139.

Waring, R.H.; K. Newman; J. Bell. 1981. Efficiency of tree crowns and stemwood production at different canopy leaf densities. Forestry. 54: 129-137.

Whitehead D.; Grace J.C.; Godfrey M.J.S. 1990. Architectural distribution of foliage on in individual *Pinus radiata* D. Don crowns and the effects of clumping on radiation interception. Tree Physiology. 7: 135-l 55

Xu, M. 1997. Growth efficiency of individual loblolly pine (Pinus taeda l.) as affected by crown morphology, stand characteristics and microenvironment. Athens, GA: University of Georgia. 132p Ph.D. dissertation.

Zhang, Y. 1997. A physiologically based simulation model for loblolly pine. Athens, GA: University of Georgia. 127p. Ph.D., dissertation.