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Performance of four yield models for predicting stand dynamics of a 30-year-old loblolly pine (*Pinus taeda* L.) spacing study

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ABSTRACT

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Observations in a 30-year-old loblolly pine (*Pinus taeda* L.) spacing study indicate that closer planting densities support greater basal areas and volumes per unit area early in the life of a plantation, but lose that advantage to wider spacings over time. In comparisons between observed stand behavior at four spacings and that predicted by four growth and yield models, only one of the models predicted the observed behavior. Workers who wish to project growth of loblolly pine plantations should be aware of this stand behavior and include this criterion in evaluating candidate models.

INTRODUCTION

Where the primary purpose of a loblolly pine plantation is to produce wood, the manager tries to optimize the yield of desired products. Depending upon the ownership objective, a loblolly pine plantation can be expected to produce pulpwood, sawtimber, or a combination of both. Short-term predictions often do not meet management needs. A growth and yield model that accurately forecasts volume through time is needed to choose an appropriate planting spacing and intermediate treatments.

Information on the effects of planting density on growth comes from long-term spacing studies. Such data are necessary for building and validating growth and yield models. One such study for loblolly pine is on the Calhoun Experimental Forest near Union in the South Carolina Piedmont. Three reports, Balmer et al. (1975), Harms and Lloyd (1981), and DeBell et al. (1989) described the growth of the plots through ages 15 years, 20 years, and 25 years, respectively. This paper describes the 30-year growth trends, documents the effects of spacing on those trends, and compares observed stand development with that predicted by four widely used growth and yield models.

METHODS

The planting site is a former cotton field abandoned after the 1955 growing season. The soil, in the Appling series, is sandy loam over a compact mottled red and yellow clay. Loblolly pine was planted on the site in January 1957. Based on tree heights measured at age 15 years and published site index curves (Clutter and Lenhart, 1968), Balmer et al. (1975) estimated the site index (base age 25 years) to be 22.9 m.

The study has a randomized complete block design with four blocks; each block has one 0.24-ha square plot of each of the four planting spacings: 1.8 m×1.8 m, 2.4 m×2.4 m, 3.0 m×3.0 m, and 3.7 m×3.7 m. Planting stock was nursery-run 1-0 loblolly pine obtained from the South Carolina Forestry Commission. After the first growing season, dead trees were replaced with seedlings from the same stock as that planted on the site at the time of initial planting.

Tree measurements were taken at ages 5, 7, 11, 15, 20, 25, and 30 years. Diameter at breast height (dbh) and total height of 16 trees per plot were measured at 5, 7, and 11 years. Thereafter, results are reported for the interior 64 trees on each plot. The dbh and total height of all surviving trees were measured at age 15 years. At age 20 years, dbh of all surviving trees was measured, and total height, height to live crown, and crown width were sampled by diameter class and spacing. At ages 25 and 30 years, dbh, total height, height to live crown, and crown width of all surviving trees were measured. Cubic foot volumes were calculated with the equations developed by Bailey and Clutter (1970), and sawtimber volumes (International $\frac{1}{4}$-in scale) were calculated for all trees greater than 25.4 cm dbh. The study was installed and measured in imperial units. Conversion to metric units was done for publication purposes.

Information about the predictive ability and behavior of growth and yield models is of great importance to land managers and others concerned with projecting stand development. Long-term data from spacing studies provide excellent opportunities to evaluate the behavior and accuracy of growth and yield models. To this end, predicted stand development obtained from four widely used growth and yield models was compared with actual stand development at the individual spacings. The models examined are readily available for use on personal computers and have been described by Bailey et al. (1985), Clutter et al. (1984), Amateis et al. (1984), and Hafley et al. (1982). Common names for the individual models used throughout this article are UGA, SE-27, COYIELD, and NCSU, respectively. The UGA and COYIELD models were built using initial measurements of permanent plots in operational plantations. The SE-27 model is based on short-term remeasurement (1–5 years) of permanent plots and temporary plot data from operational plantations. The NCSU model is based on long-term spacing study data, many of which are available in the literature, and on observations in operational plantations. The age 20 and 25 years data from the spacing study described here were used to evaluate, but not to fit, the NCSU model.

A height–age curve is a primary component of all four models. The NCSU model allows the user to enter any height–age curve. The author reprogrammed segments of the other three models to give similar flexibility. The site index curve that most closely matched the height–age sequence of each individual plot (block×spacing combination) was used to predict the development of the corresponding plot with each of the four models. Site index curves tried were Lenhart (1971), Smalley and Bower (1971), Trousdell et al. (1974), Pienaar and Shiver (1980), Golden et al. (1981), Clutter et al. (1984), Amateis and Burkhart (1985), and Lenhart et al. (1986). All the models were altered to use the same stem volume equation to calculate the plot volumes (Bailey and Clutter, 1970) so that observed volumes would be directly comparable with predicted volumes. In addition, all runs of the models were started at age 5 years using the actual number of stems surviving on each plot. Stand characteristics were predicted for age 5, 15, 20, 25, and 30 years for each plot. Predictions at each age were averaged by spacing for each model and compared with the corresponding average of the observed characteristics for that spacing.

RESULTS AND DISCUSSION

Stand structure

Average stand conditions for ages 25 years and 30 years are given in Tables 1 and 2, respectively. Crown width and crown length at ages 25 and 30 years increased as initial spacing increased, continuing a trend noted at age 20 years (Harms and Lloyd, 1981). Crown size apparently expands to occupy the area within the canopy available to the individual tree. At age 30 years, the 2.4 m×2.4 m spacing has the greatest total cubic volume per hectare and the greatest merchantable cubic volume per hectare, but the 3.0 m×3.0 m and 3.7 m×3.7 m spacings are nearly equal to it.

The distributions of basal area per hectare, total volume (inside bark; i.b.) per hectare, and total sawtimber volume per hectare at age 30 years by 2-cm diameter class are shown in Figs. 1, 2, and 3, respectively. At age 25 years, the percentage of stems large enough to qualify as sawtimber (25.4 cm dbh and larger) at the 1.8 m×1.8 m, 2.4 m×2.4 m, 3.0 m×3.0 m, and 3.7 m×3.7 m spacings at age 25 years was 0.7%, 6.4%, 17%, and 57.2%, respectively. At age 30 years, the percentages were 10.3%, 15.4%, 37.3%, and 67.8%, respectively.

TABLE 1

Average stand parameters at age 25 years

Stand characteristic	Initial spacing (m)			
	1.8×1.8	2.4×2.4	3.0×3.0	3.7×3.7
Trees per hectare				
Planted	2990	1680	1078	746
Surviving	1601	1236	939	630
% Mortality	46.5	26.4	12.9	15.5
Mean dbh (cm)	17.9	20.8	23.4	27.1
Mean height (m)	18.2	19.4	19.4	19.8
Dominant height (m)	20.3	21.2	21.1	21.2
Quadratic mean dbh (cm)	18.1	21.1	23.6	27.4
Crown width (m)	2.2	2.5	2.6	3.7
Crown length (m)	3.8	4.1	4.7	6.4
Crown ratio (%)	20.8	21.1	24.2	32.3
Basal area (m^2 ha^{-1})	41.1	42.9	41.1	37.0
20-year total	43.2	42.9	38.1	34.9
5-year net growth	−2.1	0.0	3.0	2.1
Total volume (i.b.)[a]				
(m^3 ha^{-1})	269.5	298.3	287.1	264.1
20-year total	261.3	272.0	246.6	230.3
5-year net growth	8.2	26.3	40.5	33.8
Merchantable volume (i.b.)[b]				
(m^3 ha^{-1})	242.8	276.2	270.9	254.0
20-year total	219.0	245.2	228.8	217.7
5-year growth	23.8	31.0	42.1	36.3
Total sawtimber Volume[c]				
(m^3 ha^{-1})	7.1	30.8	53.7	82.5
20-year total	0.0	10.7	26.1	56.7
5-year net growth	7.1	20.1	27.6	25.8

[a]i.b., inside bark.
[b]To a 10.2 cm top outside bark.
[c]Trees over 25.4 cm dbh.

It is clear that the proportion of stems, basal area, and volume in larger, higher-value size classes increases as planting density decreases. Stem quality has not been quantified for the various treatments.

Stand development

Survival trends and quadratic mean diameter and basal area development for each spacing are given in Figs. 4, 5 (observed), and 6 (observed), respectively. Survival trends are as expected, with mortality beginning and accelerating at an earlier age in the higher planting densities than in the lower planting densities. In the early stages, the densest initial spacing had the greatest

TABLE 2

Average stand parameters at age 30 years

Stand characteristic	Initial spacing (m)			
	1.8×1.8	2.4×2.4	3.0×3.0	3.7×3.7
Trees per hectare				
Surviving	1248	1112	813	591
% mortality	58.3	33.8	24.6	20.8
Mean dbh (cm)	19.8	22.1	24.9	28.6
Mean height (m)	19.4	20.8	21.4	21.3
Dominant height (m)	21.4	22.7	23.1	22.9
Quadratic mean dbh (cm)	20.1	22.5	25.1	29.0
Crown width (m)	2.4	2.5	3.2	3.8
Crown length (m)	4.7	4.9	5.8	6.8
Crown ratio (%)	24.2	23.5	27.1	31.9
Basal area (m^2 ha^{-1})	39.3	43.7	40.2	38.8
5-year net growth	−1.8	0.8	−0.9	1.8
Total volume (i.b.) (m^3 ha^{-1})	273.7	326.0	309.5	299.5
5-year net growth	4.2	27.7	22.4	35.4
Merchantable volume (i.b.)[a] (m^3 ha^{-1})	246.6	301.8	291.9	288.0
5-year net growth	3.8	25.6	21.0	34.0
Total sawtimber Volume[b] (m^3 ha^{-1})	18.0	52.2	77.1	104.0
5-year net growth	10.9	21.4	23.4	21.5

[a]To a 10.2 cm top outside bark.
[b]Trees over 25.4 cm dbh.

basal area and volume per hectare. Between age 10 and 15 years, however, the 1.8 m×1.8 m spacing began to fall below the others in volume per hectare and, beginning at age 20 years, in basal area per hectare. This trend was due to increased natural competition and resulting mortality at the 1.8 m×1.8 m spacing. By age 30 years, the basal area growth rate at the 2.4 m×2.4 m spacing was near zero, but volume and basal area yields had not yet begun to decrease. Except for a slight dip in basal area at the 3.0 m×3.0 m spacing, both the 3.0 m×3.0 m and 3.7 m×3.7 m spacings appear to be at least keeping pace with, or possibly catching up with the 2.4 m×2.4 m spacing in both volume and basal area per hectare.

The convergence and crossing over of the basal area and total volume curves for different spacings evident in this study also are documented in other long-term loblolly pine spacing studies, in natural and planted loblolly pine stands, and in many conifer spacing studies (Adams and Chapman, 1942; Gilmore and Gregory, 1974; Arnold, 1978, 1981; Hafley et al., 1982; Liegel et al., 1985; Harrison and Daniels, 1988). Convergence implies that the standing basal

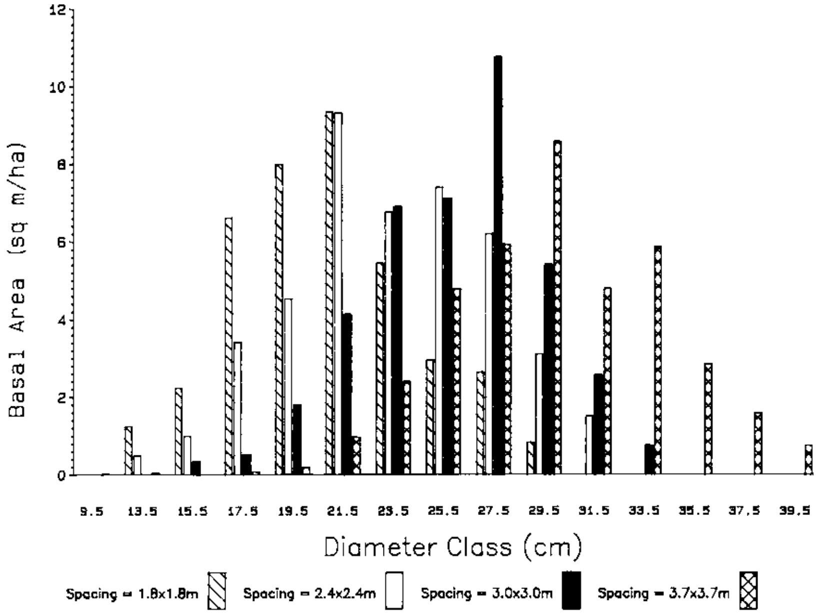

Fig. 1. Distribution of basal area per hectare by diameter class for each spacing at age 30 years.

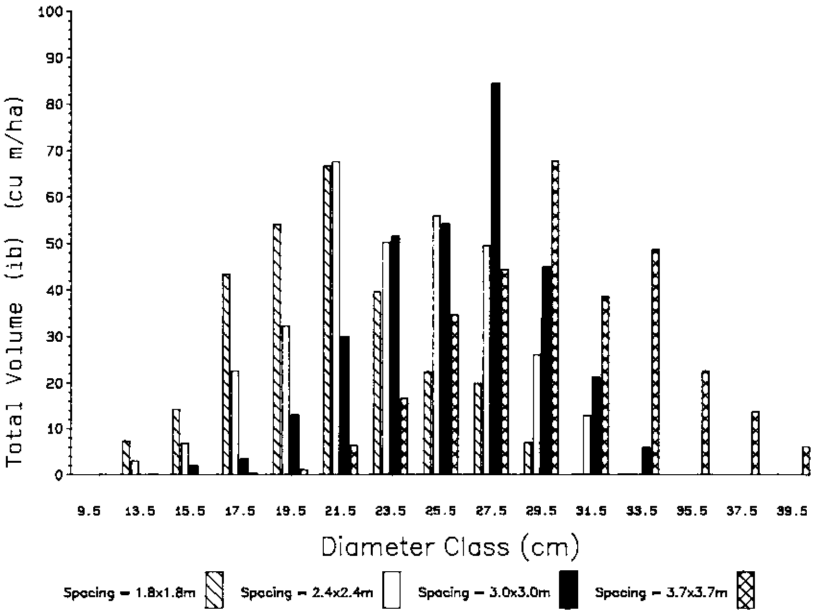

Fig. 2. Distribution of total volume (i.b.) per hectare by diameter class for each spacing at age 30 years.

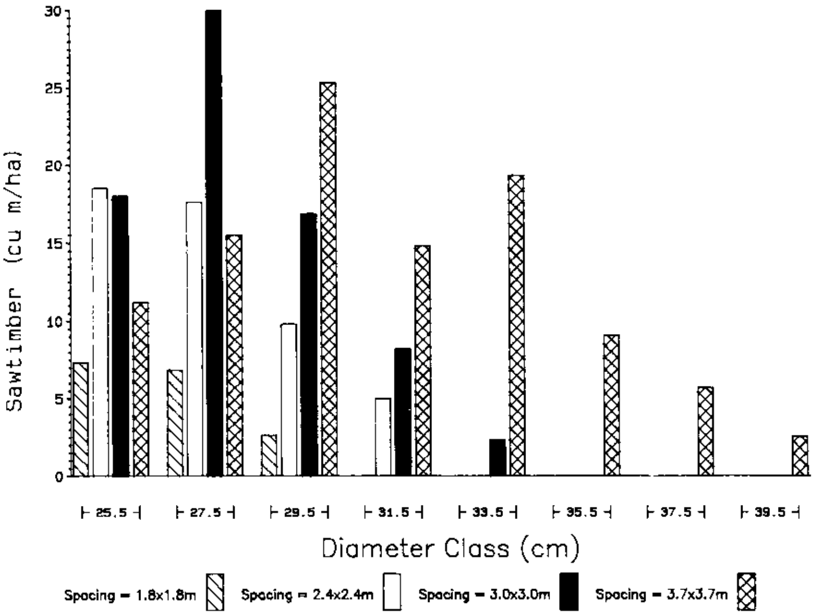

Fig. 3. Distribution of sawtimber volume per hectare (trees over 25.4 cm dbh) by diameter class for each spacing at age 30 years.

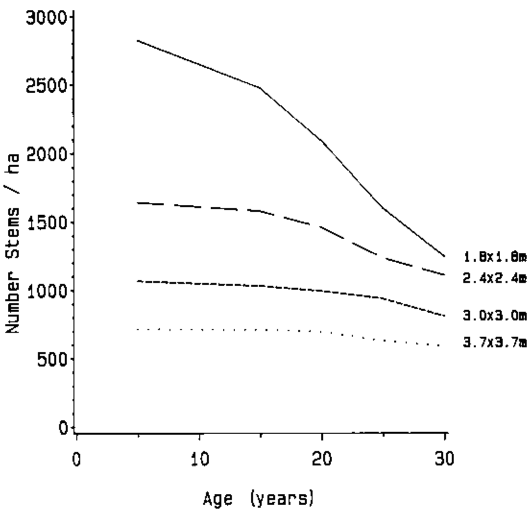

Fig. 4. Average number of surviving stems per hectare vs. age for each spacing.

areas and volumes of the various spacings approach each other in time. Crossing over means that, over time, the standing volumes and basal areas of stands planted at lower initial densities surpass those of stands planted at higher initial densities.

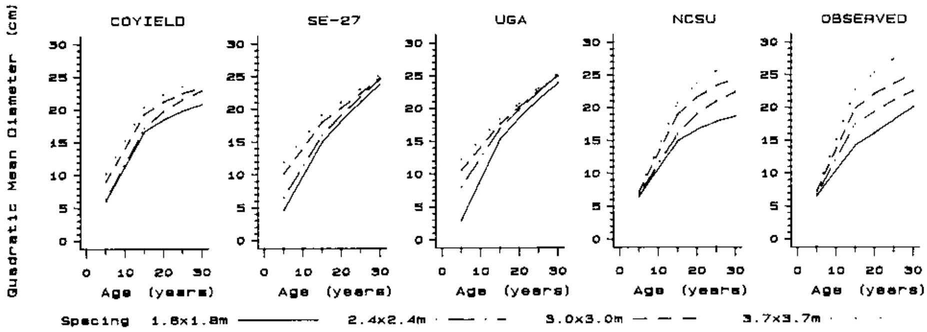

Fig. 5. Observed and predicted quadratic mean diameter vs. age for each spacing.

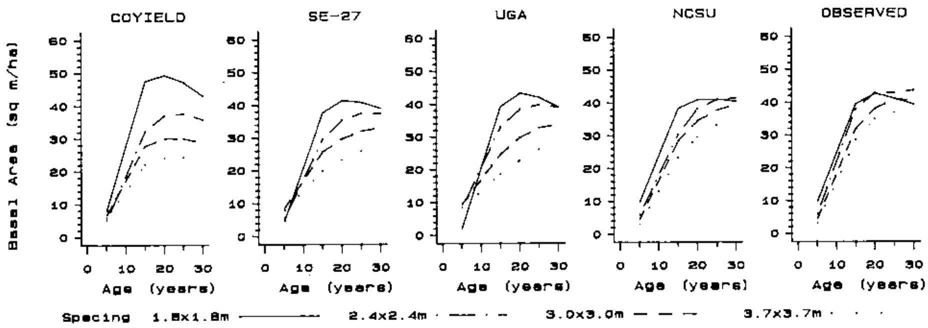

Fig. 6. Observed and predicted basal area per hectare vs. age for each spacing.

Model comparisons

Model performance can be compared by both statistical and graphical means. Users can evaluate the predictive ability of a model from measures of accuracy, precision and time dependence for principal variables (Brand and Holdaway, 1983). Tables 3, 4, 5, and 6 give some measures of model accuracy and precision for surviving stems per hectare, average height, basal area per hectare, and total volume (i.b.) per hectare. The calculations are based on plot averages at ages 5, 15, 20, 25, and 30 years. Survival information was not recorded at ages 7 and 11 years, so these ages were not used in the model comparisons. The mean difference and per cent mean difference are measures of model accuracy. The root mean square error and per cent root mean square error provide information on prediction precision. The SE-27 and UGA models have essentially the same survival function and so give virtually the same results in Table 3.

In general, all of the models underpredict basal area and total volume per hectare because they underpredict survival (Table 3). Observed and predicted quadratic mean diameter, basal area, and volume over time are shown

TABLE 3

Evaluation of model performance with respect to the number of surviving stems per hectare

Spacing (m)	Model	Criterion			
		$\bar{D}$[a]	$\%\bar{D}$[b]	RMSE[c]	%RMSE[d]
1.8×1.8	COYIELD	117.4	4.8	196.1	10.0
(n=20)	SE-27	326.7	18.4	383.6	21.8
	UGA	326.7	18.4	383.6	21.8
	NCSU	46.6	18.5	205.1	12.6
2.4×2.4	COYIELD	175.6	13.0	211.1	15.8
(n=20)	SE-27	176.4	13.5	222.7	17.3
	UGA	176.4	13.5	222.7	17.3
	NCSU	60.3	4.0	100.8	7.8
3.0×3.0	COYIELD	111.1	11.9	134.4	14.4
(n=20)	SE-27	65.3	7.1	91.0	9.9
	UGA	65.3	7.1	91.0	9.9
	NCSU	22.1	2.0	55.6	6.2
3.7×3.7	COYIELD	51.5	7.9	66.8	10.3
(n=20)	SE-27	15.3	2.2	31.6	5.0
	UGA	15.7	2.3	31.4	5.0
	NCSU	−1.4	−0.6	37.1	6.3

[a]Mean difference: $\bar{D}=\frac{1}{n}\sum(\text{observed}-\text{predicted})$.

[b]Per cent mean difference: $\%\bar{D}=\left[\frac{1}{n}\sum\left(\frac{\text{observed}-\text{predicted}}{\text{observed}}\right)\right]\times 100$.

[c]Root mean square error: $\text{RMSE}=\left[\frac{1}{n}\sum(\text{observed}-\text{predicted})^2\right]^{1/2}$.

[d]Per cent root mean square error: $\%\text{RMSE}=\left[\frac{1}{n}\sum\left(\frac{\text{observed}-\text{predicted}}{\text{observed}}\right)^2\right]^{1/2}\times 100$.

in Figs. 5, 6, and 7. It is clear that the magnitude of the underprediction increases substantially for the COYIELD, SE-27, and UGA models as initial density decreases. These models predict convergence of the quadratic mean diameters for all spacings over time. This phenomenon has not occurred in the present study (Fig. 5) and did not occur in other loblolly pine stands planted at various densities (Gilmore and Gregory, 1974; Arnold, 1978, 1981; Sprinz et al., 1979; Hafley et al., 1982). Additionally, for these three models, there is an associated increase in the root mean square error for basal area and volume, implying a considerable loss in precision as initial density decreases. There is no consistent trend in the underpredictions and root mean square error related to density for the NCSU model.

The COYIELD, SE-27, and UGA models do not predict the convergence and crossing over of basal area and volume in the time frame in which it

TABLE 4

Evaluation of model performance with respect to average stand height

Spacing (m)	Model	Criterion			
		$\bar{D}$	%$\bar{D}$	RMSE	%RMSE
1.8×1.8	COYIELD	−1.04	4.8	1.36	18.7
(n=20)	SE-27	−0.70	−6.4	1.18	9.5
	UGA	−1.23	−10.9	1.56	13.6
	NCSU	0.10	0.02	0.89	5.7
2.4×2.4	COYIELD	−0.11	−2.6	0.78	8.3
(n=20)	SE-27	0.18	1.6	0.77	5.7
	UGA	−0.30	−1.6	0.85	5.7
	NCSU	0.41	3.7	0.88	7.0
3.0×3.0	COYIELD	−0.03	−4.0	0.73	12.1
(n=20)	SE-27	0.16	−1.0	0.66	7.4
	UGA	−0.31	−4.2	0.65	9.0
	NCSU	0.16	−0.5	0.66	6.5
3.7×3.7	COYIELD	0.08	−3.3	0.69	11.5
(n=20)	SE-27	0.18	−1.2	0.64	7.6
	UGA	−0.30	−4.5	0.61	9.3
	NCSU	0.00	−1.9	0.58	6.8

TABLE 5

Evaluation of model performance with respect to basal area per hectare

Spacing (m)	Model	Criterion			
		$\bar{D}$	%$\bar{D}$	RMSE	%RMSE
1.8×1.8	COYIELD	−4.14	−8.3	6.26	18.0
(n=20)	SE-27	1.81	11.6	3.48	23.5
	UGA	1.41	14.8	5.23	36.0
	NCSU	0.38	0.7	2.28	5.8
2.4×2.4	COYIELD	5.16	14.8	6.11	16.5
(n=20)	SE-27	5.60	14.8	6.49	16.5
	UGA	3.01	1.2	5.38	22.4
	NCSU	3.29	8.1	4.87	12.2
3.0×3.0	COYIELD	6.60	7.1	8.68	35.6
(n=20)	SE-27	5.32	−3.1	7.51	49.7
	UGA	5.11	−6.0	7.53	53.8
	NCSU	2.23	6.0	3.55	9.3
3.7×3.7	COYIELD	8.48	4.1	10.73	57.8
(n=20)	SE-27	7.41	−12.0	9.89	88.2
	UGA	7.59	−14.0	10.21	97.2
	NCSU	3.54	11.2	4.34	13.3

TABLE 6

Evaluation of model performance with respect to total cubic meter volume (i.b.) per hectare

Spacing (m)	Model	Criterion			
		$\bar{D}$	$\%\bar{D}$	RMSE	%RMSE
1.8×1.8	COYIELD	−42.2	−20.2	54.6	25.9
(n=20)	SE-27	−8.2	3.8	24.4	21.5
	UGA	−19.4	4.6	40.9	35.5
	NCSU	8.1	3.2	20.3	7.9
2.4×2.4	COYIELD	29.6	11.9	36.3	15.8
(n=20)	SE-27	30.7	13.6	37.1	16.8
	UGA	11.1	−3.4	28.8	23.5
	NCSU	27.1	13.3	36.9	16.8
3.0×3.0	COYIELD	46.6	−0.4	60.7	50.5
(n=20)	SE-27	25.3	−20.1	45.9	80.0
	UGA	31.7	−15.1	41.8	68.6
	NCSU	19.8	7.0	28.8	12.1
3.7×3.7	COYIELD	61.7	−5.2	77.5	78.3
(n=20)	SE-27	53.7	−19.1	65.9	103.3
	UGA	50.5	−26.8	62.0	122.0
	NCSU	26.3	10.8	33.5	15.4

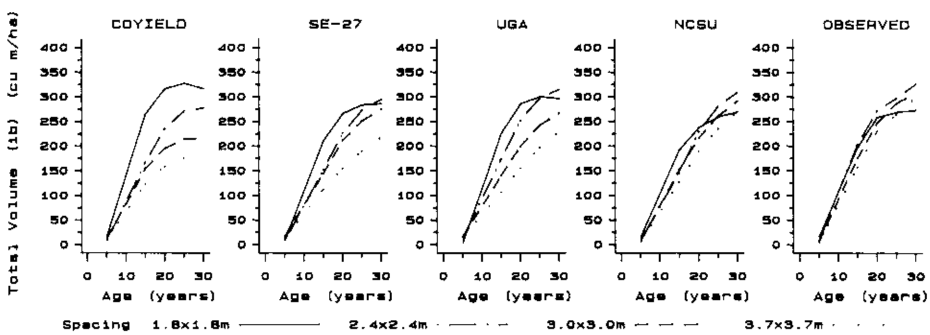

Fig. 7. Observed and predicted total volume (i.b.) per hectare vs. age for each spacing.

occurs. For either a pulpwood or sawtimber rotation, these models predict a trend of increased yield as planting density increases. For the range of planting densities in this spacing study and other loblolly pine stands for which sufficient measurements are available, this predicted trend does not occur. Long-term studies have shown that although denser plantings have more stems per unit area until at least age 30 years, they have less basal area and volume per unit area beginning at much younger ages than do wider-spaced plantings with fewer trees. The NCSU model correctly predicts the convergence and crossing over of basal area and volume of the 1.8 m×1.8 m spacing previously noted (Figs. 6 and 7).

As an illustration of how well the predicted diameter distributions from the models matched the observed diameter distributions, observed dominant height and number of stems surviving at age 25 years for each spacing were entered into each of the four models. The predicted and observed diameter distributions at age 25 years are given in Figs. 8–11. Output from the UGA model is not shown because it is essentially identical to that of the SE-27 model. It is clear from these figures that the NCSU model reproduced the observed diameter distributions most closely.

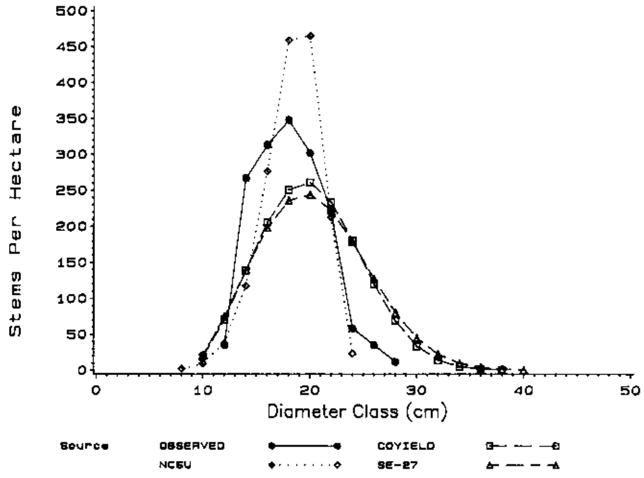

Fig. 8. Observed and predicted diameter distributions at age 25 years for the 1.8×1.8 m spacing.

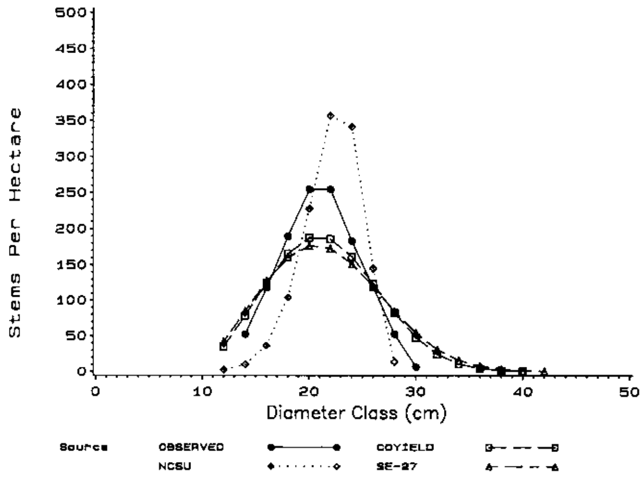

Fig. 9. Observed and predicted diameter distributions at age 25 years for the 2.4 m×2.4 m spacing.

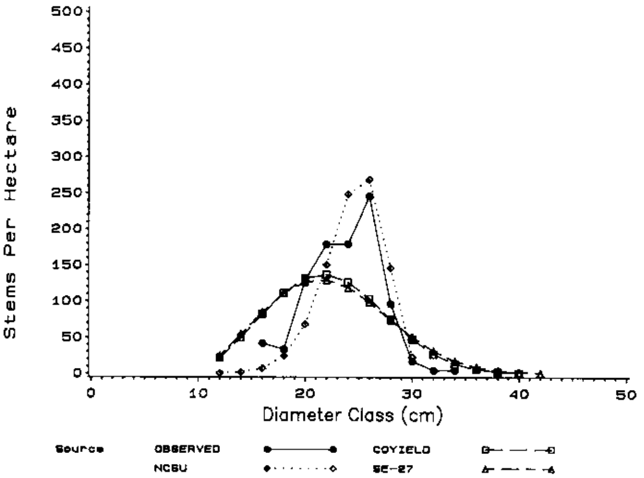

Fig. 10. Observed and predicted diameter distributions at age 25 years for the 3.0 m×3.0 m spacing.

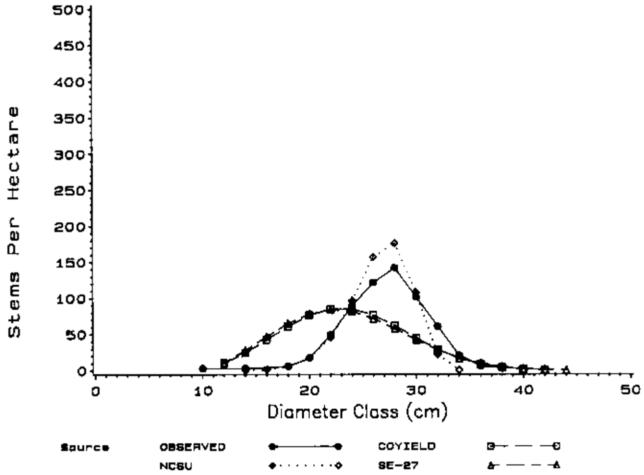

Fig. 11. Observed and predicted diameter distributions at age 25 years for the 3.7 m×3.7 m spacing.

The parameters controlling the predicted diameter distributions in the NCSU model are functions of dominant height, which changes with time, and initial planting density, which is a constant over time for any given spacing. For the COYIELD, SE-27, and UGA models, however, the parameters controlling the predicted diameter distributions at a given age are functions of either age or the corresponding dominant height and the number of stems surviving at that age. The number of surviving stems is generally greater in more densely planted stands to at least age 30 years. This formulation of the parameter predictions, as functions of the number of surviving stems, contains the implication that yield increases with density. Given the same number of stems, same dominant height, and same age, the COYIELD, SE-27, and UGA models will predict the same diameter distribution for the various spacings, regardless of differences in initial planting density. An example using age 44-year data from the Hofmann Forest spacing study plots planted at 1.2 m×1.2 m and 2.4 m×2.4 m (Hafley et al., 1982; Hafley and Buford, 1985) illustrates the problem. The observed dominant heights, 27.1 and 26.8 m, and the numbers of surviving stems, 501 and 503 stems ha^{-1}, were essentially the same for the 1.2 m×1.2 m and 2.4 m×2.4 m spacings, respectively. The diameter distributions and quadratic mean diameters, 26.2 and 29.7 cm, were substantially different for the 1.2 m×1.2 m and 2.4 m×2.4 m spacings. COYIELD predicted identical distributions with a quadratic mean diameter of 26.4 cm for both the 1.2 m×1.2 m and the 2.4 m×2.4 m spacings. SE-27 predicted the same distribution with a quadratic mean diameter of 34.3 cm for both spacings. It is clear that although the height, number of stems, and age are the same for these two spacings, the observed diameter distributions are not the same and that initial planting density greatly affects the observed diameter distributions. It is equally clear that the COYIELD, SE-27, and UGA models predicted the same distribution for the two spacings.

CONCLUSIONS

The 30 years of observations from the described spacing study confirm much that has been learned from other long-term spacing studies. Crown size increases as planting density decreases. The proportion of stems at any given age in the larger, higher-value size classes is greater at wider initial spacings. Closer planting densities maintain greater basal areas and volumes per hectare early in the life of the plantation, but lose that advantage over time because of increased competition and the resulting mortality. The 1.8 m×1.8 m spacing began to fall behind the wider spacings in both volume and basal area per hectare by ages 15 and 20 years, respectively. By age 25 years, the 3.0 m×3.0 m and 3.7 m×3.7 m spacings had slightly less merchantable cubic foot volume and substantially more sawtimber volume than the 2.4 m×2.4 m spacing.

The statistical and graphical comparisons of model behavior with observed stand development provide practical information for users trying to decide which of the four models best meets their needs. Although all the models generally underpredicted the basal area and volume of a given spacing, the COYIELD, SE-27, and UGA models clearly indicated behavior that was not in accord with actual observed stand behavior over time. The NCSU model performed best over the range of spacings in this study.

The NCSU model was developed using long-term spacing study data and observed behavior of operational plantations. The UGA, SE-27, and CO-YIELD models were developed using short-term remeasurement and temporary plot data without apparent consideration of the long-term growth trends evident in the stand dynamics literature and did not show realistic behavior in quadratic mean diameter, total basal area, and total volume development.

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