FASTLOB

(A Stand-Level Growth and Yield Model for Fertilized and Thinned Loblolly Pine Plantations)

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Abstract. A stand-level growth and yield model for managed loblolly pine plantations was developed using data from permanent remeasurement plots throughout much of the natural range of the species. Stand-level projection equations for dominant height, survival and basal area form the nucleus of a thinned and unthinned baseline model. Functions for intermediate treatments of fertilization were developed from treatment plot data reflecting typical fertilized regimes. The response functions are sensitive to specific fertilization prescriptions as well as to stand and site conditions at time of treatment. They are used to modify or adjust the baseline models in order to reflect the effects of intermediate fertilizer treatments on stand development after treatment. An assumption is made that the effect on stand response of fertilization and thinning is additive so that multiple treatments can be simulated. Level of competing overstory hardwood basal area has been incorporated into the baseline models so the effect of this component of competing vegetation can be simulated if desired. Treatment scenarios can be evaluated with convenient Windows-based software.

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INTRODUCTION

Loblolly pine (Pinus taeda L.) is one of the most productive tree species in the southern United States. Wood produced from loblolly pine plantations is processed for pulp and paper products as well as sawn, peeled and chipped for construction material. Increasingly, plantations of loblolly pine are being intensively managed by applying silvicultural treatments to enhance their productivity. Two of the most important midrotation silvicultural tools available to managers are thinning and fertilization. Thinning provides an opportunity to obtain intermediate cash flows from wood harvested in thinning operations, improve the quality of the residual stand by removing slow-growing and damaged or diseased trees and shift future growth of the stand to the larger, better quality residual trees. Fertilization stimulates loblolly pine growth and development by enhancing nutrient availability. Therefore, there is a need for growth and yield models that forecast future yields for managed plantations that have received these treatments. Such models should be useful to foresters, silviculturalists, researchers and others charged with managing loblolly pine plantation resources.

The objective of this work was to produce a growth and yield model that could be used to evaluate the effects of thinning and fertilizer treatments on loblolly pine stands. In order to accomplish this objective, two assumptions were made which guided the model development process. The first was that intermediate fertilizer treatments be modeled as response relative to a baseline. Treatment response functions are developed by regressing appropriate stand, site and treatment variables on the difference between untreated baseline plot data and observations from companion treated plots. Data suitable for this type of response model were available for fertilization.

The second assumption was that the combined effect of thinning and/or one or more fertilizer treatments is additive. That is, the effect on growth and stand development of a combination of treatments is the sum of the responses of each separate treatment. Past studies designed to evaluate the interaction between thinning and fertilization have been inconclusive. Ballard et al. (1981) found that net volume responses for thinned and fertilized stands were, on average, greater than for unthinned and fertilized stands. The same trends were observed for sawlog volume and mean diameter. They concluded that fertilization acts to speed up site reoccupancy following thinning and larger trees benefit more than smaller trees regardless of stocking levels prior to thinning. However, they were unable to relate the thinned and fertilized response to any pre-thinning stand conditions or thinning intensity variables.

In a similar type of study, Stearns-Smith et al. (1992) were unable to draw definitive conclusions regarding a fertilizer-thinning interaction effect for slash and loblolly pine. Their results showed a significant and consistent response to each treatment separately but an interaction effect in only certain cases. In other cases, the response was statistically independent and additive; thinning did not affect fertilizer response and fertilization did not affect thinning response.

In reviewing growth data from thinning and fertilizer trials outside the South it is difficult to draw firm conclusions about the strength and consistency of a thinning-fertilization interaction. For example, in Douglas-fir stands, Miller et al. (1979) found that growth was consistently greater following fertilization of lightly or moderately thinned stands than unthinned stands. However, the thinning/fertilization interaction was seldom statistically significant. Perhaps the reason these early studies are generally inconclusive is because they were limited in scope and utilized study designs inadequate to fully evaluate the effects of treatment interactions. In any case, since data were not available to model the interaction and to make predictions for combined treatments across a wide range of stand conditions, the additivity assumption was adopted here.

The following sections summarize data sources, modeling rationale and model performance for FASTLOB, a stand-level response model for thinned and fertilized loblolly pine plantations.

DATA

Thinned and unthinned regionwide

Data from the Loblolly Pine Growth and Yield Research Cooperative's regionwide thinning study were available for modeling response to thinning. Permanent plots in plantations on cutover, site-prepared areas were established during the dormant seasons of 1980-1982 throughout the Piedmont and Coastal Plain regions in the Southeast (Burkhart et al. 1985). At each location three plots were established: an unthinned control, a lightly thinned and a heavily thinned plot. Rigorous guidelines were established for selecting stands suitable for the study. In addition, site index, basal area and trees per acre of plots at a location were required to be similar in order to minimize the plot-to-plot variation of these stand characteristics at time of treatment. In general, the three plots at a location did not vary by more than 5 feet in dominant height, 20 square feet per acre in basal area and 100 stems per acre at establishment. The result was that at time of plot establishment the differences in stand conditions between plots at an installation were minimal. The average stand age at time of establishment was 15 years, ranging from 8 to 25 years. The average site index was 59 feet and ranged from 42 to 81 feet.

The plots were randomly assigned to the treatment categories: control (no thinning), light thinning (approximately 30 percent of the basal area removed), or heavy thinning (approximately 50 percent of the basal area removed). All plots assigned to thinning treatments were thinned at time of plot establishment. Forty-five stands (90 plots) received a second thinning 12 years later. Thinnings were primarily from below with some removals of larger trees due to poor form, damage, disease or spacing considerations. Plots were remeasured 3, 6, 9, 12 and 15 years after establishment. Tables 1 and 2 provide summaries for important stand characteristics used in the analyses presented here.

Table 1. Before and after thinning statistics at time of establishment and at time of second thin 12 years after establishment.

	Mean	Std. Dev.	Minimum	Maximum
	------------------------------Establishment (373 plots)---------------			
Dom. ht. Before thin (ft.)	40.6	11.6	14.7	74.5
Dom. Ht. after thin (ft.)	41.0	12.0	15.0	74.6
Diff. in dom. ht.before and after thin (ft.)	0.42	0.41	-0.50	1.80
Num. Tr/ac before thin	556	121	271	957
Num. Tr/ac after thin	300	83	92	633
Num. tr/ac removed in thin	256	86	62	575
Basal area before thin (ft^2/ac)	104.6	37.3	21.0	239.0
Basal area after thin (ft^2/ac)	68.1	25.0	12.9	155.5
Basal area removed in thin (ft^2/ac)	36.5	19.0	6.2	106.1
	--------------------------Second thinning (90 plots)------------------------			
Dom. ht. Before thin (ft.)	59.8	7.5	41.2	75.7
Dom. Ht. after thin (ft.)	60.6	7.7	41.5	75.9
Diff. in dom. ht. before and after thin (ft.)	0.83	0.71	-0.6	3.4
Num. Tr/ac before thin	280	63	142	444
Num. Tr/ac after thin	155	38	89	240
Num. tr/ac removed in thin	125	44	40	250
Basal area before thin (ft^2/ac)	120.7	23.9	53.4	176.2
Basal area after thin (ft^2/ac)	68.1	25.0	12.9	155.5
Basal area removed in thin (ft^2/ac)	36.5	19.0	6.2	106.1

Table 2. Dominant height, basal area and survival statistics by treatment at time of establishment and through five remeasurements (standard deviation in parentheses).

	---Unthinned Control---					
	Estab.	Year 3	Year 6	Year 9	Year 12	Year 15
Ave. dom. ht. (ft.)	40.9 (11.9)	47.0 (11.2)	52.1 (10.3)	56.1 (9.3)	60.5 (8.8)	65.7 (9.0)
Ave. basal area (ft^2/ac)	106.9 (36.7)	124.3 (31.1)	134.4 (28.8)	143.8 (27.2)	152.7 (27.8)	160.1 (30.5)
Ave. trees surviving per ac.	569.4 (135.4)	544.0 (135.0)	510.7 (137.0)	487.7 (127.2)	448.0 (107.8)	412.2 (92.9)
	---Light thin---					
Ave. dom. ht .after thin (ft.)	41.1 (12.0)	46.8 (11.2)	52.0 (10.2)	56.2 (9.2)	60.5 (8.6)	66.0 (8.7)
Ave. diff. of dom. ht. (light thin-control) after thinning (ft.)	0.32 (0.34)	-0.24 (2.7)	-0.07 (2.8)	0.10 (2.9)	0.03 (3.2)	0.34 (3.5)
Ave. basal area after thin (ft^2/ac)	75.5 (25.9)	92.2 (23.5)	105.7 (22.8)	117.1 (22.5)	129.7 (23.5)	140.5 (24.0)
Ave. diff. of basal area (control-light thin) after thinning (ft^2/ac)	31.8 (19.1)	32.7 (20.2)	29.7 (23.4)	27.6 (21/4)	23.4 (21.1)	20.8 (21.6)
Ave. survival after thin (trees/ac)	341.3 (78.5)	335.2 (78.0)	328.5 (79.5)	322.7 (79.4)	314.8 (70.1)	300.7 (55.4)
Ave. diff. of survival (control-light thin) after thinning (trees/ac)	230.0 (97.2)	209.9 (98.3)	182.4 (100.5)	165.4 (86.0)	132.9 (76.0)	107.6 (58.4)
	---Heavy thin---					
Ave. dom. ht. after thin (ft.)	41.1 (12.0)	46.6 (11.3)	51.7 (10.4)	56.1 (9.4)	60.8 (8.9)	66.5 (9.2)
Ave. diff. of dom. ht. (heavy thin-control) after thin (ft.)	0.53 (0.44)	-0.31 (2.4)	-0.27 (2.4)	0.09 (2.4)	0.30 (2.8)	0.92 (3.5)
Ave. basal area after thin (ft^2/ac)	60.7 (21.7)	75.8 (20.6)	89.0 (21.1)	101.0 (21.6)	114.4 (23.4)	128.1 (23.8)
Ave. diff. of basal area (control-heavy thin) after thinning (ft^2/ac)	46.1 (20.9)	48.7 (20.8)	45.9 (23.0)	42.8 (22.1)	38.2 (21.6)	32.4 (21.3)
Ave. survival after thin (trees/ac)	258.8 (64.6)	254.1 (65.4)	249.6 (66.9)	245.9 (66.6)	243.1 (60.5)	239.6 (55.4)
Ave. diff. of survival (control-light thin) after thinning (trees/ac)	309.9 (104.2)	289.4 (107.6)	260.0 (109.2)	241.0 (97.9)	204.1 (88.2)	168.3 (68.7)

Fertilized and unfertilized regionwide

Data were available from fertilized and unfertilized permanent remeasurement plots from the North Carolina State Forest Nutrition Cooperative's (NCSFNC) Regionwide 13 Study. Plots were established in existing plantations during 1984-1985 at 13 sites located across the southeastern United States (Table 3).

Table 3. Summary statistics of plot characteristics at establishment for 13 installations of the NCSFNC Regionwide 13 study.

	Mean	St. Dev.	Min.	Max.
Stand age (years)	12.8	1.2	11	14
Site index (ft)	61.3	5.9	53	74
Trees/ac	516	165	205	939
Basal area (sq ft/ac)	87.9	17.1	46.3	134.2
Dq (in)	5.72	0.65	4.14	7.70
Hd (ft)	37.5	5.1	25.2	48.8

At each study location, four levels of nitrogen (0, 100, 200, 300 lbs N/ac) and three levels of phosphorus (0, 25, 50 lbs P/ac) were applied using a factorial experimental design. At each location, two or four replicates of the basic twelve-treatment matrix were established. Sites were selected to represent a range of soil texture families, drainage classes and stand conditions throughout the natural loblolly pine growing region. Rigorous guidelines for selection of candidate stands and blocking of plots were used to minimize within site variation for stand characteristics and soil type. Plots within a block generally did not vary more than 3 feet in dominant height, 10 square feet per acre in stand basal area and 80 stems per acre at study establishment. The result was that at time of plot establishment the differences in stand conditions between plots at an installation were minimal. The observed rates of mortality during the eight-year study period were 5.8 percent of the total stem number in unfertilized plots, 6.1 percent in the plots fertilized with 100 lbs N per acre, 7.1 percent in the plots fertilized with 200 lbs N per acre and 8.6 percent in the plots fertilized with 300 lbs N per acre. Tables 4-6 present dominant height, basal area and survival summary data for the Regionwide-13 study.

Measurement plots included a minimum of 30 to 40 trees surrounded by a treated buffer of at least 30 feet. Diameter at breast height and total height were measured on all trees in each plot. Measurements were carried out at 2-year intervals during the dormant season. Details of this study can be found in Allen (in review). Results six, eight, and ten years after plot establishment can be found in NCSFNC (1992) NCSFNC (1996) and NCSFNC (1997), respectively.

Table 4. Mean dominant and codominant height (feet) for the unfertilized control and the height response (feet) by treatment at two, four, six, eight and ten years after treatment (number observations in parentheses).

Lbs/acre N	P	Year 2 (116)	Year 4 (100)	Year 6 (82)	Year 8 (64)	Year 10 (40)
		Unfertilized Control Height				
0	0	46.4	50.6	55.0	59.4	63.3
		Response to Treatment				
0	25	-0.1	-0.3	-0.1	0.0	0.3
0	50	0.3	0.3	0.6	0.7	1.4
100	0	0.5	0.4	0.8	0.5	0.6
100	25	0.7	0.9	1.1	1.3	1.5
100	50	0.7	1.0	1.4	1.5	2.1
200	0	0.6	0.6	0.8	0.5	0.3
200	25	1.0	1.4	1.8	2.2	3.0
200	50	0.7	1.3	1.8	2.4	2.8
300	0	0.6	0.6	0.4	0.5	0.7
300	25	0.5	1.2	1.5	1.9	2.7
300	50	0.5	1.3	1.9	2.6	2.8

Table 5. Mean basal area (square feet per acre) for the unfertilized control and the basal area response (square feet per acre) by treatment at two, four, six, eight and ten years after treatment (number observations in parentheses).

Lbs/acre N	P	Year 2 (116)	Year 4 (100)	Year 6 (82)	Year 8 (64)	Year 10 (40)
		Unfertilized Control Basal Area				
0	0	107.4	120.2	131.2	143.0	148.4
		Response to Treatment				
0	25	-1.0	-0.8	-0.5	-0.7	-0.7
0	50	-0.2	0.4	1.2	0.7	2.3
100	0	0.8	2.3	3.2	2.6	1.0
100	25	1.6	4.3	4.8	4.3	3.5
100	50	2.0	4.5	5.5	7.3	6.7
200	0	1.9	3.7	5.1	4.3	1.9
200	25	4.0	8.4	10.5	12.0	13.3
200	50	3.4	6.9	9.4	11.7	13.7
300	0	2.9	4.9	5.9	5.6	3.6
300	25	4.1	9.4	12.8	14.5	14.0

300	50	4.7	11.1	14.6	16.4	12.1

Table 6. Mean survival (trees per acre) for the unfertilized control and the additional mortality (trees per acre) by treatment at two, four, six, eight and ten years after treatment (number observations in parentheses).

Lbs/acre N	P	Year 2 (116)	Year 4 (100)	Year 6 (82)	Year 8 (64)	Year 10 (40)
		Unfertilized Survival				
0	0	464	465	462	478	476
		Mortality				
0	25	3.8	1.5	-4.6	0.5	10.4
0	50	3.0	-1.0	-7.2	-4.0	16.9
100	0	-0.3	-6.2	-11.6	-8.1	10.2
100	25	8.9	3.9	0.0	3.0	18.4
100	50	7.2	5.2	0.4	-0.1	13.8
200	0	10.2	7.8	6.5	10.7	18.5
200	25	9.3	6.4	7.7	12.1	22.6
200	50	8.1	6.9	7.0	8.3	19.7
300	0	10.8	13.2	10.0	15.6	30.9
300	25	4.8	5.1	-0.8	7.3	18.7
300	50	-2.5	-4.9	-5.1	-1.4	25.4

MODEL DEVELOPMENT - BASELINE

The basic procedure followed for developing component models used in FASTLOB was to combine the control plots from the regionwide fertilizer data to the thinning study data to develop appropriate baseline projection models for dominant height, basal area and survival. Then dominant height and basal area response models for fertilizer treatments relative to the baseline were applied where appropriate. Other models necessary for constructing a complete growth and yield modeling system were obtained from the literature or developed from a portion of the datasets described previously. The following sections provide a brief summary of the baseline component equations developed for FASTLOB. They reflect average development trends for loblolly pine plantations over much of the natural growing region.

Stand-level survival for young stands

The model developed by Amateis et al. (1997) for young loblolly pine plantations and based on the functional form presented by Pienaar and Shiver (1981):

$$\ln N_2 = \ln N_1 + b_1 [A_2^{b_2} - A_1^{b_2}] \tag{1}$$

where A_1, A_2 = stand age (years) at time 1 and 2, respectively
N_1, N_2 = number of trees per acre at A_1, A_2, respectively
b_1, b_2 = parameters to be estimated

was chosen for projecting survival in young stands prior to crown closure. This model assumes that relative mortality is density-independent and not affected by site index. It has been parameterized for two drainage/site preparation regimes:

$$\ln N_2 = \ln N_1 - [0.000997 + 0.000724\ D]\ [A_2^{2.0525} - A_1^{2.0525}] \tag{2}$$

$$MSE = 0.0058$$

where
D = 1 if site is poorly drained and not bedded; 0 otherwise
and all other variables are as previously defined. All parameter estimates were significant at the 0.05 level.

In order to evaluate the suitability of Equation (2), a percent residual number of trees per acre surviving ((obs-pred)/obs*100) was computed for each observation. The mean percent residual number of trees per acre for the poor drainage/no bedding regime at age five was -0.6 (std. dev. = 6.9) and at age eight was -1.0 (std. dev. = 19). For the other regimes, the mean percent residual at age five was 0.2 (std. dev. = 4.0) and at age eight was -0.4 (std. dev. = 7.9). The data were grouped into eight classes for each drainage/site preparation regime according to surviving trees per acre (<150, 150-300, 300-400, 400-500, 500-650, 650-800, 800-900, >900). Table 7 shows the mean percent residuals for these survival classes.

Table 7. Mean percent residual ((obs-pred)/obs*100) for 1402 survival observations by density class for two drainage/site preparation regimes using Equation (2).

	Poor drainage/no bedding			All other drainage/site preparation		
Density	Mean	Std Dev	N	Mean	Std Dev	N
<150	-15.6	19.3	23	-2.1	9.3	55
150-300	-0.5	18.5	128	-0.1	6.0	328
300-400	-2.1	10.5	24	-4.5	11.2	43
400-500	-0.6	16.1	65	1.5	2.6	168
500-600	-4.5	10.3	21	-7.7	13.9	32
600-700	0.2	8.7	45	-0.2	5.0	104
700-800	1.7	5.6	43	1.1	3.9	95
>800	2.7	4.7	73	1.0	3.0	155

Stand-level survival for older stands

A stand-level survival equation similar to Amateis et al. (1997) was developed to reflect survival patterns for a wide range of site and stand conditions in thinned and unthinned plantations:

$$N_2 = N_{min} \left(N_1 / N_{min} \right)^{\exp[\, b_1 ((A_2/10)^{b_2} - (A_1/10)^{b_2})]} \qquad (3)$$

where: $b_1 = \alpha S(G_a/G_b)$
S = site index (base age 25)
G_b = Basal area before thinning
G_a = Basal area after thinning
b_2, α, N_{min}=parameters
A_1, A_2 = stand age at time one and two, respectively
N_1, N_2 = number of trees per acre at A_1, A_2, respectively

In Equation (3), the rate parameter, α is affected by site index and thinning intensity. Equation (3) was fitted to the control plots of the fertilization data and all plots in the thinning study data to obtain parameter estimates for thinned and unthinned conditions. Table 8 presents final parameter estimates and fit statistics for Equation (3).

Table 8. Parameter estimates and fit statistics for Equation (3) fitted to the thinned and unthinned plot observations of the regionwide thinning and fertilization loblolly pine plantation survival data.

Parameter	Estimate	Asymptotic Std. Error
α	-0.00021	0.00002842
b_2	2.8919	0.1087
N_{min}	121.2	15.155
	MSE = 517.2	

Basal area

A basal area projection equation for thinned and unthinned stands was developed for use as a baseline model by applying the projection equation of Hasenauer et al. (1997) to the control plots of the regionwide fertilizer study and the control and thinned plots of the regionwide thinning study.

$$G_2 = G_1^{Hd_1/Hd_2} \exp\{ [G_1/G_t]^{b_0} b_1 S^{b_2} TR[1 - Hd_1/Hd_2] \} \quad (4)$$

where

Hd_1, Hd_2 = dominant stand height (ft.) at age 1 and age 2, respectively
G_1, G_2 = loblolly pine basal area (sq. ft./ac) at Hd_1 and Hd_2, respectively
S = site index (ft., base 25)
G_t = total basal area including hardwoods (sq. ft./ac) at Hd_1

$$TR = G_a / G_b^{\,b_3(Hdt/Hd_2)}$$

G_a = basal area after thinning
G_b = basal area before thinning
Hdt = dominant height at time of thinning
b_0, b_1, b_2, b_3 = parameters.

Equation (4) has the following basic properties:

1. $G_2 = G_1$ when $Hd_2 = Hd_1$
2. Better sites will produce more basal area at a faster rate than poorer sites.
3. Denser stands produce basal area faster than less dense stands.
4. Hardwood competition reduces the rate of pine basal area production.
5. Basal area development of a thinned stand will approach the basal area of a similar unthinned stand.

Equation (4) was fitted to the data with and without specifiying levels of hardwood competition (with and without estimating b_0). Parameter estimates and fit statistics are shown in Table 9.

Table 9. Parameter estimates and fit statistics for Equation (4) fitted to the untreated control plot observations of the regionwide fertilizer study and the thinned and control plots of the regionwide thinning study data.

	Percent Hardwood Basal Area Specified		Percent Hardwood Basal Area Not Specified	
Parameter	Estimate	Asymptotic Std. Error	Estimate	Asymptotic Std. Error
b_0	0.1049	0.0245		
b_1	4.6064	0.2274	4.4390	0.2164
b_2	0.0548	0.0120	0.0632	0.0118
b_3	-0.0759	0.0102	-0.0693	0.0101
	MSE = 30.9		MSE = 32.2	

Dominant height / site index

Because many stand dynamic relationships are influenced by site quality, an appropriate dominant height/site index equation is a central component equation of most growth and yield models. As a base model, we examined several candidate models and found the following model form presented by McDill and Amateis (1992) to be most suitable:

$$H_2 = \frac{M}{1 - \left(1 - \frac{M}{H_1}\right)\left(\frac{A_1}{A_2}\right)^{\gamma}} \qquad (5)$$

where: A_1, A_2 = age (years)
H_1, H_2 = average height of dominant and codominant trees (ft.) at A_1 and A_2
M, γ = parameters to be estimated.

Equation (5) was fitted using the dominant height data from the untreated control plots. Table (10) presents parameter estimates and fit statistics.

Table 10. Mean squared error, parameter estimates and asymptotic standard errors for Equation (5) fitted to the untreated control plot data.

Parameter	Estimate	Asymptotic Standard Error
M	147.22	7.34
γ	1.1741	0.0322
	MSE = 2.89	

By substituting a site index value, S, for H_1 at A_1 and solving for S, Equation (5) can be used to estimate site index from dominant height:

$$S = \frac{M}{1 - \left(1 - \frac{M}{H}\right)\left(\frac{A}{25}\right)^{\gamma}} \qquad (6)$$

where S = site index (base age 25), H = dominant stand height at A.

Basal area prediction

When the basal area for an existing stand is not available or when initiating a plantation from young ages before crown closure, FASTLOB generates an estimated basal area from:

$$\ln(BA) = b_0 + \frac{b_1}{A} + b_2 \ln(Hd) + b_3 \ln(N) \qquad (7)$$

when the percent hardwood basal area is not specified, and

$$\ln(BA) = b_0 + \frac{b_1}{A} + b_2 \ln(Hd) + b_3 \ln(N) + b_4 PHDWD \qquad (8)$$

where: PHDWD = percent of total basal area in hardwoods and all other variables are as previously defined, when the percent hardwood basal area is specified.

Table 7. Mean squared error, parameter estimates and asymptotic standard errors (in parentheses) for Equations (7)-(8) fitted to the untreated region wide data.

Equation	b_0	b_1	b_2	b_3	b_4	MSE	R^2
8	-1.7525 (0.1677)	-1.5902 (0.3747)	0.9880 (0.2738)	0.4522 (0.0122)		0.0195	0.76
9	-1.3112 (0.1706)	-2.6259 (0.3828)	0.9201 (0.0277)	0.4356 (0.0120)	-0.6763 (0.0736)	0.0186	0.77

Total and merchantable yield prediction

Total and merchantable yield prediction equations in FASTLOB are used for determining the wood content of stands to any merchantable limit. The approach presented by Amateis et al. (1986) was used to develop a set of equations for predicting total and merchantable stand yield to any desired top or diameter threshold merchantability limit. Recognizing that thinning alters stem volume and taper relationships, separate coefficients were obtained for unthinned stands and for thinned stands using the volume equations of Tasissa et al. (1997) to generate stand-level yields from the plot tree data.

While fertilization can affect stem volume and taper, no volume equations are currently available for fertilized loblolly pine trees. Therefore, FASTLOB does not contain separate stand-level yield equations for fertilized plantations. The form of the total yield equation in FASTOLOB is:

$$\ln Y = b_1 + b_2(1/A) + b_3 \ln(S) + b_4(H/A) + b_5(A \ln(N)) + b_6 \ln(BA) \tag{9}$$

where Y = total ib or ob volume (ft^3 /ac)
b_1, - b_5 = parameters to be estimated
and all other variables are as previously defined.

Equation (9) was fitted separately to the unthinned and thinned plot data. In accord with the restrictions noted by Tasissa et al. (1997), the coefficients for thinned stands are used only for stands where at least 30 percent of the total basal area was removed during thinning and where the thinning occurred at least three years prior to the current age.

For estimating merchantable yields to any diameter class threshold or top diameter limit, a stand-level volume ratio equation was formulated:

$$Y_m = Y \exp\left\{ b_1\left(t/\bar{D}\right)^{b_2} + b_3 N^{b_4}\left(d/\bar{D}\right)^{b_5} \right\} \tag{10}$$

where Y_m = merchantable cubic foot volume (ob or ib to top ob)
t = top diameter limit (in.) ob.
d = threshold diameter limit (in.)

$\overline{D}$ = quadratic mean dbh (in.)
$b_1 - b_5$ = parameters to be estimated
and all other variables are as previously defined.

Equations (9) and (10) were fitted to the ob volumes to a top diameter ob limit for the thinned and unthinned plot data. Table (8) presents parameter estimates and fit statistics for Equations (9) and (10).

Table 8. Parameter estimates and standard errors (in parentheses) for Equations (9) and (10) fitted to the thinned and unthinned plot data.

Parameter	Equation (9) ob	Equation (10) ob
	------Unthinned------	
b_1	0.9835 (0.0734)	-0.9497 (0.0058)
b_2	-7.4058 (0.1961)	4.1377 (0.0263)
b_3	0.4200 (0.0209)	-0.7312 (0.0266)
b_4	0.2297 (0.0089)	-0.0970 (0.0061)
b_5	0.0037 (0.0001)	5.5520 (0.0158)
b_6	0.9473 (0.0058)	
MSE (R^2)	0.001 (0.99)	55562 (0.98)
	------Thinned------	
b_1	1.7048 (0.0547)	-1.1659 (0.0049)
b_2	-11.7628 (0.1743)	4.6249 (0.0172)
b_3	0.3154 (0.0163)	-1.2564 (0.0267)
b_4	0.2903 (0.0072)	-0.1920 (0.0038)
b_5	0.0029 (0.0001)	6.7378 (0.0115)
b_6	0.9269 (0.0040)	
MSE (R^2)	0.0007 (0.99)	26903 (0.98)

For obtaining cordwood volume outside bark to a 4-inch outside bark top, the cubic feet of wood and bark per standard cord conversion factors of Burkhart et al. (1972) were used. International ¼-inch, Scribner and Doyle equations (Burkhart et al., 1987) were used to compute board-foot volumes by diameter class for the sawtimber quality trees greater than 7.5 inches dbh to a 6-inch top dib in the region-wide thinning study. Cubic foot volumes for the same trees were computed and the average ratio of board-foot to cubic foot volume outside bark by diameter class was obtained. These ratios allow conversion of cubic foot volumes to board-foot volumes by diameter class. For obtaining green tons outside bark to a 4-inch outside bark top, the green weight equations from Burkhart et al. (1972) were used to compute green weight by diameter class. Then the average ratio of green tons to cubic foot volume outside bark by diameter class was determined. These ratios allow conversion of cubic foot volumes to board-foot volumes and green tons by diameter class. Using this ratio method ensures that no matter how the stand is merchandised, the sum of the volume components will be equivalent to the total cubic foot yield production.

In a similar way, topwood cord volume for the sawtimber quality trees greater than 7.5 inches dbh was computed using the topwood prediction equation in Burkhart et al. (1972) Cubic foot volume between the 6-inch and 4-inch top diameters outside bark was computed and an average cubic-foot to cord conversion factor for topwood determined for each diameter class.

The proportion of pulpwood and sawtimber volume by diameter class was assumed to be the same as the proportion of trees in these product classes. Therefore, the product proportions of Burkhart and Bredenkamp (1989) can be applied. Table 9 presents the sawtimber product proportions and all volume conversion factors used in FASTLOB.

Table 9. Sawtimber proportions and product conversion factors by diameter class for cordwood, green tons and board-foot volumes.

Dbh Class	Cubic ft./cd	Topwood Cubic ft./cd	Green tons/cu. ft. ob	Proportion sawtimber volume	Int. ¼ board-ft/cu. ft. ob	Scribner board-ft/cu. ft. ob	Doyle board-ft./cu. ft. ob
5	84	0	0.0252	0	0	0	0
6	85	0	0.0261	0	0	0	0
7	87	0	0.0266	0	0	0	0
8	90	54	0.0270	0.488	2.63	2.47	2.35
9	91	57	0.0272	0.726	3.25	3.07	2.39
10	92	61	0.0274	0.837	3.72	3.49	2.45
11	93	64	0.0275	0.900	4.08	3.78	2.59
12	94	67	0.0275	0.937	4.36	3.97	2.81
13	95	70	0.0276	0.960	4.58	4.09	3.06
14	95	73	0.0276	0.975	4.76	4.17	3.33
15	95	74	0.0277	0.984	4.89	4.22	3.58
16	95	77	0.0277	1.0	5.03	4.27	3.91
17+	95	79	0.0277	1.0	5.16	4.29	4.28

MODEL DEVELOPMENT – RESPONSE TO FERTILIZER TREATMENTS

Fastlob incorporates response functions for midrotation fertilizer applications. The RW-13 data provided the foundation for the response models developed here. However, the model forms were contrived in order to (1) reflect response to a wider set of initial stand conditions than reflected in the RW-13 study, (2) reflect expected response to multiple fertilizer treatments, and, (3) provide reasonable results for fertilization of thinned stands . The following sections provide information about the parameterization and behavior of the models.

Fertilizer response functions for dominant height and basal area

Equations which model the effect of nitrogen (N) and phosphorus (P) fertilization on loblolly pine plantations were incorporated into FASTLOB. These equations are response functions relative to a control for dominant height and basal area. The response models in FASTLOB reflect the following general relationships:

1. Increasing amounts of N produce a greater response but at a decreasing rate. That is, increasing the amount of N by 100 lbs/ac from 100 to 200 lbs/ac produces a greater relative response than from 200 to 300 lbs/ac.

2. The amount of P applied is not as important as whether it's applied. Thus, in FASTLOB, P is a "switch" – either yes or no.

3. Adding P alone has a relatively small effect on dominant height and basal area response for these sites. Poorer sites have a greater response to P than better sites.

4. The effect of adding N and P together is considerably greater than either alone.

5. General site conditions, as expressed by site index, affect response. Poorer sites, in general, will exhibit a greater response to fertilization than better sites.

6. For basal area the response above the unfertilized control reaches a maximum at some point after fertilization and then diminishes (Type C response). The time to maximum response and the total duration of response are influenced by the amount of N and whether P is applied.

7. For dominant height, N gives a Type B response, and P alone gives a small Type A response.

8. Once P has been applied, its effect persists for the rotation.

9. Basal area at time of fertilization has a positive effect on basal area response up to some maximum. Thereafter it is unclear what effect, if any, basal area will have on response. For FASTLOB, basal areas at time of treatment above 90 ft^2/ac will not induce either more or less response. That is, in FASTLOB the same maximum response will be achieved on any given site at all basal areas above 90 ft^2/ac.

The following dominant height response model for stands where N or N plus P has been applied was developed and parameterized using the nitrogen alone and nitrogen plus phosphorus plots in the Regionwide 13 data:

$$R = \left\{(b_0 + (D_1 b_1))\ln(1 + N) + D_2 (S/10)^{b_2}\right\}\tanh(b_3 Z) \qquad (11)$$

where: R = response above the control
N = nitrogen (lbs/ac)
S = site index (ft at age 25)
Z = years since fertilization
D_1 = 1 if phosphorus applied, 0 otherwise
D_2 = 1 if nitrogen applied, 0 otherwise
tanh = hyperbolic tangent function
$b_0 - b_3$ = parameters

The following dominant height response model for stands where P alone has been applied was developed and parameterized using the phosphorus only treated plots in the Regionwide 13 data:

$$R = S^{b_0} Z \qquad (12)$$

where: b_0 = parameter and all other variables are as previously defined.

The following model estimates the basal area response to fertilizer treatments:

$$R = \left\{(1 - \exp(b_0 N))(B/10)^{b_1} \exp(b_2 B/10)(S/10)^{b_3}\right\} Z^{b_4} \exp((b_5 + D_1 b_6) Z) + D_2 (S/10)^{b_7} Z \qquad (13)$$

where: R = response above the control
N = nitrogen (lbs/ac)
B = stand basal area at time of application (ft^2/ac)

S = site index (ft at age 25)
Z = years since fertilization
D_1 = 1 if phosphorus applied, 0 otherwise
D_2 = 1 if only phosphorus applied (no nitrogen), 0 otherwise
$b_0 – b_7$ = parameters

Table 10 presents the parameter estimates and fit statistics for Equations (11) - (13).

The Regionwide 13 data indicate that mortality has been little affected by fertilization over most of the study. For the installations that have reached 8 years since treatment, it appears that survival has been somewhat affected by treatment but not as significantly as dominant height and basal area. The minimal effect of treatment on survival may be due to the requirement that stands selected for this study not have more than 120 ft^2/ac of basal area. Thus, stands had not yet begun self-thinning at time of plot establishment. Also, suppressed trees in approximately half the installations were removed at time of plot establishment (NCSFNC 1997). Given these stand conditions at establishment, most of the additional mortality on the treated plots has been attributed to density dependent factors related to increased growth following treatment rather than factors directly related to treatment.

Table 10. Parameter estimates and standard errors (in parentheses) for Equations (11), (12) and (13) fitted to the Regionwide-13 fertilizer data.

Parameter	Equation (11)	Equation (12)	Equation (13)
b_0	0.1051 (0.0315)	-0.7113 (0.0464)	-0.0027 (0.00093)
b_1	0.3706 (0.0468)		2.4900 (0.4699)
b_2	-0.4122 (0.1482)		-0.2826 (0.0570)
b_3	0.1081 (0.0171)		-0.7944 (0.2532)
b_4	-0.7113 (0.0464)		1.7097 (0.2595)
b_5			-0.3703 (0.0514)
b_6			0.1706 (0.0192)
b_7			-1.4473(0.5889)
MSE (R^2)	2.92 (0.13)	2.46 (0.03)	51.8 (0.28)

MODEL TESTING

The models introduced above comprise a system for projecting the growth of loblolly pine plantations. Although each equation may perform well as a separate component, the entire system of equations must also be evaluated for predictive ability at the stand level.

Untreated baseline predictions

Ninety-nine plots from the regionwide thinning study that had survived through 5 remeasurements (a portion used to estimate model parameters) were loaded into the FASTLOB software and a 15-year projection was made from the first through the fifth remeasurement. After 15 years, the mean observed total cubic feet per acre was 4875. The mean predicted total cubic feet per acre was 4678. A percent residual, defined as 100*(observed-predicted)/observed, was calculated for each plot. The mean percent residual for stand volume was 0.6% (Std. Dev. = 26).

Predictions for fertilized stands

Using the starting stand conditions at plot establishment for the 24 RW-13 sites that had reached 8 years following fertilization and the 14 sites that had reached 10 years following fertilization, projections were made and a percent residual computed for each site at each remeasurement following fertilization. Table 11 shows that for these once-fertilized stands there is generally close agreement between observed and predicted values.

Table 11. Mean percent residual (100*(observed-predicted)/observed) of total volume by treatment at 2, 4, 6, 8, and 10 yr after fertilization for the loblolly pine midrotation fertilizer study sites that had reached at least 8 yr from treatment.

		Growing Seasons After Fertilization*				
N (lbs/ac)	P	2	4	6	8	10
		Unfertilized control				
0	No	-8.0	-4.4	-1.7	-6.2	-3.7
		Fertilizer treatments				
0	Yes	-7.6	-4.6	-1.3	-5.0	-2.2
100	No	-5.5	-4.6	-1.3	-6.4	-5.6
100	Yes	-5.2	-2.2	0.2	-5.1	-3.0
200	No	-6.5	-3.9	-1.4	-5.9	-6.9
200	Yes	-5.1	-1.8	0.9	-3.0	0.5
300	No	-6.5	-4.2	-1.4	-4.6	-3.0
300	Yes	-7.3	-3.0	0.4	-3.5	-2.1

*Number of observations is 24 for yr 2-8 and 14 for yr 10.

Predictions for thinned stands

Two hundred six plots from the regionwide thinning study which had survived through 5 remeasurements were loaded into the FASTLOB software and a 15-year projection was made from the first through the fifth remeasurement. At twelve years after treatment a second thinning was applied to 90 plots. Output was obtained at each remeasurement over the 15-year period. Table 12 shows the mean total cubic foot volume per acre and the mean percent residual, defined as 100*(observed-predicted)/observed, for each plot at each remeasurement.

Table 12. Mean total cubic foot volume and mean percent residual (defined as 100*(observed-predicted)/observed)) for 206 plots at each remeasurement over 15 years (std. dev. in parentheses).

	Years after establishment					
	3	6	9	12	15 one thin	15 two thin
Observed	1752 (758)	2294 (807)	2886 (879)	3514 (970)	4229 (1135)	2664 (669)
Percent resid.	2.6 (12.4)	-1.5 (15.7)	1.2 (17.0)	4.5 (17.7)	5.6 (18.4)	2.7 (9.3)

Sensitivity analyses

An extensive set of stand scenarios was specified and FASTLOB runs were conducted to test the sensitivity of the models to initial stand conditions, amounts and timing of fertilizer treatments, and multiple fertilizer treatments. Results of these tests may be obtained from the authors in the form of Excel spreadsheets that may be examined and modified by interested users.

APPLYING FASTLOB

FASTLOB can be used for a variety of purposes including inventory updating, evaluating thinning, hardwood control and fertilization treatments and as input to management decisions. The simulation test results show that the growth models in FASTLOB provide reasonably precise stand-level predictions when used as an integrated model system. Consequently, the FASTLOB model system should be suitable for predicting yields of unthinned, thinned and fertilized loblolly pine plantations. The following should be kept in mind by those applying the model:

- The data used to develop all component equations for FASTLOB come from loblolly pine plantations growing across much of the range of the species including both the Coastal Plain and Piedmont physiographic regions. As such the model reflects the general growing conditions and yield relationships found in the data. Growth and yield relationships exhibited in FASTLOB may, to a greater or lesser degree, mimic individual stands growing in specific localities.

- The data used to develop FASTLOB reflect site preparation techniques common to southern plantation forestry during the late 1950s to early 1970s. On average, five percent of the total basal area of these plantations was hardwood or non-planted pine basal area. When hardwood competition levels are not explicitly specified by the user, projections from FASTLOB will reflect these inherent site preparation and hardwood component characteristics.

- No plots from genetically improved plantations were used in the development of FASTLOB. If projections of genetically improved stands are to be made, appropriate adjustments to the input parameters must be made by the user.

- The light-thinned and heavy-thinned plots used in FASTLOB received primarily selection thinnings from below with a few plots first receiving a row thinning to provide access followed by a selection thinning. Thinnings were, for the most part, accomplished by research personnel using chain saws. Trees were selected for removal based on size, vigor, quality and spacing. All plots were thinned once and allowed to grow for twelve years. Then, 90 plots received a second thinning and grew for 3 years. Long-term projections for twice-thinned stands are not available.

- The fertilizer response functions in FASTLOB were developed from the NCSFNC Regionwide 13 study. These permanent plots were fertilized one time at approximately age 13 with specific amounts of P and N and allowed to grow for eight years. A comprehensive sensitivity analyses suggests that FASTLOB provides acceptable estimates for one and perhaps two fertilizations. While the software allows as many as four midrotation fertilizer treatments, it is unclear whether multiple fertilizer applications will produce growth response that will be additive. At some point it is likely that factors other than nitrogen or phosphorus become limiting. Therefore, using FASTLOB to simulate multiple fertilizer treatments, especially at older ages, may not be appropriate.

- While FASTLOB can be used for evaluating multiple silvicultural treatments, users should be aware that the interactions between thinning and fertilization and between fertilization and hardwood control are not reflected in the data used to develop the component growth equations. Therefore, care must be taken when projecting stands where multiple silvicultural treatments have been applied.

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FASTLOB USERS MANUAL

Preface

The equations that comprise FASTLOB have been programmed into a dynamic linked library (DLL) for implementation with the GYST growth and yield software shell. Input data for FASTLOB and output results are displayed in the GYST spreadsheet views. The GYST-FASTLOB software provides a convenient way for users to implement the equations producing output that can be evaluated and ported to other Windows applications for additional analyses.

The GYST shell is available for $295 and the FASTLOB DLL for $100 by contacting:

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Installing GYST and FASTLOB

Before implementing FASTLOB, the GYST software shell must be installed like other Windows applications. Both FASTLOB and GYST are compatible with Windows 95, 98, NT and 2000. In order to execute FASTLOB, the Digital Visual Fortran run-time libraries must be installed. These can be obtained as a free download from the following web site: http://www.digital.com/fortran/dvf/redist.html

The following files are necessary to execute FASTLOB and must be copied into the same directory as the GYST software shell:

fastlob.dll	-executable containing the growth and yield equations
fastlob.dsc	-file containing column header and variable information. It is not to be altered by the user.
fastlob.txt	-text file that provides a brief online description of fastlob.
fastlob.err	-error message file. It is not to be altered by the user.
example.gst	-an example fastlob file for a quick tutorial

Initializing a plantation

The following user supplied input variables will initialize a plantation:

Stand number	-integer from 0 to 99999 (default = 0)
Drainage	-1=poor, no bedding (default=0)
Site index	-either site index or dominant height (not both) in ft.
Dominant height	-either site index or dominant height (not both) in ft.
Age	-stand age (required input from 1 to 35)
Number trees	-required input from 200 to 1200 trees/acre
Basal area	-optional input (ft^2/ac)

Percent basal area in hardwoods	-99=unknown and uses data average of about 5%. (This variable may be altered during interactive execution to simulate hardwood control.)
Log rule	-required input to obtain board foot predictions

Once inputs have been established, predicted values at initiation can be obtained by clicking the **I** (for Initialize) button on the toolbar. Existing stands from age 1 to 35 can be initialized. Predicted volumes can only be obtained for stands older than 4 years.

Multiple stands can be established and then initialized in the spreadsheet view – one stand per row of the spreadsheet view. This can be easily accomplished through the Windows clipboard.

Midrotation fertilization and thinning

FASTLOB can simulate the effects of multiple midrotation treatments of nitrogen and phosphorus fertilizations, and thinnings. Multiple treatment simulations can be scheduled at time of plantation initiation in a batch mode. Alternatively, a plantation may be grown to a desired age, basal area or dominant height and then the treatment(s) applied interactively.

FASTLOB can accommodate a maximum of four midrotation fertilizations scheduled at any time after age 4. Inputs for each of the fertilizations include the age of fertilization and the amount of nitrogen (lbs/ac) and whether phosphorus was applied (1=YES) or not (0=NO).

FASTLOB can accommodate a maximum of two midrotation thinnings scheduled at any time after age 4. The first thinning can be a row, low, or combination row/low thinning. Inputs include the age of first thinning, the row removal rate (entering a 5 simulates every fifth row removed, entering a 3 simulates every third row removed, etc.). The assumption for row thinning is that basal area, numbers of trees and volumes are removed proportionately across all diameter classes. The low thinning target residual can be expressed in terms of number of trees or basal area (but not both).

The second thinning must be a low thinning with a target residual expressed in terms of number of trees or basal area (but not both).

Projecting (growing) a plantation

Using the GYST shell, FASTLOB projections can be made for a specified number of years or to a target age, dominant height or basal area. To grow a plantation, input the desired variables in the proper columns of the Stand spreadsheet view. Then click the **G** toolbar button (or press <cntl G>. Options for displaying output intervals and projection targets are presented in dialog boxes.

Individual stands or groups of stands can be grown by highlighting appropriate rows of the stand level spreadsheet view and clicking the **G** toolbar button.

Output

Simulations using FASTLOB produce aggregate stand level yields in the stand level spreadsheet view. At each output age the stand level view displays predicted total cubic foot outside bark yield and three measures of merchantable yield: pulp cords and green tons for the 5-inch class to a 4-inch top diameter outside bark, and board feet for the 8-inch class to a 6-inch top diameter outside bark. At ages where thinning has occurred, the amount of volume removed in the thinning operation for each of these categories is shown.

A size class distribution breakdown of stand level yield can be obtained by highlighting the desired output row (a specified age for a particular stand ID) in the stand level view and clicking the **D** toolbar button. For each stand ID and age, a 1-inch diameter class breakdown of number of trees, basal area, cubic foot outside bark, cords, green tons, merchantable cords and board feet is displayed. The merchantable cords and board feet are mutually exclusive volumes. That is, the sum of these two columns are equivalent to the total merchantable volume of the stand for the 5-inch class to a 4-inch top diameter outside bark.

For ages where a thinning has occurred, the amount of removed and residual volumes by diameter class are also shown. The sum of the removed and residual volumes equals the before thinning volume.