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TAUYIELD: A STAND-LEVEL GROWTH AND YIELD MODEL FOR THINNED AND UNTHINNED LOBLOLLY PINE PLANTATIONS

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Abstract. A stand-level growth and yield model for thinned and unthinned loblolly pine plantations was developed using data collected from permanent remeasurement plots throughout most of the natural range of the species. The model was constructed around three dynamic equations which reflect height-age, survival and basal area development in thinned and unthinned plantations. A yield prediction system was developed which apportions total yield and total number of trees surviving into diameter classes so that merchantable yields for any portion of a stand can be obtained. Performance of the component equations as well as the overall model was examined using independent data from thinned and unthinned stands. Test results indicate the model should provide reliable estimates of stand-level yields for many stand conditions and thinning regimes.

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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. One important silvicultural tool available to managers is mid-rotation thinning. 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. Therefore, there is a need for growth and yield models which can reliably forecast future yields for either thinned or unthinned stand conditions. Such models should be useful to foresters, silviculturalists, researchers and others charged with managing loblolly pine plantations.

In the early 1980s, Amateis et al. (1984) developed a stand-level growth and yield model for unthinned loblolly pine plantations based on initial measurements from a large region-wide set of permanent plots. Subsequently, the thinned and unthinned permanent plots established in 1980-1982 have been remeasured four times. This enhanced data base provides an opportunity to develop an improved stand-level model (TAUYIELD) based on thinned and unthinned dynamic relationships.

The objective of this work was to produce a growth and yield model which could be used for a variety of purposes including inventory updating, harvest scheduling, predicting wood yields for different stand conditions and evaluating the effects of thinning on stand dynamics and wood production. In order to accomplish this objective, two criteria were established to guide the model development process. The first was that predictive ability of the model would be of primary concern. That is, both individual component equations and the model as a whole should predict well for the development and independent testing data available. The second criterion was that component equations and the overall model should reflect our understanding of how thinned and unthinned plantations grow and develop through time. Including such biological and physical precepts in the model development process increases the likelihood that the model will perform well for stand conditions outside the range of the data used to develop the model. This makes the model more reliable when applied to other data and when extrapolated to conditions beyond those reflected in the development data. It also provides a more robust framework for any future enhancements such as the inclusion of other silvicultural treatments.

The following sections summarize data sources, modeling rationale and model performance for TAUYIELD, a stand-level growth and yield model for thinned and unthinned loblolly pine plantations.

DATA

Several sources of data were used for model development and testing. The following sections summarize the stand characteristics associated with each.

Unthinned Coastal Plain

Stand data were available from loblolly pine plantations established on cutover sites in the Coastal Plain areas of Alabama, Florida, Georgia, North Carolina and South Carolina. Seven hundred twenty nine permanent remeasurement plots were established in these plantations at age two and remeasurements occurred at three-year intervals to age 14, 17 or, in some cases, to age 20.

Site preparation methods prior to plantation establishment consisted primarily of chop, burn, disk, bed, KG or some combination of these treatments. A general soil drainage class (poor, moderately well or excessive) was known for each site. Site index values averaged 65 feet (std. dev. = 13.0 feet). Table 1 presents average survival and basal area values for selected ages in the data set.

Table 1. Stand summary statistics for unthinned Coastal Plain data at ages 2, 8 and 14 (standard deviations in parentheses).

Variable	Age		
	2 (n=831)	8 (n=722)	14 (n=116)
Number surviving per acre	548 (310)	472 (277)	378 (252)
Basal area (sq. ft./ac.)	9.2 (11.4)	37.3 (25.7)	98.0 (46.6)

Thinned and unthinned region-wide

Stand data were available from loblolly pine plantations established on cutover sites from much of the natural range of the species. One hundred eighty-six plot locations were established during 1980-1982 dormant seasons in 8- to 25-year-old (mean=15) plantations in the southern Coastal Plain and Piedmont. Site and stand conditions at plot establishment for these locations were summarized by Burkhart et al. (1985). At each location, three plots, comparable in initial site index, number of trees and basal area per acre, were established: (1) an unthinned control plot, (2) a lightly thinned plot from which approximately one-third of the basal area was removed, and, (3) a heavily thinned plot from which approximately one-half of the basal area was removed. Thinnings were primarily from below removing smaller, poorly formed and slower growing trees. However, the considerations of spacing and stem quality dictated the removal, in some cases, of selected larger trees.

Five measurements, one taken at plot establishment and four subsequent remeasurements, have been completed with a measurement interval of three years. While some plots have been abandoned during this period due to heavy insect attacks, hurricane damage, or other problems, observations over the twelve-year period were obtained for most of the plots. One site index value was determined for each plot using the measurement closest to index age (25 years). Dominant height was defined as the average height of the dominant and codominant trees. The site index equation from Burkhart et al. (1987), which was developed from these data, was used to compute site index. Site index ranged from 40 to 85 feet (mean = 60; std. dev. = 8.5). Table 2 summarizes other pertinent stand conditions for these plots at establishment and twelve years later.

Table 2. Summary statistics of plot characteristics for unthinned, light-thin and heavy-thin Coastal Plain and Piedmont plots at establishment and at the fourth remeasurement.

	Unthinned		Light-thin		Heavy-thin	
Variable	Establishment	12 years	Establishment	12 years	Establishment	12-years
Age (years)	15 (4)	27 (4)	15 (4)	27 (4)	15 (4)	27 (4)
Trees/ac.	567 (137)	440 (105)	338 (77)	311 (69)	257 (63)	241 (59)
Basal area/ac	110 (35)	151 (28)	77 (25)	127 (23)	63 (21)	113 (23)
Percent basal area left	---	---	0.73 (0.07)	---	0.59 (0.08)	---

Thinned-stand data sets

Three small thinned-stand data sets were available for testing basal area and survival predictions from the model and for examining basic stand development relationships. The first data set consisted of nineteen operationally thinned plots in the Coastal Plain area of Virginia. All plots received a heavy thinning from below at age 20 or 21. Table 3 summarizes the pre- and post-thinning stand conditions as well as stand conditions five years after thinning.

Table 3. Stand summary of mean conditions (standard deviations in parentheses) at plot establishment and five years later for nineteen operationally thinned plots in the Virginia Coastal Plain.

Variable	Before thin	After thin	Five years later
Site index	57.5 (3.3)	---	---
Basal area (sq.ft/ac)	126.9 (19.2)	60.8 (12.7)	81.5 (17.6)
Number trees/ac	528 (65)	194 (36)	194 (36)

A second small data set consisted of eighteen paired plots, half of which were unthinned and the other half thinned to a residual basal area close to that of the unthinned plots. Thinnings were from below at ages 18 or 23 and the plots were measured five years later. These plots, discussed by Bower and Baldwin (1993) are located near Merryville, Louisiana. Table 4 summarizes these data.

Table 4. Summary statistics of mean conditions (standard deviations in parentheses) for eighteen paired thinned and unthinned plots near Merryville, Louisiana.

	Unthinned		Thinned		
Variable	Establishment	Five years	Before thin	After thin	Five years
Site index (ft.)	65 (2.8)	---	67 (3.2)	---	---
Number trees/ac	348 (90)	317 (71)	---	321 (62)	302 (56)
Basal area (sq. ft/ac)	116.2 (12.9)	142.4 (12.0)	131.9 (15.8)	113.1 (8.5)	141.1 (9.5)

A third small data set consisting of eight tenth-acre plots, called the "Heywood Lease" study (Xydias, et al, 1982) was also available for model evaluation. At one location, there were two replications each containing an unthinned plot, a plot thinned to 300 trees per acre, a plot thinned to 200 trees per acre and a plot thinned to 100 trees per acre. Plots were established at age eleven and the site index was about 85 (feet at age 25). Remeasurements were collected at ages 12, 13, 15, 16,17, 20, 21, 22, 24, 25, 26, 27, and 29. Because the plot size was rather small and the two replications were quite similar, the two plots for each treatment were combined into one fifth-acre plot. Table 5 provides a summary of basal area and survival for each treatment at selected ages.

Although limited in size and scope, these data sets provided useful insights into how thinned and unthinned stands develop with regard to basal area and survival. They were also used as confirmation data sets to test models.

Table 5. Basal area and survival for each of four thinning treatments at plot establishment, five years, ten years and eighteen years after treatment for the Heywood Lease data.

	Treatment			
Variable	Unthinned	300 trees/ac	200 trees/ac	100 trees/ac
Number trees/ac				
Before thin	580	594	623	568
After thin	580	300	195	100
Age 16	475	290	195	100
Age 21	375	265	190	100
Age 29	275	250	190	100
Basal area (sq.ft/ac)				
Before thin	167	169	172	160
After thin	167	109	74	41
Age 16	200	141	108	71
Age 21	207	158	132	97
Age 29	207	191	176	138

MODEL DEVELOPMENT

This section provides a description of all component equations used in TAUYIELD and how each was developed. There are two subsections. The first describes the dynamic equations needed to project three critical stand parameters through time: dominant height, survival and basal area. The second section describes the yield prediction system for the model.

PROJECTION EQUATIONS

TAUYIELD was developed around three dynamic equations that project stand attributes into the future: height-age (site index), survival and basal area projection. Analyses of the region-wide thinning study data indicated that thinning affected all three of these dynamic stand attributes. In addition, the effect of the thinning appeared to be similar for these attributes. That is, the effect gradually increased from time of treatment to some maximum and then gradually diminished over time. Therefore, the thinning response function developed by Liu et al. (1995) was incorporated into each dynamic equation of the system. The general form of the function is:

$$T = \left(\frac{G_a}{G_b} \right)^{\frac{r[-(A-TA)^2 + k(A-TA)]}{A^2}} \qquad (1)$$

where: T = thinning response
G_a, G_b = stand basal area after and before thinning, respectively
A = stand age
TA = age of thinning
r, k = parameters to be estimated

Equation (1) has certain desirable biological properties. The first is that when no thinning has occurred, the before to after thinning basal area ratio is 1 which means T has no effect on the equation of which it is a part. Second, at time of thinning the response is also conditioned to be 1 which means there is no immediate response at the time of thinning. Third, response to thinning begins at zero and, depending on the magnitudes and signs of r and k, affects the equation into which it has been incorporated to an increasing degree up to some maximum effect and then diminishes over time. The duration of thinning response (in years) is determined by the value of the duration parameter, k. The rate parameter, r, is dimensionless and along with G_a , G_b, A and TA defines the shape of the response function. The first derivative of the exponential part of Equation (1) with respect to A-TA, the time elapsed since thinning, indicates that the maximum thinning response will occur at $\frac{k\,TA}{k+2\,TA}$ years after the thinning. Thus, age of maximum response depends on the age of the stand at time of thinning and the value of k. The following sections describe the development and evaluation of each of the dynamic component equations in TAUYIELD.

Dominant height / site index

An appropriate dominant height/site index equation is a central component equation of most growth and yield models. This is because many stand dynamic relationships are influenced by site quality. As a base model, we selected the site index equation developed by Amateis and Burkhart (1985) and formulated it in its untransformed configuration (Cao, 1993):

$$H_2 = e^{\ln H_1 (A_1/A_2)^{b_1} e^{b_2(A_2^{-1} - A_1^{-1})}} \qquad (2)$$

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
b_1, b_2 = parameters to be estimated.

Using the thinned and unthinned region-wide data, we examined dominant height growth relationships after thinning for the three treatments. Figure 1 shows the height growth for each 3-year period after thinning for the unthinned, light-thinned and heavy-thinned plots. It can be seen that over the first few years after treatment, the thinned plots produce less height growth than the unthinned plots. This differential seems to have reached a maximum before the second remeasurement (6 years after thinning) and gradually declines thereafter. By 12 years after thinning the unthinned and light-thinned plots have converged with the heavy-thin plots growing slightly more on the average. This height growth suppression

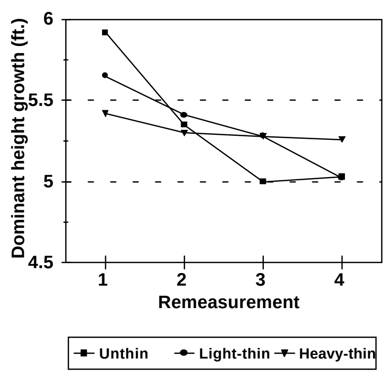

Figure 1. Mean dominant height growth by thinning treatment at each of four remeasurements (3, 6, 9 and 12 years after plot establishment).

following thinning has also been documented by other researchers (Ginn et al., 1991; Harrington and Reukema, 1983). In order to examine this effect more closely, Equation (2) was fitted using the dominant height data from thinned and unthinned plots. Then, Equation (2) was modified by incorporating the thinning response function in such a way that the path-invariant property of the function was maintained (Smith, 1994):

$$H_2 = e^{\ln H_1 (A_1/A_2)^{b_1} e^{b_2(T_2 A_2^{-1} - T_1 A_1^{-1})}} \qquad (3)$$

Equation (3) was also fitted using the thinned and unthinned plot data. Table (6) presents the fit statistics for each model and Figure 2 shows the mean residuals by plot and time since thinning for Equation (3).

Table 6. Mean squared error, parameter estimates and asymptotic standard errors (in parentheses) for Equations (2) and (3) fitted to the thinned and unthinned data.

Parameter	Equation (2)	Equation (3)
b_1	-0.0775 (0.0051)	-0.0525 (0.0055)
b_2	-1.9160 (0.0937)	-2.4007 (0.1039)
r	---	-0.7384 (0.1610)
k	---	12.878 (2.7719)
	MSE = 3.19	MSE = 3.00

Inclusion of the thinning response function in the dominant height growth equation reduced the error sum of squares by about six percent and produced a model more responsive to the effects of thinning on dominant height growth. Thus, Equation (3) was selected as the dominant height growth model for TAUYIELD. By substituting a site index value, S, for H_1 at $A_1 = A_I$ and solving for S, Equation (4) can be used to estimate site index from dominant height:

$$S = e^{\left(\frac{\ln(H_1)}{(A_I/A_1)^{b_1} e^{b_2(T_1 A_1^{-1} - T_I A_I^{-1})}} \right)} \qquad (4)$$

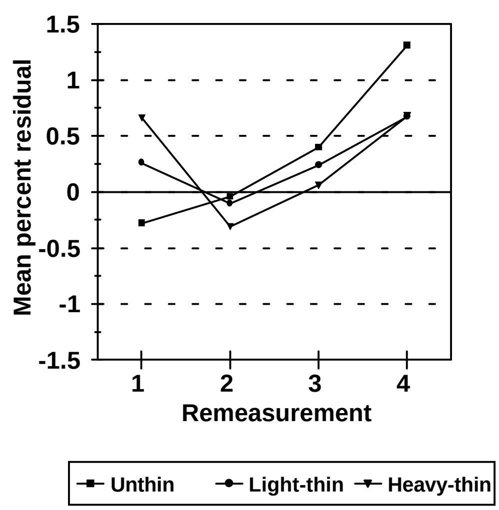

Figure 2. Mean percent residual ((obs-pred/obs*100) by thinning treatment at each of four remeasurements (3, 6, 9 and 12 years after plot establishment).

Survival

The second dynamic component of TAUYIELD is an appropriate set of survival equations which reflect survival patterns over the entire life of a plantation. We hypothesized that there are at least three distinct survival patterns found during the life of a plantation which must be recognized if the total survival pattern is to be modeled. The first pattern occurs during the first year after planting. Survival during the first year is highly variable and depends on many factors including care of the planting stock at the nursery and at the planting site, time of seedling storage, planting crew practices and first year climatic factors (such as the amount and distribution of rainfall during the growing season). The second easily identifiable survival pattern occurs from year one to some time beyond crown closure. Mortality during this period is random and can be attributed to factors other than intra-specific competition (although intra-specific competition, i.e. crown closure, may begin during this period). Important factors here which may influence survival include levels of inter-specific competition (both woody and herbaceous), stand establishment practices and certain stochastic elements such as insect, rodent or disease attacks.

The third survival pattern occurs from the onset of intra-specific competition induced mortality to rotation. During this period, the effects of intra-specific competition are the dominant forces affecting survival (although random mortality can still occur). Two important factors which must be considered when modeling survival during this period include stand density and site index. These factors will also affect when competition induced mortality begins (obviously, denser stands on better sites will enter this stage of stand development sooner). In addition, intermediate silvicultural treatments applied to plantations during this period may also affect survival patterns. Thinning, in particular, has a direct effect on stand survival because it alters the amount and distribution of the growing stock. It also changes the overall vigor of the stand by removing smaller, slower growing trees (if the thinning is from below) and providing additional growing space for the residual stand. Therefore, appropriate survival models for this period of intra-specific competition should be sensitive to natural changes in stand density due to self-thinning as well as artificial changes due to thinnings applied as silvicultural treatments.

TAUYIELD contains equations which can be used to predict and project survival for the second and third survival patterns just described. Due to the highly variable nature of first-year survival, it is doubtful that meaningful prediction equations can be developed for this period. However, if managers can provide a reasonable estimate of first-year survival based on their own data or experience, survival at year one can be specified. Then, the equations presented here can be useful for modeling survival over the remainder of the rotation for thinned and unthinned loblolly pine plantations.

<u>Pre-competitive model</u>

The model developed by Pienaar and Shiver (1981):

$$\ln N_2 = \ln N_1 + b_1 [A_2^{b_2} - A_1^{b_2}] \tag{5}$$

where 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 modeling survival in young stands. This model assumes that the relative mortality is density-independent and not affected by site index. During preliminary analyses using the young stand data there appeared to be differences in survival between stands established on poorly drained sites where there was no bedding prior to planting and the other drainage/site preparation areas.

In order to determine if separate b_1 and/or b_2 coefficients were needed for the poor drainage/no bedding regime, a full versus reduced model F-test was performed. Results showed that the b_1 coefficient was significantly different between the poor drainage/no bedding regime and all the other drainage/site preparation regimes. The b_2 coefficient, however, was not significantly different. Thus, the pre-competitive stand model was defined as:

$$\ln N_2 = \ln N_1 - [0.000997 + 0.000724\,D]\,[A_2^{2.0525} - A_1^{2.0525}] \qquad (6)$$

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 (6), 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 5 was -0.6 (std. dev. = 6.9) and at age 8 was -1.0 (std. dev. = 19). For the other regimes, the mean percent residual at age 5 was 0.2 (std. dev. = 4.0) and at age 8 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 (6).

	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

It can be seen that there were no obvious trends by stand density for these pre-competitive stands.

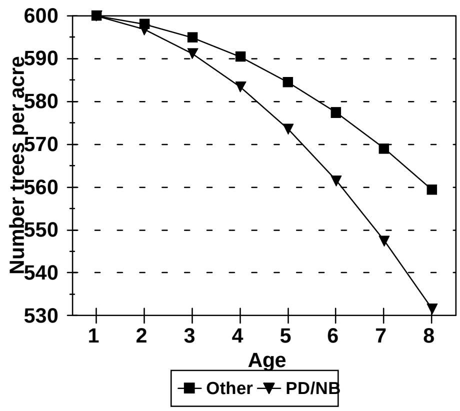

Figure 3. Young stand survival trajectories for 600 trees per acre surviving at age 1 using Equation (6) for the poor drainage/no bedding regime (PD/NB) and all other regimes.

Figure 3 shows example survival trajectories for a hypothetical stand with 600 trees per acre at age 1 growing on the two drainage/site-preparation areas.

Post-competitive model

Using the region-wide thinning study data, some preliminary analyses were conducted to determine if survival patterns differed for the three thinning treatments. Survival patterns for the twelve years following thinning indicated that for the same density class, there was less mortality in the thinned plots than the unthinned plots. By removing the smaller, less vigorous trees, survival rates were higher in the thinned plots. Therefore, we determined that an appropriate survival equation for these stands must incorporate a thinning response function in order to adequately reflect these survival differences. As a base survival model, we used the stand-level process model derived by Khil'mi (1957) from basic biophysical energetic relationships and discussed more recently by Amateis (1994):

$$N_2 = N_{min}(N_1/N_{min})^{e^{-\alpha(A_2-A_1)}} \qquad (7)$$

where

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
N_{min} = minimum asymptotic survival at the end of self-thinning
α = rate parameter.

Equation (7) can be reparameterized to reflect survival patterns for a wide range of site and stand conditions in thinned or unthinned plantations:

$$N_2 = N_{min}(N_1/N_{min})^{e^{b_1 S[T_2 A_2^{b_2} - T_1 A_1^{b_2}]}} \quad (8)$$

where:

S = site index

$$T_2 = I^{\frac{r((A_2-A_t)^2+k(A_2-A_t))}{A_2^2}}$$

$$T_1 = I^{\frac{r((A_1-A_t)^2+k(A_1-A_t))}{A_1^2}}$$

b_1, b_2, N_{min}, r, k = parameters to be estimated

and all other variables are as previously defined. Table 8 presents final parameter estimates and fit statistics for Equation (8). Figure 4 shows the mean residual at each remeasurement for the three thinning treatments.

Table 8. Parameter estimates and fit statistics for Equation (8) fitted to the Coastal Plain and Piedmont survival data.

Parameter	Estimate	Asymptotic Std. Error
b_1	-0.000000314303	0.00000005935
b_2	2.7331	0.1155
N_{min}	54.09	24.27
r	6.3133	1.2667
k	5.9648	3.3216

MSE = 325.1

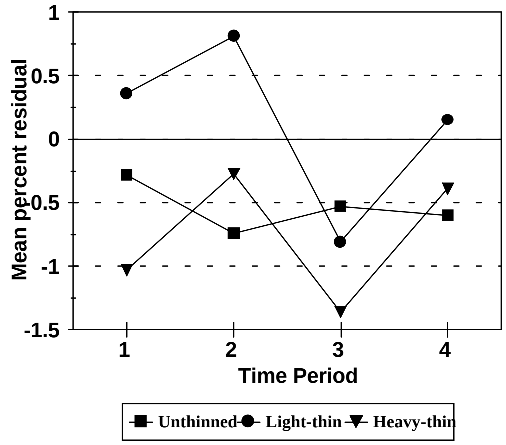

Figure 4. Mean percent residual ((obs-pred)/obs*100) for Equation 8 across time periods and thinning intensities.

One shortcoming of the model is that for certain combinations of thinning age and intensity it is possible to obtain survival predictions greater than the residual number of trees after thinning for short projection periods after thinning. This seems to only occur for heavy-thinned conditions (I typically less than 0.5) and when thinning age is young (typically less than 10 years). This anomaly occurs only for the first few years after thinning. When this occurs, TAUYIELD sets predicted survival equal to residual trees after thinning.

Basal area

In order to develop an appropriate basal area projection equation the relationship between basal area growth and certain stand characteristics was evaluated. Segregation of the unthinned plots in the region-wide thinning study data into site classes indicated that stands established on better sites produced more basal area at a faster rate than stands on poorer sites. Table 9 summarizes the basal area development for the unthinned plots with average site index (between 55 and 65) by 5-year age increments centered at 10, 15, 20, 25, 30 and 35.

Table 9. Simple statistics for basal area (sq. ft/ac) by age for the unthinned plots with an average site index (60 feet).

Age	Mean	Std. Dev.	Minimum	Maximum	Number plots
10	85.0	29.4	55.4	128.5	5
15	119.3	23.8	70.6	176.5	55
20	140.0	21.7	101.1	191.8	88
25	152.2	24.2	82.7	212.1	94
30	159.9	21.4	117.5	200.8	32
35	149.2	21.8	125.2	176.3	6

Table 9 shows increasing basal area to about age 30 and then a subsequent downturn. Only six plots have reached age 35 so it is difficult to determine the reliability of the downturn. However, other researchers have noted its occurrance especially in denser stands (e.g. Hafley, et al., 1982; Harrison and Daniels, 1988).

Comparing the mean tree growth rates for the unthinned, light-thinned and heavy-thinned plots indicated that the relative rate of basal area production for thinned stands was greater than for unthinned stands, at least for some period of time following thinning. This finding was corroborated by the Merryville data in which plots thinned to the same basal area as unthinned plots grew faster in basal area for at least the first five years after thinning (Bower and Baldwin, 1993). Relative rates of basal area production on the Heywood Lease plots also show that basal area growth rates in thinned stands exceed those of unthinned stands, all else the same.

While thinning can increase basal area relative growth rates, thinning reduces the maximum basal area carrying capacity. The Heywood Lease data show that 18 years after thinning, the thinned plots show no sign of converging to the same maximum basal area level as the unthinned plots. For the region-wide thinning study, after 12 years, the thinned plots have not achieved the same basal areas as the unthinned plots and do not indicate they will do so at least for typical rotation ages. It seems that thinning hastens basal area development to an asymptotic maximum that is less than that for unthinned stands. This may be due to the fact that thinning disrupts the normal stand development process making less efficient use of the available growing space. By removing trees in the thinning operation, growing space once occupied by pines can now be utilized by encroaching hardwoods and other vegetation. Regression analyses of pine basal area growth on understory basal area indicated that for many of these cutover sites the understory basal area had a significant negative impact on overstory basal area growth. This was the case for both the thinned and unthinned plots.

With these relationships in mind, a simple growth function was selected as a base model and then modified to incorporate these observed relationships. This general approach has been used by other researchers (e.g. Clutter and Allison, 1974; Clutter and Jones, 1980; Harrison and Daniels, 1988). For our base model we selected the growth function derived by McDill and Amateis (1992):

$$Z_2 = \frac{M}{1 - \left[1 - \frac{M}{Z_1}\right]\left(\frac{A_1}{A_2}\right)^{a}} \tag{9}$$

where: Z_1, Z_2 = size attribute
A_1, A_2 = age at time 1 and time 2
M = asymptotic maximum size parameter
a = dimensionless rate parameter

For our application, the size attribute selected for modeling was mean tree basal area. We incorporated site index into both the rate and asymptotic maximum parameter. Thus, basal area development on better sites will proceed at a faster rate to a greater asymptotic maximum than poorer sites. We incorporated the thinning response function into the model so that the rates of basal area production are modified by both the timing and intensity of thinning. This was done in such a way as to maintain the path invariance property of projection. Using dummy variables, we fit separate maximum basal area parameters to each of the thinning treatments. The light-thin and heavy-thin parameters were not significantly different from each other, but both were different from the unthinned maximum basal area parameter, which was significantly larger. For these data the basal area carrying capacity is not particularly sensitive to the timing or intensity of the thinning, but just to the fact that the stand has been thinned or not. The final basal area projection equation is:

$$G_2 = \frac{N_2 M}{1 - \left[1 - \frac{N_1 M}{G_1}\right]\left(\frac{A_1 T_1}{A_2 T_2}\right)^{a}} \tag{10}$$

where:

$$M = b_1 \left(\frac{G_a}{G_b}\right) \ln S$$

$$a = b_2 (\ln S)^{b_3}$$

$$T_1 = \left(\frac{G_a}{G_b}\right)^{\frac{-r[(A_1 - TA)^2 + k(A_1 - TA)]}{A_1^2}}$$

$$T_2 = \left(\frac{G_a}{G_b}\right)^{\frac{-r[(A_2 - TA)^2 + k(A_2 - TA)]}{A_2^2}}$$

and:

G_1, G_2 = basal area (sq.ft/ac) at A_1 , A_2 , respectively
N_1, N_2 = number trees/ac at A_1, A_2, respectively
G_a, G_b = basal area after and before thinning, respectively
S = site index (ft at age 25)
TA = thinning age
b_1 - b_3, r, k = parameters to be estimated

Equation (10) was fitted to the thinning study data and parameters were estimated using nonlinear least squares. Table 10 presents the parameter estimates and fit statistics.

Table 10. Parameter estimates and fit statistics for Equation (10) fitted to the thinning study data.

Parameter	Estimate	Asymptotic Std. Error
b_1	0.6579	0.0553
b_2	0.3346	0.0997
b_3	0.8710	0.2141
r	0.9121	0.1344
k	9.0648	1.7980
	MSE = 23.2	

Figure 5 shows the mean residuals by plot and time since thinning.

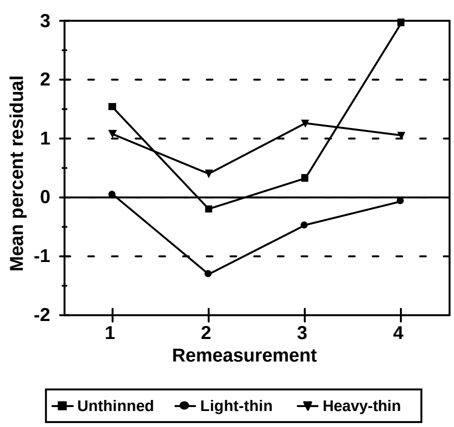

Figure 5. Mean percent residual ((obs-pred)/obs*100) for Equation (10) fitted to the thinning study data by thinning treatment and time since thinning (remeasurement).

Equation (10) was tested against the Merryville data, the thinned Virginia Coastal Plain data, the unthinned Coastal Plain data and the Heywood Lease data. For the Merryville data, the average percent bias ((observed-predicted)/observed)*100) was 5.0 percent. For the thinned Virginia Coastal Plain data the average percent bias was 3.5 percent. For the unthinned Coastal Plain data the average percent bias was 7.4 percent and for the Heywood Lease plots the average percent bias was -9.0 percent. Figures 6a-6d show the predicted and observed basal area development for the four Heywood Lease plots. The general overprediction trend for these plots may be due to the uncertainty of the site index estimate for these plots.

In order to project stand basal area, it is necessary to provide TAUYIELD with an initial basal area. When one is not available, the following basal area prediction equations can be used:

$$\ln G = b_0 + b_1(1/A) + b_2(\ln N) + b_3(\ln H) + b_4(\ln S) + b_5\left(\frac{N_t\, TA}{N_a\, A}\right) \qquad (11)$$

$$\ln G = b_0 + b_1(1/A) + b_2(\ln N) + b_3(\ln H) + b_4(\ln S) + b_5\left(\frac{G_t\, TA}{G_a\, A}\right) \qquad (12)$$

where: N_t = number of trees removed in the thinning operation
N_a = number of trees remaining after thinning
G_t = basal area removed in the thinning operation
b_0 - b_5 = parameters to be estimated

and all other variables as previously defined. Equations (11) and (12) are similar in form to that presented by Pienaar and Shiver (1986) and can be used to initialize basal area for thinned or unthinned stand conditions. When the stand is unthinned, N_t is zero and the last term of the equation has no effect on the prediction of basal area. For a thinned stand, predictor variables include the age of thinning and a measure of thinning intensity in terms of percent of basal area or percent of trees removed in the thinning operation. As the time since thinning increases, the effect of thinning on basal area diminishes. Table 11 presents the parameter estimates and fit statistics for Equations (11) and (12).

Table 11. Parameter estimates and fit statistics for Equations (11) and (12) fitted to the thinning study data.

	Equation (11)	Equation (12)
Parameter	Estimate (Std. Err.)	Estimate (Std. Err.)
b_0	-3.1166 (0.1479)	-3.2002 (0.1446)
b_1	-5.5462 (1.0438)	-5.6477 (1.0461)
b_2	0.5318 (0.0126)	0.5393 (0.0124)
b_3	0.7330 (0.0782)	0.7216 (0.0784)
b_4	0.5120 (0.0791)	0.5331 (0.0791)
b_5	-0.0663 (0.0117)	-0.0946 (0.0187)
	R^2 = 0.85 MSE = 0.0160	R^2 = 0.85 MSE = 0.0161

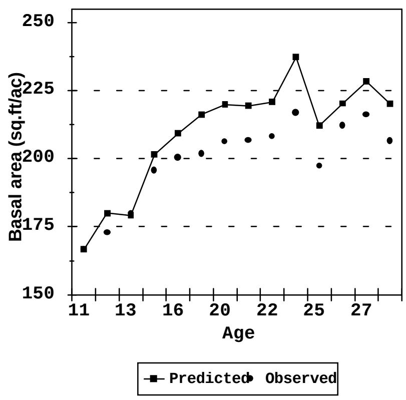

Figure 6a. Observed and predicted basal area development for the unthinned Heywood Lease plot.

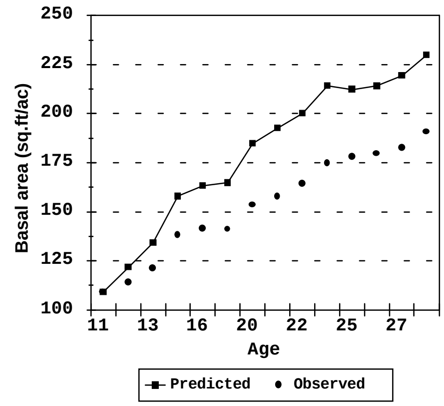

Figure 6b. Observed and predicted basal area development for 300-trees per acre Heywood Lease plot

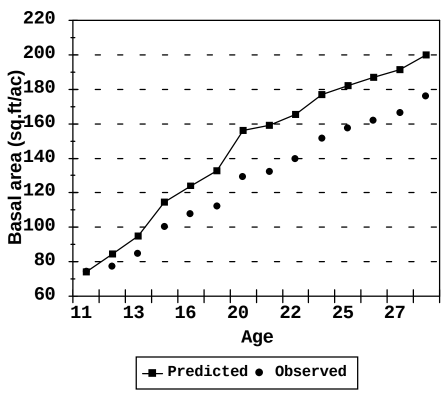

Figure 6c. Observed and predicted basal area development for 200-trees per acre Heywood Lease plot

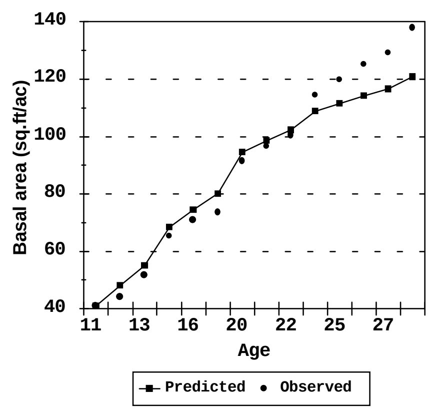

Figure 6d. Observed and predicted basal area development for 100-trees per acre Heywood Lease plot

YIELD PREDICTION

This section documents the yield prediction system developed for TAUYIELD. The general approach taken by Amateis, et al. (1986) was used as a base and then appropriate modifications made to predict yields and distributions for thinned as well as unthinned plantations. The following sections describe some investigations into yield relationships between thinned and unthinned stands as well as the development of component equations for the system.

Yield relationships

Total yields in cubic feet per acre were generated for each plot in the region-wide thinning study data using the tree volume equations developed from the same data and presented by Amateis and Burkhart (1987). Analyses of the data indicated that thinning has two major effects on the development of yield. The first is a negative effect on total cubic-foot yield production. That is, accelerated basal area growth of the residual stand does not compensate for the amount of lost productive capacity incurred by the thinning operation. At twelve years after thinning the standing yield on the thinned plots had not achieved that of the unthinned plots. (However, it is interesting to note that by twelve years after thinning the total production from the thinned plots which includes the volume harvested in the thin plus the standing volume has achieved the standing volume of the unthinned plots.) Figures 7 and 8 show cubic-foot volume outside bark growth over the twelve year period for the unthinned, light-thinned and heavy-thinned plots.

The second important relationship is that thinning shifts the diameter distribution to the right by causing even the largest diameter classes to grow faster than their unthinned counterparts. Thus the percentage of merchantable yield is increased by thinning. Figure 9 shows the average maximum diameter growth over the twelve year period for each thinning treatment.

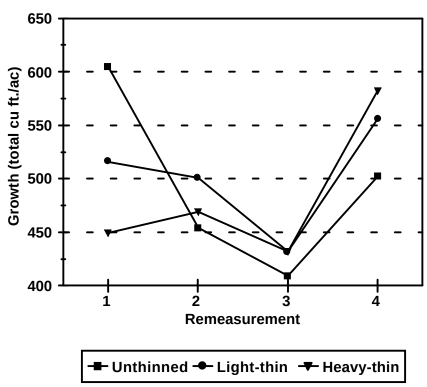

Figure 7. Average total cubic foot volume growth by thinning treatment for each 3-year remeasurement period.

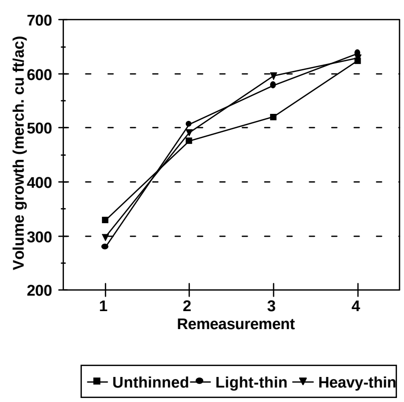

Figure 8. Average cubic foot volume growth of the 8-inch class to a 6-inch top diameter by thinning treatment for each 3-year remeasurement period.

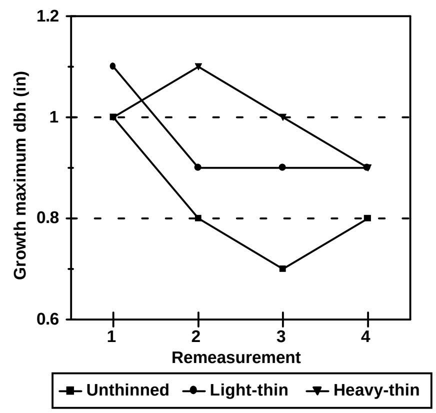

Figure 9. Average growth of the maximum dbh class by thinning treatment for each 3-year remeasurement period.

Total yield prediction

In order to predict total cubic foot volume, a multiple linear regression equation was formulated:

$$\ln Y = b_0 + b_1(1/A) + b_2(\ln S) + b_3(H/A) + b_4(A \ln N) + b_5(\ln G) + b_6\left(\frac{G_t\, TA}{G_a\, A}\right) \tag{13}$$

where: b_0 - b_6 = parameters to be estimated

and all other variables as previously defined. Equation (13) is formulated such that when the stand is unthinned, G_t is zero and the last term of the equation has no effect on the prediction of volume. For a thinned stand, predictor variables include the age of thinning and a measure of thinning intensity in terms of percent of basal area removed in the thinning operation. As the time since thinning increases, the effect of thinning on volume diminishes. Table 12 presents the parameter estimates and fit statistics for Equation (13) fitted to the total inside and outside bark volume data. All parameter estimates were highly significant (Pr >0.0001). The large positive value of b_5 relative to the small positive value of b_6 ensures that total yield for unthinned stands will be greater than for thinned stands. The fact that b_6 is positive ensures that lightly thinned stands will have more volume than heavily thinned stands.

Table 12. Parameter estimates and fit statistics for Equation (13) fitted to the total inside and outside bark cubic foot volume data of the thinning study.

	Outside bark	Inside bark
Parameter	Estimate (Std. Err.)	Estimate (Std. Err.)
b_0	1.15173 (0.0521)	0.98320 (0.05611)
b_1	-9.33466 (0.1480)	-13.011 (0.1594)
b_2	0.40538 (0.0156)	0.40357 (0.0168)
b_3	0.24032 (0.0067)	0.27825 (0.0072)
b_4	0.00321 (0.0001)	0.00251 (0.0001)
b_5	0.96176 (0.0042)	0.98736 (0.0045)
b_6	0.06322 (0.0041)	0.08764 (0.0044)
	R^2 = 0.99 MSE = 0.0009	R^2 = 0.99 MSE = 0.0011

Merchantable yield

In order to predict merchantable yield for any diameter class threshold or top diameter limit, a stand-level volume ratio equation was formulated. The thinning response function (Equation 1) was incorporated into the equation in order to model the effect of thinning on the prediction of merchantable yield:

$$Y_m = Y e^{b_1 (t/\bar{D})^{b_2} + b_3 N^{b_4} (d/\bar{D})^{b_5 T}} \qquad (14)$$

where Y_m = merchantable yield (cu ft./ac) for trees *d* inches and above to a *t* inch top diameter limit
Y = total yield (cu ft./ac)
N = number trees per acre
D = quadratic mean dbh (in)
t = top diameter limit (in)
d = threshold diameter limit (in)
T = thinning response function (Equation (1)):

$$T = \left(\frac{G_a}{G_b} \right)^{\frac{r[-(A-TA)^2 + k(A-TA)]}{A^2}}$$

b_1 - b_5 , r, k = parameters to be estimated

and all other variables are as previously defined.

Equation (14) is structured so that thinning affects the parameter b_5 causing the prediction of merchantable yield to be somewhat larger than for a corresponding unthinned stand. When there is no thinning, the b_5 parameter is unaltered. Equation (14) was fitted to the inside and outside bark merchantable yield data. Table 13 presents the parameter estimates and fit statistics for Equation (14).

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 1/4-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. 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 14 presents the sawtimber product proportions and all volume conversion factors used in TAUYIELD.

Table 13. Parameter estimates and fit statistics for Equation (14) fitted to the merchantable inside and outside bark cubic foot volume data of the thinning study.

	Outside bark	Inside bark
Parameter	Estimate (Std. Err.)	Estimate (Std. Err.)
b_1	-0.61101 (0.00399)	-0.64451 (0.00400)
b_2	3.37678 (0.02180)	3.31852 (0.02016)
b_3	-1.02117 (0.01580)	-1.11606 (0.01758)
b_4	-0.14372 (0.00268)	-0.16181 (0.00274)
b_5	5.55350 (0.01049)	5.58466 (0.01073)
r	-2.81786 (0.07767)	-2.74538 (0.07846)
k	20.6673 (0.29892)	20.79355 (0.31187)
	MSE = 29701	MSE = 20048

Table 14. Sawtimber proportions and product conversion factors by diameter class for cord wood and board-foot volumes.

Dbh class	Cubic feet per cord	Topwood cubic feet per cord	Proportion sawtimber volume	Int. 1/4 board-feet per cu. ft. ob	Scribner board-feet per cu. ft. ob	Doyle board-feet per cu.ft. ob
5	84	0	0	0	0	0
6	85	0	0	0	0	0
7	87	0	0	0	0	0
8	90	54	0.488	2.63	2.47	2.35
9	91	57	0.726	3.25	3.07	2.39
10	92	61	0.837	3.72	3.49	2.45
11	93	64	0.900	4.08	3.78	2.59
12	94	67	0.937	4.36	3.97	2.81
13	95	70	0.960	4.58	4.09	3.06
14	95	73	0.975	4.76	4.17	3.33
15	95	74	0.984	4.89	4.22	3.58
16	95	77	1	5.03	4.27	3.91
17+	95	79	1	5.16	4.29	4.28

Number of trees

Most users of TAUYIELD will be primarily interested in estimates of yield. However, sometimes it is useful to know how the yield is distributed with regard to number of trees and basal area. Equation (15) allows portioning of the total number of trees across the diameter distribution:

$$N_m = Ne^{-\Gamma^{(b_1 T/2)}(1+2/b_1 T)(d/\bar{D})^{b_1 T}} \qquad (15)$$

where: N_m = trees per acre larger than *d* inches
Γ = gamma function
T = thinning response function (Equation (1)):

$$T = \left(\frac{G_a}{G_b}\right)^{\frac{r[-(A-TA)^2 + k(A-TA)]}{A^2}}$$

b_1, r, k = parameters to be estimated

and all other variables are as previously defined.

By including the thinning response function as a modifier of b_1, the shape of the diameter distribution can be altered to reflect the effect of thinning on the distribution of trees and basal area. Equation (15) is conditioned such that the sum of both the number of trees and the basal area across the diameter distribution will equal the total stand values. Table 14 shows the parameter estimates and fit statistics for Equation (15) fitted to the thinning study data.

Table 14. Parameter estimates and fit statistics for Equation (15) fitted to the diameter distribution data of the thinning study.

Parameter	Estimate (Std. Err.)
b_1	4.9022 (0.01066)
r	-4.3136 (0.18004)
k	18.2586 (0.42730)
	MSE = 214.7

Height prediction

Although height-diameter relationships are not utilized within the TAUYIELD framework for computing volumes by diameter class, users may wish to view heights by dbh class as part of stand and stock table output. Analysis of height-diameter relationships in the thinning study data showed that thinning has a negative effect on total height development similar to that found for the dominant and codominant portion of the stand (at least for some period of time following thinning). The model:

$$h = b_1 H^{b_2} 10^{\left[\frac{b_3}{A} + \left(\frac{1}{D} - \frac{1}{D_{max}}\right)\left(b_4 + b_5 \frac{\log_{10} N}{A}\right)\right]} \qquad (16)$$

where: h = tree height (ft)
H = dominant stand height (ft)
D = tree dbh (in.)
D_{max} = maximum dbh (in.) in the stand
A = stand age
N = number of trees per acre
b_1 - b_5 = parameters to be estimated

incorporates the effect of thinning on height development (through the dominant height "potential" variable) and was found to be suitable for thinned and unthinned stands. Table 15 presents parameter estimates and fit statistics for Equation (16).

Table 15. Parameter estimates and fit statistics for Equation (16) fitted to the total height data of the thinning study.

Parameter	Estimate (Std. Err.)
b_1	1.4504 (0.00965)
b_2	0.9366 (0.00141)
b_3	-0.4413 (0.01268)
b_4	-1.3504 (0.00788)
b_5	2.8095 (0.05485)
	MSE = 9.94

MODEL RELATIONSHIPS

Unthinned

Figures 10a - 10f present some basic unthinned stand development relationships in TAUYIELD. In general stand developmental relationships proceed faster on higher sites planted at greater densities.

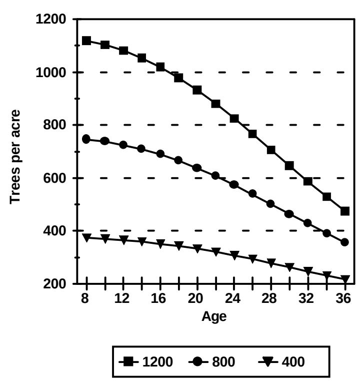

Fig. 10a. Survival trajectories for 1200, 800 and 400 trees per acre planted (site index 60).

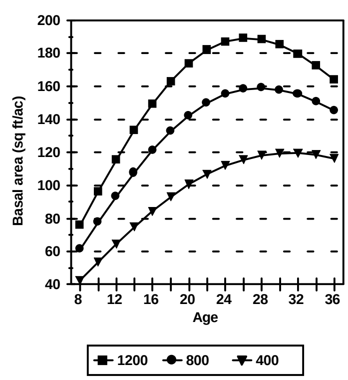

Fig. 10b. Basal area trajectories for 1200, 800 and 400 trees per acre planted (site index 60).

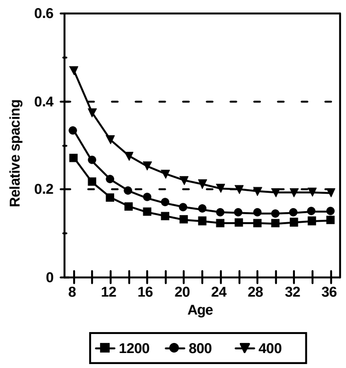

Fig. 10c. Relative spacing trajectories for 1200, 800 and 400 trees per acre planted (site index 60).

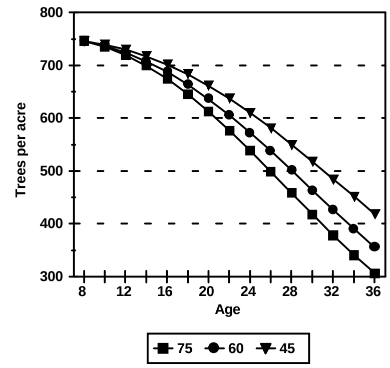

Fig. 10d. Survival trajectories for site index 75, 60 and 45 (800 trees per acre planted).

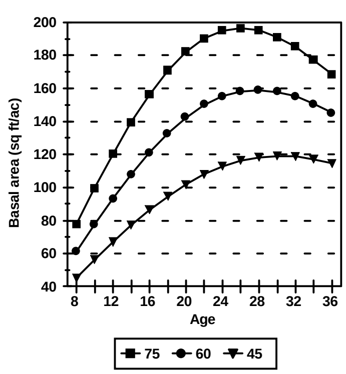

Fig. 10e. Basal area trajectories for site index 75, 60, and 45 (800 trees per acre planted).

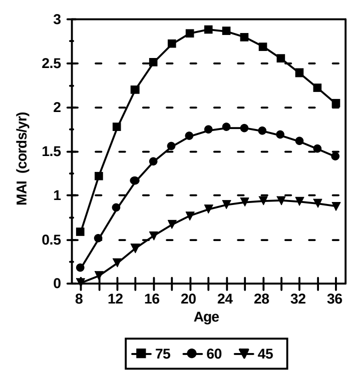

Fig. 10f. Mean annual increment (cords/year) for site index 75, 60, and 45 (800 trees per acre planted).

Thinned-unthinned

Figures 11a - 11e compare some basic stand development relationships for the average unthinned, light-thinned and heavy-thinned stand in the region-wide plantation data set. At plot establishment, the average stand conditions were age 15, site index 60, 566 trees per acre and 110 square feet per acre of basal area. Following thinning, the average light-thinned conditions were 315 trees per acre and 80 square feet per acre of basal area. For the average heavy-thinned stand, the mean residual number of trees per acre was 238 and the mean residual basal area was 65 square feet per acre. These figures present projections to age 35 which, for the average stand, is 20 years following thinning.

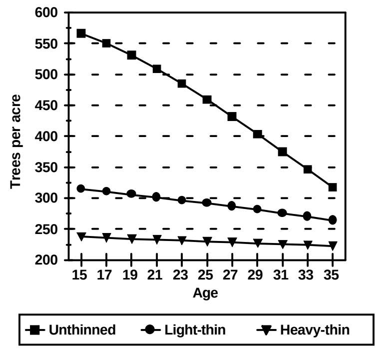

Fig. 11a. Survival trajectories (trees per acre) for the average unthinned, light-thin and heavy-thin stand.

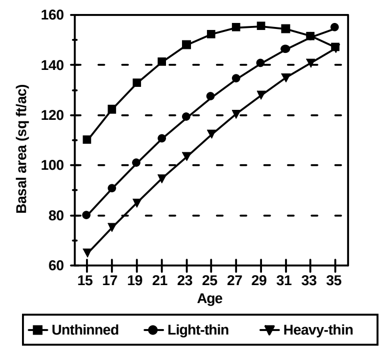

Fig. 11b. Basal area trajectories for the average unthinned, light-thin and heavy-thin stand.

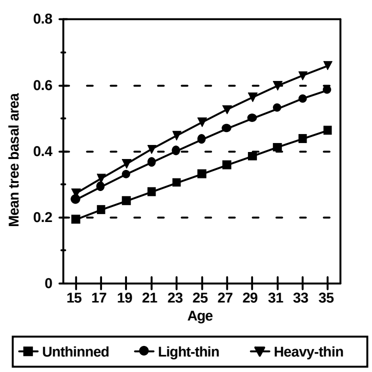

Fig. 11c. Mean tree basal area for the average unthinned, light-thin and heavy-thin stand.

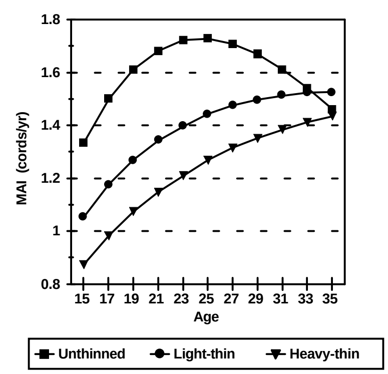

Fig. 11d. Mean annual increment (cords/year) for the average unthinned, light-thin and heavy-thin stand.

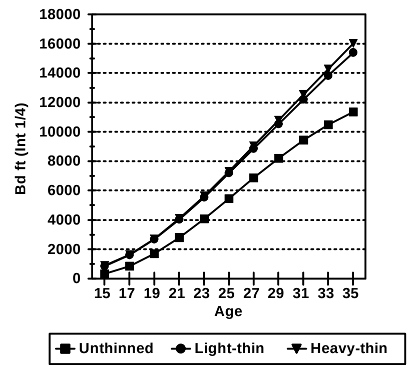

Fig. 11e. Board-foot production (Int. 1/4) for the average unthinned, light-thin and heavy-thin stand.

APPLYING TAUYIELD

TAUYIELD can be used for a variety of purposes including inventory updating, evaluating thinning as a silvicultural alternative and as input to management decision-making. As such it is a tool available to a variety of forestry professionals, land managers and practitioners. The following should be kept in mind by those applying the model:

- The data used to develop all component equations for TAUYIELD 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 is a "stand average" model reflecting general growing conditions and yield relationships found in the data. Growth and yield relationships exhibited in TAUYIELD may, to a greater or lesser degree, mimic individual stands growing in specific localities.

- The data used to develop TAUYIELD reflect site preparation techniques common to southern plantation forestry during the late 1950s to early 1970s. On the average, five percent of the total basal area of these plantations was hardwood or non-planted pine basal area. Thus, projections from TAUYIELD will reflect these inherent site preparation and hardwood component characteristics.

- No plots from genetically improved or fertilized plantations were used in the development of TAUYIELD. Application of TAUYIELD to these types of stands is inappropriate without adjustment of input values or modification of component equations.

- The light-thin and heavy-thin plots used in developing TAUYIELD 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. Applying TAUYIELD to stands thinned under different criteria, stands thinned multiple times, or making projections beyond twelve years after thinning may not be appropriate.

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TAUYIELD USER'S MANUAL

PREFACE

The following sections describe the DOS version of TAUYIELD, which predicts growth and yield of thinned and unthinned cutover site-prepared loblolly pine plantations. The user interface for TAUYIELD was primarily developed by Dr. Robert C. Weih, School of Forest Resources, University of Arkansas, Monticello, AR, 71656-3468 and originally used as the interface for PCWTHIN (Weih, et al., 1990). Certain changes have been made to the interface to accommodate specific requirements of the growth and yield models within TAUYIELD. The authors wish to acknowledge Dr. Weih's contribution and express appreciation for the use of his source code and user interface libraries.

To obtain a diskette containing TAUYIELD write to:

Biometrics Section
Department of Forestry
Virginia Tech
Blacksburg, VA 24061-0324

or send e-mail to:

ralph@vt.edu

To defer the cost of development, postage and handling, a charge of $80.00 will be made. Checks should be made payable to the Department of Forestry, Virginia Tech.

Although all software on the TAUYIELD diskette has been extensively tested and checked for accuracy and, to the best of our knowledge, contains no errors, neither Virginia Tech, the Department of Forestry, nor the authors claim any responsibility for any errors that do arise. The authors would appreciate having any errors or problems brought to their attention.

INTRODUCTION TO THE TAUYIELD SOFTWARE

Purpose of TAUYIELD

TAUYIELD is a computer program which can be used to predict the growth and yield of thinned or unthinned cutover, site-prepared loblolly pine plantations and do basic financial analyses based on those predictions. Predictions are obtained by choosing options from pop-up menus and responding to requests for stand level characteristics on a per acre basis. Results are displayed on the monitor in terms of trees per acre, basal area and various volumes per acre by one inch diameter at breast height (dbh) classes. The diameter distribution of the stand can be displayed as a 3D bar graph. At the end of a session, a stand summary and financial analysis of that stand summary can be displayed. If a parallel printer is attached to the computer system, all output on the screen can be printed. Also all screen output can be directed to a disk file in American Standard Code for Information Interchange (ASCII) format which can be imported into most word processors or spreadsheets. Options are available to initialize a plantation, initialize a thinned or unthinned plantation, thin a plantation using various methods, grow a stand, set values for board feet and cords, set the log rule and set minimum harvest volumes. Using TAUYIELD, the user can grow and compare, within a short period of time, numerous thinning strategies for different stands.

TAUYIELD files

TAUYIELD requires three files:

TAUYIELD.EXE (the executable file)
FIN.DAT (financial data file)

Running TAUYIELD

To run TAUYIELD, go to the drive and directory in which TAUYIELD is located and type TAUYIELD at the DOS prompt. TAUYIELD will be loaded and the program logo will appear. Press any key to see the main menu screen. Alternatively, the TAUYIELD executable can be added as an item to a group window in the Windows environment. An icon must be selected from those available in Windows since no icon is supplied with TAUYIELD.

Input keys

When TAUYIELD prompts for data using an input window, only printable characters (ASCI 32-126) are accepted as input. Invalid keystrokes are ignored. The return key signals the completion of the input for that question and continues to the next question or with the program. When a typing mistake has been made, certain keys can be used to correct the mistake as long as the return key has not been pressed. The keys and their functions are described below.

ESCAPE KEY	(erases everything you typed)
ARROW KEYS	(move the cursor left or right)
HOME KEY	(move the cursor to the beginning)
END KEY	(move the cursor to the end)
DELETE KEY	(deletes the character under the cursor)
BACKSPACE KEY	(deletes the character to the left of the cursor)

TAUYIELD main menu screen

The main menu screen for TAUYIELD has a top-bar menu with five items: Initialize, Thin Stand, Grow, Options and Quit. This menu will appear on the screen when first entering TAUYIELD and after each operation performed on the stand. Moving around the top-bar menu is accomplished using the ARROW keys, HOME key and the END key. To choose any of the commands highlight the command and then press the ENTER key. Whenever an invalid operation is requested the computer will beep and display a message at the bottom of the screen. Each of the commands and the information required for each command are explained in the following sections. TAUYIELD shows a status line at the bottom of the screen. This shows the current age, quadratic mean dbh, basal area, and number of trees for the stand. The status line also gives the drive, directory and log rule in use.

INITIALIZING A PLANTATION

This section describes how to initialize a plantation using TAUYIELD. Initializing a plantation is always the first step when using TAUYIELD. Attempting to use any of the other commands, except the options command, before initializing a plantation will produce an error message.

Requesting an initialization

Highlight the main menu command INITIALIZE and press return and a drop-down menu offering four options is presented. The QUIT option returns to the main menu. When any of the other three options is selected TAUYIELD requests plantation level information. Selecting the INITIALIZE UNTHINNED option from the Initialize menu requests information on the age of the stand, the site index, the current basal area and how many trees are in the stand. For unthinned stands the basal area is optional input. If the basal area is unknown, type 0 (zero) or press return. An existing juvenile stand between the ages of 0 and 8 can be initialized with just the site index, age, number of trees surviving and whether the stand was planted on a poorly drained site without bedding or some other type of site. The juvenile stand is then advanced to age 8.

When the INITIALIZE THINNED option is selected from the Initialize menu TAUYIELD prompts for the current age of the stand, the site index, the basal area (optional), the age of thinning and percent of trees or basal area removed in the thinning operation. By pressing <enter> the user can toggle back and forth to make a selection of thinning intensity (percent removed) based on number of trees or basal area.

The third option of the Initialize menu is to INITIALIZE PLANTATION. When this option is chosen TAUYIELD prompts for the number of trees planted, percent surviving at age 1, site index of the stand and whether the stand was planted on a poorly drained site without bedding or some other type of site. The stand is then advanced to age 8.

Output from an initialization

Two screens of output will be generated when initializing a stand. The first screen will be the Stand Summary. This is a summary of plantation-level information computed directly from the stand-level equations. If trees per acre or basal area was not an input, TAUYIELD will compute the value and show it. Dominant and codominant tree height is computed using age and site index. Quadratic mean dbh is calculated from trees per acre and basal area and arithmetic mean dbh is computed by TAUYIELD. Total cubic-foot volume outside bark is presented. At the bottom of the screen are options to choose from. The CONTINUE option means continue on with the program. The PRINT SCREEN option means print the stand summary. The WRITE TO FILE option writes the stand summary to a file in ASCII text format. When the option WRITE TO FILE is chosen, a menu will appear on the screen offering three options. Selecting

SAVE TO A NEW FILE will prompt for the drive, sub-directory, and file name of the ASCII text file where the information will be saved. The program will not write over existing files. If the file already exists it will give an error message. The SAVE TO AN EXISTING FILE option will add the previous screen (stand summary) to the last file opened by the program. If this option is chosen and there is not an open file TAUYIELD will prompt for the drive, sub-directory and file name of the ASCII file. The QUIT option means not to save the previous screen (stand summary) to a file and to continue on with the program.

The second screen is the Stand/Stock Table on a per acre basis. Basal area, height, and various volumes are computed and displayed by diameter class. There may be slight discrepencies between the stand/stock table summary values and the stand-level equation values from the Stand Summary screen due to rounding and truncation. The total outside bark volumes are for all trees. The pulpwood volume is for all trees in the 5 inch dbh class and above to a 4-inch top diameter outside bark. The sawtimber volume (IB) is in board feet using the specified log rule. To choose the log rule see the Options section of this manual. The extreme right column is a user-defined merchantable cubic-foot volume column. It displays inside or outside bark volumn to any specified top diameter limit. At the bottom of the screen are the same options as previously discussed, except that an additional option to graph the diameter distribution is available. Selecting this GRAPH option produces a 3D bar graph of the diameter distribution of the stand.

Program initialization limits and error messages

The stand age must be less than 37 years old. Site index can be between 39 and 86 based on a base age of 25. Basal area must be greater than 20 and less than 200. Trees per acre must be greater than 80 and less than 1501. If data outside these limits are specified, an error message will appear. If an unrealistic combination of inputs is specified projections and predictions will be unrealistic. For some heavy low thins, illogical stand tables for the first few years after thinning can occur (when the total stand table basal area differs from the basal area projection equation value by more than 5 percent due to "ghosting" of thinned trees). In such cases, TAUYIELD will not display a stand table but instead notify the user to project to an older age. This anomaly will not occur for most typical low thinning regimes.

THINNING A PLANTATION

This section describes how to use TAUYIELD to thin a plantation using several different methods. Thinnings can be conducted at any time and with varying intensities once a plantation has been initialized.

Request a thinning

To request a thinning, highlight the THIN STAND option of the main menu and the Thinning menu will appear on the screen displaying six options. To chose an option from the Thinning menu, highlight a choice and press RETURN. Each thinning option will request information. Exceeding the limits of the information will result in a pop-up error message and then return to the location of the incorrect entry. This section discusses all the options except the HARVEST option which is discussed in a separate section. The QUIT option returns to the main menu.

Thinomatic thinning

The THINOMATIC thinning option will prompt for the basal area desired after thinning. The desired basal area must be greater than 20 square feet per acre and less than the current basal area shown on the status line.
The THINOMATIC method removes trees according to the average pattern observed in certain types of operational thinnings where all diameter classes are subject to removals. The proportion of basal area removed in a 1 inch dbh class according to the thinomatic rule is given by the following equation (Burk et al., 1984):

$$P_i = \exp[-.73148*(D^2_i/Q^2)^{1.45759}]$$

where: P_i = proportion of basal area to remove in class i

D_i = midpoint dbh of class I
Q = quadratic mean dbh before thinning

Basal area is removed according to the equation starting in the smallest dbh class and working upward until the desired residual basal area remains. If the entire dbh distribution is gone through without removing the required basal area, the remainder is obtained by removing all trees in the smallest dbh classes until the specified residual basal area is reached. Whenever only a proportion of the trees in a dbh class are removed, the remaining trees are assumed to be uniformly distributed across the diameter class.

Row thinning

The ROW option will prompt for the desired basal area after thinning. The screen is the same as the THINOMATIC thinning option. The desired basal area must be greater than 20 square feet per acre and less than the current basal area shown on the status line. The ROW option removes a constant proportion from each dbh class. The proportion is equal to 1.0- (basal area after thinning/basal area before thinning). ***Note:*** *The thinning response function in TAUYIELD for pure row thinnings is set to 1.0. This means that growth after thinning for pure row thinnings will be as an unthinned plantation with reduced numbers of trees and basal area.*

Low thinning

To choose any of the three LOW thinning options, highlight the option and press return. The SPECIFY DBH option allows specification of the threshold dbh. When specifying a threshold dbh, all trees below the threshold dbh will be removed. Specifying a threshold dbh that will leave less than 20 square feet of basal area causes the program not to remove all the trees below the threshold dbh. The program will leave at least 20 square feet of basal area. The SPECIFY BASAL AREA option lets you specify the residual basal area in square feet after a low thinning. The basal area specified must be between 20 square feet and the current basal area shown on the status line. Trees will be removed starting at the smallest diameter class until the remaining basal area is what was specified. The QUIT option returns to the main menu.

Row/Low thinning

The ROW/LOW thinning option will prompt for the desired residual basal area after thinning. Residual basal area must be between 20 square feet and the current basal area shown on the status line. Of the basal area to be removed, a percentage will be removed by row thinning and the rest will be removed by low thinning. Specify the percentage (between 1 and 100) to be removed by row thinning.

The ROW/LOW thinning option gives results nearly identical to conducting a ROW thinning followed by LOW thinning. Basal area to be removed is computed as current basal area minus the user-specified residual basal area. A percentage of the “to be removed” basal area is first removed by ROW thinning. The rest is removed from the smallest dbh classes. For example, specifying 70 square feet of residual basal area on a stand currently at 150 square feet gives a removal basal area of 80 square feet. Then, specifying 40 percent to be removed by row thinning will instruct the program to remove 32 square feet by row thinning, followed by the removal of 48 square feet from the smallest diameter classes. ***Note****: The thinning response function in TAUYIELD for ROW/LOW thinnings is determined only from the low portion of the thinning. In the example above, the after-thinning to before-thinning basal area ratio for the thinning response function would be(150 - 80)/(150 - 32) = 70/118 or 0.59.*

The ROW/LOW thinning option is used to obtain thinnings from below with a different stand structure than that provided by the THINOMATIC option. The ROW/LOW option differs from conducting a row followed by a low thinning in two respects. In the ROW/LOW option only one stock table is displayed. Performing a ROW and then a LOW thinning will cause two different stock tables will be displayed. Also, no provision is made to specify the low thinning component of a ROW/LOW thin in terms of a threshold dbh class. This task can only be accomplished by performing the ROW and LOW thinnings separately.

Output from a thinning

Two screens of output will be generated after a thinning. The first indicates the type of thinning and the amount of basal area left after the thinning. The second screen pertains to the quantities removed. These quantities are on a per acre basis. This screen also shows a Stand Summary after the thinning. At the bottom of the screen are the three options discussed previously.

GROWING A PLANTATION

This section describes how to use TAUYIELD to grow a plantation to some point in time beyond its current age. A plantation must be initialized before it can be grown.

Request to grow a plantation

To grow a plantation to some future age, highlight the GROW option on the main menu. TAUYIELD prompts for the projected age. The projected age must be greater than the current age, shown on the status line at the bottom of the screen, and less than 37 years. A value outside this range will produce an error message and a reprompt for the projected age. Two screens of output will be generated when a stand is grown. These two screens are the same as generated when initializing a plantation.

HARVESTING AND FINANCIAL ANALYSIS

This section describes how to harvest a plantation, display a plantation history for a session and perform a financial analysis of that session.

Harvesting a plantation

To harvest a plantation, choose the THIN STAND option from the main menu and the Thinning menu will be displayed as discussed in the Thinning a Plantation section. Choose the HARVEST option from the Thinning menu to obtain a stand history of everything done since the plantation was initialized. It displays the age, action performed on the plantation, trees per acre, basal area, cubic foot volume, cords and board foot volume based on the log rule in effect when the action was performed. At the bottom of the table, the total volume removed is shown. In the Cords column only one product (pulpwood) is assumed of interest, whereas in the Pulpwood+Sawtimber column integrated utilization for the two products is assumed. The minus signs indicate removals. At the bottom of the screen are four options. The CONTINUE option will return to the main menu and set all the values on the status line to zero. The PRINT SCREEN and WRITE TO FILE options were discussed in the Initializing a Plantation section.

Financial analysis

When the FINANCIAL option at the bottom of the stand history screen is chosen a financial analysis summary is displayed. The Financial Analysis screen displays any action that removed volume. It displays the age in which the action was performed, the action performed, the dollar value returned for cords, the dollar value returned for board feet, the present value for cords and the present value for board feet and top cords. If the volume removed per acre is less than the minimum commercial volumes, the dollar value is zero. The present value sum for cords and board feet and top cords are given based on separate products. The present value is used to determine the value today of some future value. The equation used for present value in TAUYIELD is shown below.

$V_0 = V_n/(1 + i)^n$

V_0 = present value
V_n = value of product in the future
n = number of periods (years) in the future
i = interest rate per period (year)

At the bottom of the screen are three options. PRINT SCREEN and WRITE TO FILE were previously discussed in the Initializing a Plantation section. The CONTINUE option will return to the main menu and set all the values on the status line to zero.

TAUYIELD OPTIONS

This section describes how to change the default parameters of TAUYIELD.

Request to change an option

One of the main menu commands is OPTIONS. Selecting this displays the Option menu on the screen. There are four options in the Options menu. Choosing QUIT returns to the main menu. The other three are presented below.

Log rule

To choose this option, highlight LOG RULE and press return. This option allows selecting the log rule used to determine board feet. The default is International 1/4 Log Rule. To choose a different log rule highlight the log rule and press return. The Stand History will reflect all changes in log rules used during the projection. **Warning**: It is possible to switch log rules at any point in the simulation to view stand tables generated from different log rules. However, this is not recommended if a harvest is anticipated followed by a financial analysis because it may result in multiple log rules being used to calculate board feet in the Stand History.

Merchantablilty Limit

This option allows the user to specify a merchantable volume for the extreme right column of the stand table. Pressing <enter> will toggle back and forth between an inside or outside bark volume selection and entering a top diameter will define the limits of merchantablilty. This merchantable volume is not used in the harvest or financial analyses. As in the log rule option, users can switch merchantablilty limits at any time during the simulation.

Financial values

This option allows changing the interest rate, product values and minimum commercial volumes to be considered commercial products. These values are used to compute a financial analysis of the stand. When this pop-up window is shown it displays the current values. Typing an 'N' returns to the main menu. To change the current values type a 'Y'. The ranges for the values are shown on the screen. Entering data outside the range produces an error message and a reprompt for the value. After entering all the values a prompt appears to save the values. Answering YES, saves these values for use every time TAUYIELD is used (until they are changed again). The next time TAUYIELD is activated, the last saved values will be the current values.