YIELD PREDICTION AND GROWTH PROJECTION
FOR SITE-PREPARED LOBLOLLY PINE
PLANTATIONS IN THE CAROLINAS,
GEORGIA, FLORIDA, AND ALABAMA

by

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Athens, Georgia  30602

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YIELD PREDICTION AND GROWTH PROJECTION
FOR SITE-PREPARED LOBLOLLY PINE
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GEORGIA, FLORIDA, AND ALABAMA

INTRODUCTION AND MODEL STRUCTURE

Loblolly pine (*Pinus taeda* L.) is the most widely planted conifer in the southeastern United States. In the late 1940's and 1950's most plantations were established on abandoned agricultural fields. Following harvest of these old field plantations and natural stands, loblolly pine plantations are usually established following some type of mechanical site preparation.

To help forest managers make rational informed decisions concerning loblolly pine plantations on cutover site-prepared lands the Plantation Management Research Cooperative (PMRC) of the School of Forest Resources at the University of Georgia initiated an effort to develop a yield prediction system for unthinned stands grown on these lands. Initial work on this project led to development and publication of individual tree volume, weight, and taper equations as well as yield models for site-prepared loblolly pine plantations in the piedmont and upper coastal plain of Alabama, Georgia, and South Carolina (Bailey et al. 1985) and a yield model for site-prepared loblolly pine plantations in the lower coastal plain of the Carolinas, Georgia, and North Florida (Clutter et al. 1984). Since release of the models cited above, additional individual tree volume and taper data have been obtained and a 4-year remeasurement of monumented yield plots has been made for all geographic regions (i.e. piedmont, upper coastal plain, lower coastal plain).

Pienaar et al. (1987) developed new individual tree volume, weight, and taper functions using the augmented individual tree PMRC data base. Below we present a simulation model for cutover site-prepared loblolly pine plantations in the Carolinas, Georgia, Florida, and Alabama. This model was developed using all remeasured permanent plot growth and yield data available to date. This new simulation model has three separate and individual yield (volume or weight yields) components:

1) a diameter distribution yield prediction system;
2) a stand table projection system;
3) a whole stand explicit prediction system.
All three yield components are driven by whole stand prediction and projection models for basal area per acre, trees per acre, and dominant height (site index).

The Weibull based diameter distribution yield prediction system should be used when it is desired to have an estimate of present or future per acre yield as well as an estimate of the associated stand and stock table when the inputs of present dominant height (site index), age (present or future), and present number of trees per acre are available. The stand table projection system should be used when it is desired to have an estimate of future per acre yield and the associated future stand and stock table when the present dominant height, present and future age, present number of trees per acre, and the present stand table are available as input into the system. The whole stand explicit yield prediction system should be used when it is desired to obtain an estimate of present or future per acre yields (total or by product class) without an estimate of the associated stand table when the present dominant height, age (present or future), and present number of trees per acre are available as input. Note that it is also possible to enter present basal area per acre when using any of these yield systems.

Thus, we have developed this model to accommodate various user's needs. If a user has obtained estimates of stand tables in their inventory system then this information can be used to estimate future yields via the stand table projection system which is more accurate than the Weibull based system which disregards information about the current stand table (Patterson and Borders 1990). If a user does not need stand and stock tables the explicit yield prediction equation provides a much simplified as well as accurate tool to obtain per acre yield estimates by product classes defined by the user.
CHAPTER 1 - DATA

The data come from three a-priori defined physiographic regions: piedmont, upper coastal plain, and lower coastal plain (figure 1.1). These three regions have been assumed to exhibit different growth patterns (Clutter et al. 1984; Bailey et al. 1985) and have been shown to require different individual tree volume and weight functions (Pienaar et al. 1987). In development of the current model data for all three regions were combined. Model forms were then developed and differences in parameter estimates by physiographic region were investigated using statistical tests of hypotheses. When possible (i.e. no significant differences among regions) a single model was used for all regions.

All data come from permanent plots that were measured at time of plot installation and then remeasured after four years. The first data base comes from lower coastal plain loblolly pine plantations in North and South Carolina from plots installed in 1977 and remeasured in 1981. A second data base is composed of plots installed in the lower coastal plain of Georgia and north Florida in 1981 and remeasured in 1985. These first two data bases were combined into one lower coastal plain data base. There was a total of 160 permanent plots distributed geographically as shown in figure 1.2 and distributed by age, site index, and trees per acre (tpa) at time of plot installation as shown in table 1.1. One hundred fifty nine of these plots were remeasured four years after installation. All plots in this sample were approximately .1 acre containing approximately 64 original planting spaces. All sample plots were purposively located to avoid obvious "holes" in plantations with the following characteristics:

1) at least 10 years old,
2) planted following mechanical site preparation,
3) unthinned, unfertilized, and unpruned,
4) no evidence of excessive insect or disease damage,
5) no evidence of interplanting or excessive numbers of wildings.

The following data were collected for the 1977-81 plots:

1) method of site preparation (from company records),
2) plantation age (from planting records),
3) plot length and width,
Figure 1.1 Three physiographic regions defined across the Carolinas, Georgia, Florida, and Alabama.
Figure 1.2. Geographic distribution of sample plots in the lower coastal plain of the Carolinas, Georgia, and North Florida.
4) number of trees in each one-inch diameter breast height (dbh) class,
5) crown class and total height of at least two trees in each dbh class,
6) number of wildings and cronartium infected trees in each one-inch dbh class,
7) a complete soil profile description.

Information obtained for the 1981-85 plots was identical to that for the 1977-81 plots except that all tree dbh's were measured and recorded to the nearest .1 inch.
Table 1.1. Number of sample plots distributed by age class, site index class, and trees per acre class at time of installation in the lower coastal plain of the Carolinas, Georgia, and north Florida.

<table>
<thead>
<tr>
<th>Age</th>
<th>Trees/ac</th>
<th>≤50</th>
<th>51-60</th>
<th>61-70</th>
<th>&gt;70</th>
<th>Total</th>
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<td>&gt;25</td>
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<td>&gt;700</td>
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<td>56</td>
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There was a total of 199 permanent plots in the piedmont of Alabama, Georgia, and South Carolina distributed geographically as shown in figure 1.3 and distributed by age, site index, and tpa at time of plot installation as shown in table 1.2. One hundred eighty four plots were remeasured four years after installation. All plots installed in the piedmont were approximate .1 acre rectangular plots with approximately 64 original planting spaces. Plantations selected for plot installation had to meet the same criteria as plantations selected in the lower coastal plain. The following information was obtained for each sample plot:

1) plantation age (from planting records),
2) plot length and width,
3) dbh to the nearest .1 inch for all trees,
4) crown class and total height of at least two trees in each one-inch dbh class,
5) number of wildings and cronartium infected trees in each one-inch dbh class.

A sample of 116 plots was available from the upper coastal plain of Georgia, Alabama and South Carolina. Plantations chosen for sample plot installation met the same criteria as plantations in the lower coastal plain and piedmont. Furthermore, the same plot and individual tree information was collected for these plots as for the piedmont plots. Geographic distribution and distribution by age, site index, and trees per acre at time of installation are shown in figure 1.3 and table 1.3, respectively. One hundred four of the plots were remeasured four years after installation.

A small number of plots were deleted from the lower coastal plain, piedmont, and upper coastal plain data bases for several reasons. Plots with excessive numbers of wildings were deleted because it was assumed these plots would not be representative of the majority of plantation acres under management. A small number of plots were also deleted from the data base because they were found to be outliers which were not representative of the population under consideration.
Figure 1.3. Geographic distribution of sample plots in the piedmont and upper coastal plain of Alabama, Georgia, and South Carolina.
Table 1.2. Number of sample plots distributed by age class, site index class, and trees per acre class at time of installation in the piedmont of Alabama, Georgia, and South Carolina.

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<tr>
<th>Age</th>
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<th>51-60</th>
<th>61-70</th>
<th>&gt;70</th>
<th>Total</th>
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Table 1.3. Number of sample plots distributed by age class, site index class, an acre class at time of installation in the upper coastal plain of Alabama, Georgia, Carolina.

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<th>Age</th>
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<th>61-70</th>
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</tr>
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CHAPTER 2
INDIVIDUAL TREE VOLUME, WEIGHT, AND TAPER FUNCTIONS

Individual tree volume, weight, and taper functions were developed by Pienaar et al. (1987) for the three physiographic regions described above and illustrated in figure 1.1. A detailed description of the data and procedures used fit the functions are given by Pienaar et al. (1987). Distribution of sample trees by physiographic region, age class, and total height class is shown in table 2.1. Final equations are given below.

Outside Bark Stem Volume and Taper Functions

Lower Coastal Plain (Flatwoods)

\[ VOB_m = 0.00145519 \ D^{1.826051} \ H^{1.221965} - 0.00253872 \ \left( \frac{D_m^{3.741575}}{D^{1.741575}} \right) (H - 4.5) \]

where:

\( VOB_m \) = outside bark merchantable stem volume in cubic feet to a top diameter limit outside bark of \( D_m < D \),

\( D_m \) = top merchantable diameter outside bark (inches),

\( D \) = dbh (inches),

\( H \) = total tree height (feet).

\[ D_m = D \left( \frac{H - M}{H - 4.5} \right)^{0.574193} \]

\[ M = H - (H - 4.5) \left( \frac{D_m}{D} \right)^{1.741575} \]

where:

\( M \) = height above ground (feet) to the outside bark merchantable diameter limit \( D_m \) (inches).
Table 2.1. Distribution of sample trees used in volume and taper equation development by physiographic region, Dbh class and total height class.

a.) Lower coastal plain

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Upper Coastal Plain

\[
VOB_m = 0.00431899 \ D^{1.953207} \ H^{0.896934} - 0.00251744 \left( \frac{D_m^{3.714466}}{D^{1.714466}} \right)(H - 4.5)
\]

\[
D_m = D \left( \frac{H - M}{H - 4.5} \right)^{0.583272}
\]

\[
M = H - (H - 4.5) \left( \frac{D_m}{D} \right)^{1.714466}
\]

where all symbols are as previously defined.
Piedmont

\[ V_{OB_m} = 0.00401246 \, D^{1.829011} \, H^{0.969142} - 0.00249374 \left( \frac{D_m^{3.684725}}{D^{1.684725}} \right) (H - 4.5) \]

\[ D_m = D \left( \frac{H - M}{H - 4.5} \right)^{0.593569} \]

\[ M = H - (H - 4.5) \left( \frac{D_m}{D} \right)^{1.684725} \]

where all symbols are as previously defined.
Inside Bark Stem Volume and Taper Equations

Lower Coastal Plain (Flatwoods)

\[ VIB_m = 0.00071193 \ D^{1.876991} \ H^{1.321458} - 0.00217131 \left( \frac{D_m^{3.592491}}{D^{1.592491}} \right) (H - 4.5) \]

where:

\( VIB_m \) = inside bark merchantable volume in cubic feet to a top diameter limit outside bark \( D_m < D \).

\[ D'_m = \left[ 0.821198 \ D^2 \left( \frac{H - M}{H - 4.5} \right)^{1.062783} \right]^{1/2} \]

where:

\( D'_m \) = inside bark diameter in inches where the outside bark diameter is \( D_m \) inches,

and all else is as previously defined.

Upper Coastal Plain

\[ VIB_m = 0.00210741 \ D^{1.957418} \ H^{1.021763} - 0.00209273 \left( \frac{D_m^{3.584111}}{D^{1.584111}} \right) (H - 4.5) \]

\[ D'_m = \left[ 0.802118 \ D^2 \left( \frac{H - M}{H - 4.5} \right)^{1.090512} \right]^{1/2} \]

where all symbols are as previously defined.

Piedmont

\[ VIB_m = 0.00171199 \ D^{1.870407} \ H^{1.110322} - 0.00210729 \left( \frac{D_m^{3.437603}}{D^{1.437603}} \right) (H - 4.5) \]

\[ D'_m = \left[ 0.788358 \ D^2 \left( \frac{H - M}{H - 4.5} \right)^{1.040453} \right]^{1/2} \]

where all symbols are as previously defined.
Green Weight With Bark

Lower Coastal Plain (Flatwoods)

\[ GWWB_m = 0.0740959 \ D^{1.829983} H^{1.247669} - 0.123329 \ \left( \frac{D_m^{3.523107}}{D^{1.449947}} \right) (H - 4.5) \]

where:

\( GWWB_m \) = green weight of wood and bark in pounds to a top diameter limit outside bark \( D_m < D \).

and all else is as previously defined.

Upper Coastal Plain

\[ GWWB_m = 0.141534 \ D^{1.917146} H^{1.038452} - 0.0932063 \ \left( \frac{D_m^{3.589155}}{D^{1.413061}} \right) (H - 4.5) \]

where all symbols are as previously defined.

Piedmont

\[ GWWB_m = 0.110069 \ D^{1.935455} H^{1.080621} - 0.0775771 \ \left( \frac{D_m^{3.439954}}{D^{1.178473}} \right) (H - 4.5) \]

where all symbols are as previously defined.

Dry Weight Without Bark

Lower Coastal Plain (Flatwoods)

\[ DW_m = 0.0106276 \ D^{1.882913} H^{1.478766} - 0.0298084 \ \left( \frac{D_m^{3.825425}}{D^{1.517983}} \right) (H - 4.5) \]

where:

\( DW_m \) = dry weight of wood in pounds to a top diameter outside bark of \( D_m < D \)

and all else is as previously defined.
Upper Coastal Plain

\[ DW_m = 0.0290299 \cdot D^{2.017530} \cdot H^{1.157743} - 0.0222220 \left( \frac{D_m^{3.782287}}{D^{1.367710}} \right) (H - 4.5) \]

where all symbols are as previously defined.

Piedmont

\[ DW_m = 0.0360196 \cdot D^{1.742939} \cdot H^{1.232462} - 0.0356069 \left( \frac{D_m^{3.668307}}{D^{1.479158}} \right) (H - 4.5) \]

where all symbols are as previously defined.

Dry Weight Without Bark (if tree age is known)

Lower Coastal Plain (Flatwoods)

\[ DW_m = 0.0113113 \cdot D^{1.901901} \cdot H^{1.303882} \cdot A^{0.210461} - 0.0309330 \left( \frac{D_m^{3.821368}}{D^{1.526992}} \right) (H - 4.5) \]

where:

- A = tree age,
- and all else is as previously defined.

Upper Coastal Plain

\[ DW_m = 0.0275683 \cdot D^{1.973518} \cdot H^{1.093663} \cdot A^{0.137418} - 0.0217837 \left( \frac{D_m^{3.769104}}{D^{1.345945}} \right) (H - 4.5) \]

where all symbols are as previously defined.

Piedmont

\[ DW_m = 0.0288583 \cdot D^{1.769315} \cdot H^{1.161088} \cdot A^{0.154501} - 0.0363042 \left( \frac{D_m^{3.654891}}{D^{1.474768}} \right) (H - 4.5) \]

where all symbols are as previously defined.
Green Weight Without Bark

This quantity can only be estimated for trees in the piedmont.

Piedmont

\[ GWIB_m = 0.120931 \ D^{2.323008} \ H^{0.823979} - 0.076815 \ \frac{D_m^{3.446656}}{D^{1.238789}} (H - 4.5) \]

where:

- \( GWIB_m \) = green weight of wood without bark in pounds to a top diameter outside bark \( D_m < D \)

and all else is as previously defined.
CHAPTER 3
DOMINANT HEIGHT-AGE FUNCTION (SITE INDEX EQUATION)

Yields of even-aged pine plantations have been shown to be highly correlated with site index. Site index is defined as the average height of domin and codominant trees within a stand at a given base-age. The base-age used in Southeast pine plantations is usually 25 years and will be defined as such here. Site index (dominant height - age) functions are usually developed for relativael small geographic regions on a species by species basis. For example, Smalley and Bower (1971) present site index equations for old-field loblolly pine plantations the highlands of Tennessee, Alabama, and Georgia and Popham et al. (1979) published site index equations for cutover loblolly pine plantations in the West Gulf region of the southern United States.

Pienaar and Shiver (1980) published site index equations for cutover site prepared loblolly pine plantations in the lower coastal plain of Florida, Georgia, the Carolinas. These equations were developed using stem analysis data taken from the lower coastal plain plots described above. In their study, Pienaar and Shiver (1980) defined two soil groups (A and B) that exhibited significantly different dominant height growth patterns. Almost all soil group B plots were North Carolina pocosin river swamp soils that had been ditched to remove exce water. The following soil series were put into this group B classification: Ballah Torhunta, Bayboro, Pantego, and Byars. Soil group A contained all plots not in group B. Twenty six sample plots were used to develop the following site equation for cutover site-prepared loblolly pine stands growing on soil group B soils:

\[
S = H_D \left( \frac{0.7476}{1 - \exp(-0.5507 A)} \right)^{1.4350}
\]

(3.1)

\[
H_D = S [1.3376 \left(1 - \exp(-0.05507 A))\right)]^{1.4350}
\]

(3.2)

where:

\[
S = \text{site index (base age 25) (feet)},
\]

\[
H_D = \text{dominant height at age A (feet)},
\]

\[
A = \text{age from planting (years)},
\]

\[
\exp \text{ is the base of the natural logarithms.}
\]
Pienaar and Shiver (1980) also developed a site index equation for soil group A based on stem analysis data obtained at time of initial plot installation. However, Clutter et al. (1984) developed a new soil group A site index equation using remeasurement data obtained from 122 of the plots installed in the lower coastal plain in 1977 because they found that the equation presented by Pienaar and Shiver (1980) did not reflect height growth patterns observed in the remeasurement data.

Bailey et al. (1985) developed a site index equation for cutover site-prepared loblolly pine plantations in the piedmont and upper coastal plain of Alabama, Georgia, and South Carolina. This equation was based on stem analysis data obtained at the time of installation of permanent plots previously described.

Using all remeasurement data available for all plots except soil group B plots in the lower coastal plain (only 4 plots in this soil group were remeasured) a new site index equation was developed. Lenhart's generalization of the Schumacher growth model (Clutter and Lenhart 1968) was used to test for differences in dominant height growth patterns for piedmont, upper coastal plain, and lower coastal plain (soil group A) plots. No statistically significant differences were found (Adams 1989). The following model was fitted using 4-year remeasurement data from 490 permanent plots located across all three physiographic regions:

\[
S = \exp[-1.4128 + 1.1744\ (\ln H_D + 35.3202/A) \exp(-4.01832/A)] \tag{3.3}
\]

\[
H_D = \exp[-35.3202/A + 0.85152\ (\ln S + 1.4128) \exp(4.01832/A)] \tag{3.4}
\]

where:

- In denotes natural logarithm,
- and all else is as previously defined.

Model 3.4 was found to be superior to three previously published dominant height-age models (Clutter and Lenhart 1968, Amateis and Burkhart 1983, Clutter et al. 1984) based on statistics of fit generated from the PMRC data base. Graphical representation of equation 3.4 for various site indices is shown in figure 3.1.
Figure 3.1 Site index curves for loblolly pine plantations on cutover, prepared sites in the Southeast.
CHAPTER 4
SURVIVAL FUNCTION

Predicting per acre volume (weight) yields for even-aged pine plantations usually requires measures of site quality (site index or dominant height-age), stand age, and stand density. An often used measure of stand density is surviving number of trees per acre (tpa). If tpa can be projected to a future age, future yield can be obtained from a volume (weight) projection model. Equations used to project tpa to future ages are referred to as survival functions (or mortality functions). Clutter et al. (1984) presented a survival function for cutover site-prepared loblolly pine plantations in the lower coastal plain of the Carolinas, Georgia, and north Florida. Their model was based on remeasurement of 130 permanent plots installed in 1977 and remeasured in 1981. Bailey et al. (1985) suggest using the model of Clutter et al. (1984) for cutover site-prepared loblolly pine plantations in the piedmont and upper coastal plain of Alabama, Georgia, and South Carolina.

A new survival function has been derived and fitted to all remeasurement data currently available for cutover site-prepared loblolly pine plantations. The model form, which is a variation of the Clutter and Jones (1980) survival function, is similar to that suggested by Harrison and Daniels (1987):

\[ N_2 = N_L + [(N_1 - N_L)^{\lambda} + \beta(H_{D2}/100 - H_{D1}/100)]^{1/\lambda} \]

where:

- \( N_1 \) = surviving trees per acre at time 1,
- \( N_2 \) = surviving trees per acre at time 2,
- \( N_L \) = lower asymptote for trees per acre,
- \( H_{D1} \) = dominant height at time 1,
- \( H_{D2} \) = dominant height at time 2,
- \( \lambda, \beta \) are parameters to be estimated.

This model was found to be superior to several other model forms both in terms of statistics of fit and extrapolative properties. No significant differences were detected among the three physiographic regions. Thus, a single survival model that applies to all physiographic regions, fitted to 475 plot observations with a lower asymptote of 25 trees per acre is:
\[ N_2 = 25 + [(N_1 - 25)^{-1.45382} + 0.00047089((H_{D2}/100)^{4.08722} - (H_{D1}/100)^{4.08722})]^{-1/1.45382} \] (4.1)

Average Residual = -5.2 tpa,
Percent Variation Explained = 91.3.

Note that site index does not appear in the model explicitly. However, since dominant height appears as shown above the implication is that for a given projection period survival rates are lower on higher site index land (figure 4.1). This implies that inter-tree competition is more intense earlier in the life of a stand on high quality land than for a similar stand on low quality land. This same relationship has been reported by others for both loblolly pine (Smalley and Bailey 1974, Bailey et al. 1985) and slash pine (Bailey et al. 1985b, Clutter and Jones 1980). It is interesting to note that several model forms that allowed for various levels of cronartium rust infection were fitted and compared with equation 4.1. All models allowing for variable rust infection levels were inferior in terms of average residuals, average residuals by rust infection classes, and overall percentage variation explained by the model. This finding supports the contention that loblolly pine, although infected readily by cronartium rust, does not exhibit accelerated mortality rates in stands greater than 10 years of age due to the presence of the rust. However, this is contradictory to the finding by Clutter et al. (1984b) that loblolly pine stands with high levels of fusiforme infection exhibit higher mortality rates than loblolly pine stands with low levels of fusiforme infection.
Figure 4.1 Trees per acre survival for three site indices (45, 60, 75 ft.) implied by survival function 4.1.
CHAPTER 5
BASAL AREA PREDICTION AND PROJECTION

Per acre volume (weight) yield prediction in even-aged pine plantations requires an estimate of stand density. One measure of stand density, discussed above, is tpa. A second measure of stand density is basal area per acre (BA). BA is defined as the cross sectional area of all living trees on an acre at 4.5 feet above average ground level. Volume (weight) yield models presented below use both tpa and BA to obtain accurate yield estimates. Often, model users know tpa but not BA. Thus, we have developed a basal area prediction model that is a function of tpa. When making yield projections to a future age it is necessary to have estimates of expected tpa and expected BA at the future age. The survival model presented above (equation 4.1) is used to obtain the expected future tpa. Expected future BA is obtained using a BA projection model which is compatible with the BA prediction model.

Several BA prediction and projection models were fitted to the data and compared for goodness of fit. Statistically significant differences were found between lower coastal plain stands and the combined piedmont and upper coastal plain stands. The model form used was originally presented by Pienaar and Shiver (1966). The BA prediction and projection models for the piedmont and upper coastal plain, fitted with 633 plot observations, are:

\[
\ln BA_1 = -1.24123 - 30.36552/A_1 + 1.04601 \ln(H_{D1}) + 0.32623 \ln(N_1) \\
2.75391 (\ln(N_1)/A_1) + 3.14466 (\ln(H_{D1})/A_1)
\] (5.1)

Average Residual = 1.0 ft²/acre  
Percent Variation Explained = 82.4

\[
\ln BA_2 = \ln BA_1 - 30.36552 (1/A_2 - 1/A_1) + 1.04601 (\ln(H_{D2}) - \ln(H_{D1})) \\
+ 0.32623 (\ln(N_2) - \ln(N_1)) + 2.75391 (\ln(N_2)/A_2 - \ln(N_1)/A_1) \\
+ 3.14466 (\ln(H_{D2})/A_2 - \ln(H_{D1})/A_1)
\] (5.2)

Average Residual = -1.6 ft²/acre  
Percent Variation Explained = 88.6

where:

BA_1 = basal area per acre at time one,  
BA_2 = basal area per acre at time two,  
H_{D1} = dominant height at time one,
\( H_{D2} = \) dominant height at time two, and all else is as previously defined.

The BA prediction and projection models for the lower coastal plain, fitted with 328 plot observations, are:

\[
\ln B_1 = -51.13703/A_1 + 0.81396 \ln(H_{D1}) + 0.28078 \ln(N_1) + 4.84386 \left( \ln(N_1)/A_1 \right)
+ 5.23322 \left( \ln(H_{D1})/A_1 \right) 
\]

Average Residual = 1.4 ft²/acre
Percent Variation Explained = 73.9

\[
\ln BA_2 = \ln BA_1 - 51.13703 \left( 1/A_2 - 1/A_1 \right) + 0.81396(\ln(H_{D2}) - \ln(H_{D1}))
+ 0.28078(\ln(N_2) - \ln(N_1)) + 4.84386(\ln(N_2)/A_2 - \ln(N_1)/A_1)
+ 5.23322(\ln(H_{D2})/A_2 - \ln(H_{D1})/A_1) 
\]

Average Residual = -0.1 ft²/acre
Percent Variation Explained = 82.3

where:
all symbols are as previously defined.

Note that each pair of equations are compatible simultaneous BA prediction and projection models. No differences in survival rates were detected among the three physiographic regions (chapter 4) thus implying for given site index land and a given stand density and age, individual trees exhibit slightly faster diameter growth rates in the lower coastal plain than in the upper coastal plain and piedmont. Note, however, that piedmont and upper coastal plain stands surpass BA for comparable lower coastal plains as age increases (figure 5.1). It is not known whether this phenomenon is real or simply a function of the data used in parameter estimation.
Figure 5.1 Basal area per acre production for stands with 450 trees per acre at age 10 on site index 65 land located in the lower coastal plain (equation 5.4) and in the piedmont or upper coastal plain (equation 5.2).
CHAPTER 6
VOLUME AND WEIGHT GROWTH AND YIELD

As discussed in chapter 1 above, different users of growth and yield models have different needs which may be dictated by data availability and/or information requirements. Some users can provide estimates of tpa, SI(H_D), age while others can provide this information as well as an estimate of the existing stand and stock table. Likewise, some users require per acre yield estimates and associated stand and stock tables while other users require only per acre yield estimates. Three volume (weight) yield options are presented and discussed below.

Diameter Distribution Yield Model

All available data from all physiographic regions were combined for development of the diameter distribution yield model. The Weibull probability distribution function (pdf) was used to model stand tables. This pdf has been used successfully in many published growth and yield models for many species around the world. The general form of the Weibull pdf is:

\[
f(x) = \frac{c}{b} \left( \frac{x-a}{b} \right)^{c-1} \exp \left[ -\left( \frac{x-a}{b} \right)^c \right] \tag{6.1}
\]

where:
\[
x = \text{dbh}, \\
a, b, c \text{ are parameters unique to each stand.}
\]

By integrating equation 6.1 we obtain the cumulative distribution function (cdf) of the Weibull pdf:

\[
F(x) = 1 - \exp \left[ -\left( \frac{x-a}{b} \right)^c \right] \tag{6.2}
\]

where:
\[
\text{all symbols are as previously defined.}
\]

F(x) gives the proportion of the total trees per acre that have dbh less than x. Using the cdf it is possible to obtain the proportion of the
total trees per acre between two diameters, say the upper and lower limits of a one-inch diameter class. To make practical use of the Weibull pdf and cdf, we need to obtain estimates of a, b, and c for individual stands. In the past, equations have been developed to predict a, b, and c as a function of site quality, stand age, and stand density. This procedure, known as parameter prediction, has been found to be less than desirable. Parameter prediction has been replaced by a procedure known as parameter recovery. Parameter recovery methods equate analytic forms of certain dbh percentiles to dbh percentiles observed or predicted for individual stands to obtain estimates of a, b, and c. Parameter recovery is preferred to parameter prediction because variation in dbh percentiles is much more highly correlated with site quality, age, and stand density than are the a, b, and c Weibull parameters.

The parameter recovery method used here is that presented by Bailey et al. (1989). This procedure uses the 0th (minimum diameter), 25th, 50th, and 95th percentiles to obtain estimates of a, b, and c. First obtain an estimate of the "a" parameter using predicted values of the 0th and 50th percentiles assuming the c parameter is 3.0. This translates mathematically to:

\[
\hat{D}_0 = a + (b/n^{1/3}) (0.9)
\]  

\[
\hat{D}_{50} = a + b (0.9)
\]  

where:

\[\hat{D}_0 = \text{predicted minimum DBH,}\]

\[\hat{D}_{50} = \text{predicted 50th DBH percentile,}\]

\[n = \text{number of trees per plot.}\]

Combining equations 6.3 and 6.4 we obtain our estimate of "a"

\[
\hat{a} = (n^{1/3} \hat{D}_0 - \hat{D}_{50})/(n^{1/3} - 1)
\]  

if \(\hat{a} < 0.0\) then \(\hat{a} = 0.0.\)
Next, using a along with analytic forms for the 25th and 95th percentiles, the estimate of the "c" parameter is:

\[
\hat{c} = \frac{2.343088}{2.777427/}\ln(\hat{D}_{95} - a) - \ln(\hat{D}_{25} - a)]
\]  

where:
\[
\hat{D}_{95} = \text{predicted 95th dbh percentile.}
\]
\[
\hat{D}_{25} = \text{predicted 25th dbh percentile.}
\]

Finally, we obtain an estimate of "b" as:

\[
\hat{b} = -\left(\hat{a} \Gamma_1/\Gamma_2 \right) + \left[ \left(\frac{a^2}{\Gamma_2}\right) (\Gamma_1^2 - \Gamma_2) + D^2/\Gamma_2 \right]^{1/2}
\]  

where:
\[
\Gamma_1 = \Gamma [1 + (1/\hat{c})]
\]
\[
\Gamma_2 = \Gamma [1 + (2/\hat{c})]
\]

\(\Gamma\) is the gamma function
\(D\) = quadratic mean dbh.

This parameter recovery procedure constrains the predicted stand table to have the same quadratic mean dbh as that implied by the whole stand measures of basal area per acre and trees per acre.

Equations to predict \(D_0\), \(D_{25}\), \(D_{50}\), and \(D_{95}\) were developed and differences by physiographic region were investigated. Statistically significant differences were found among the three physiographic regions for all four percentiles. The dbh percentile prediction equations are:
Piedmont

\[ \hat{D}_0 = \exp[2.7711029 + 0.9906964 \ln(BA/N) - 0.00657661(SI)] \]  \hspace{1cm} (6.8)

Average Residual = 0.126 inches
Percent Variation Explained = 57.6

\[ \hat{D}_{25} = \exp[-3.6523041 + 1.5432169 \ln(\hat{D}_{50}) + 1.4435789(RS) + 0.3417899 \ln(N)] \]  \hspace{1cm} (6.9)

Average Residual = 0.020 inches
Percent Variation Explained = 83.7

\[ \hat{D}_{50} = \exp[3.2888147 + 0.6114272 \ln(BA/N) + 0.04215482 \ln(N) - 0.20125037 \ln(H_D) - 0.6020401(1/A)] \]  \hspace{1cm} (6.10)

Average Residual = 0.005 inches
Percent Variation Explained = 96.1

\[ \hat{D}_{95} = \exp[0.584578 + 0.8988592 \ln(\hat{D}_{50}) - 0.200558(RS)] \]  \hspace{1cm} (6.11)

Average Residual = 0.033 inches
Percent Variation Explained = 83.7

Upper Coastal Plain

\[ \hat{D}_0 = \exp[1.8945007 + 0.9472899 \ln(BA/N) + 0.0069688(SI)] \]  \hspace{1cm} (6.12)

Average Residual = 0.118 inches
Percent Variation Explained = 65.1
\[ \hat{D}_{25} = \exp[-1.7792268 + 1.2742723 \ln(D_{50}) + 0.44517(RS) + 0.1578344 \ln(N)] \]  \hspace{1cm} (6.13)

Average Residual = 0.012 inches
Percent Variation Explained = 91.7

\[ \hat{D}_{50} = \exp[2.9142853 + 0.5379221 \ln(BA/N) - 0.0724977 \ln(H_D)] \]  \hspace{1cm} (6.14)

Average Residual = 0.003 inches
Percent Variation Explained = 97.2

\[ \hat{D}_{95} = \exp[0.5636465 + 0.9031187 \ln(D_{50}) - 0.19434368(RS)] \]  \hspace{1cm} (6.15)

Average Residual = 0.019 inches
Percent Variation Explained = 90.4

**Lower Coastal Plain**

\[ \hat{D}_0 = \exp[2.7029308 + 0.9580700 \ln(BA/N) - 0.0053987(SI)] \]  \hspace{1cm} (6.16)

Average Residual = 0.138 inches
Percent Variation Explained = 66.2

\[ \hat{D}_{25} = \exp[-1.1394798 + 1.193879 \ln(D_{50}) + 0.3758646(RS) + 0.079841 \ln(N)] \]  \hspace{1cm} (6.17)

Average Residual = 0.016 inches
Percent Variation Explained = 90.6

\[ \hat{D}_{50} = \exp[2.5753352 + 0.5009179 \ln(BA/N)] \]  \hspace{1cm} (6.18)

Average Residual = 0.008 inches
Percent Variation Explained = 95.6
$D_{95} = \exp[0.5297791 + 0.9166737 \ln(D_{50}) - 0.1490178(RS)]$ \hspace{1cm} (6.19)

Average Residual = 0.016 inches
Percent Variation Explained = 92.0

where:

$\hat{D_i}$ = predicted value of the $i^{th}$ dbh percentile,
$\text{BA}$ = basal area/acre (square feet),
$\text{N}$ = trees per acre,
$\text{SI}$ = site index base 25 (feet),
$H_D$ = dominant height (feet),
$A$ = stand age from planting,
$\text{RS} = \text{relative spacing} = \frac{\sqrt{43560/\text{N}}}{H_D}$.

To obtain a stand table we first predict $D_0$, $D_{25}$, $D_{50}$, and $D_{95}$ using equations appropriate for the physiographic region. We then obtain $\hat{a}$, $\hat{b}$, and $\hat{c}$ using equations 6.5, 6.6, and 6.7. Then we use equation 6.2 to obtain the proportion of trees less than the upper diameter class limit and the lower diameter class limit. We then subtract the proportion less than the lower diameter class limit from the proportion less than the upper diameter class limit to obtain the proportion of trees within the diameter class. We can then multiply this proportion by the surviving number of trees per acre to obtain the number of trees per acre in the diameter class.
Example Calculations

Suppose we have a 20 year-old loblolly pine plantation in the Georgia piedmont that has 340 tpa, 104 ft$^2$ of basal area, and a dominant height of 53 feet. Determine the number of trees in the 8" dbh class using 8.5" as the upper diameter class limit and 7.5" as the lower diameter class limit.

Calculate SI using equation 3.3

$$SI = \exp[-1.4128 + 1.1744(\ln(53) + 35.3202(1/20)) - \exp(-4.01832(1/20))]$$

$$SI = 60.2$$

Calculate Quadratic Mean DBH (D) as

$$D=\sqrt{104/340/0.005454154} = 7.4888221$$

Calculate Relative Spacing (RS) as

$$RS=\sqrt{43560/340} / 53 = 0.2135643$$

Now calculate $\hat{D}_0$, $\hat{D}_{25}$, $\hat{D}_{50}$, and $\hat{D}_{95}$ using equations 6.8, 6.9, 6.10, and 6.11

$$\hat{D}_0 = \exp[2.7711029 + 0.9906064 \ln(104/340) - 0.00657661(60.2)]$$

$$\hat{D}_0 = 3.3259771$$

$$\hat{D}_{50} = \exp[3.2888147 + 0.6114272 \ln(104/340) + 0.04215482 \ln(340) - 0.20125037 \ln(53) - 0.6020401(1/20)]$$

$$\hat{D}_{50} = 7.2509983$$
\[ \hat{D}_{25} = \exp[-3.6523041 + 1.5432169 \ln(7.2509983) + 1.4435789 (.2135643) + 0.3417899 \ln(340)] \]

\[ \hat{D}_{25} = 5.50446600 \]

\[ \hat{D}_{95} = \exp[0.584578 + 0.8988592 \ln(7.2509983) - 0.200558(.2135643)] \]

\[ \hat{D}_{95} = 10.2012588 \]

Now

\[ \hat{a} = [(34)^{1/3}(3.3259771) - 7.2509983]/[(34)^{1/3} - 1] \]

\[ \hat{a} = 1.5734 \]

\[ \hat{c} = 2.777427/[(\ln(10.2012588 - 1.5734) - \ln(5.50466 - 1.5734)] \]

\[ \hat{c} = 3.5335 \]

\[ \Gamma_1 = \Gamma(1 + 1/3.5335) = 0.9002032 \]

\[ \Gamma_2 = \Gamma(1 + 2/3.5335) = 0.8901409 \]

\[ \hat{b} = -[1.5734(0.9002032/0.8901409)][(1.5734^2/0.8901409^2) \]

\[ (0.9002032^2 - 0.8901409) + 7.4888221^2/0.8901409]^{1/2} \]

\[ \hat{b} = 6.3675194 \]
Now, to obtain the number of trees in the 8" dbh class (TPA$_8$) we use equation 6.2 as follows

\[
TPA_8 = N \left[ \left( 1 - \exp \left( -\frac{8.5 - a}{b} \right)^c \right) \right] - \left[ \left( 1 - \exp \left( -\frac{7.5 - a}{b} \right)^c \right) \right]
\]

\[
TPA_8 = 340 \left\{ \exp \left( -\left( \frac{7.5 - 1.5734}{6.3675194} \right)^{3.5335} \right) \right\} - \exp \left( -\left( \frac{8.5 - 1.5734}{6.3675194} \right)^{3.5335} \right)
\]

TPA$_8$ = 68

Stock Table Calculations

After obtaining the stand table we can calculate the associated stock table using a height - dbh function and individual tree volume (weight) equations. To obtain the volume within a given dbh-class first predict the height of the dbh-class midpoint using the height-dbh function and then obtain the volume (weight) using the dbh-class midpoint and its associated height via an individual tree volume (weight) equation. This volume represents the average volume (weight) of each tree within the dbh-class. To obtain the total class volume (weight) simply multiply by the number of trees in the dbh-class. Per acre volume (weight) is then obtained by summing over all dbh-classes.

The following height-dbh function was fitted to the loblolly pine data

\[
H_i = H_D \alpha \left( 1 - \beta \exp \left( -\gamma \frac{dbh_i}{D} \right) \right)
\]

\[\text{(6.20)}\]

where:

\[
\begin{align*}
H_i & = \text{height of tree } i, \\
H_D & = \text{dominant height}, \\
dbh_i & = \text{diameter breast height of tree } i, \\
D & = \text{quadratic mean dbh of the stand}, \\
\alpha, \beta, \gamma & = \text{parameters to be estimated.}
\end{align*}
\]

This function was found to fit the observed height-dbh data very well. It has the desirable feature of predicting individual tree heights larger than average dominant height for the largest dbh trees.
in the stand. The height-dbh relationship was found to be statistically significantly different for the lower coastal plain stands. No differences were detected between upper coastal plain and piedmont stands. The final equation for the piedmont and upper coastal plain, fitted with 7250 individual tree measurements, is

\[
H_i = H_D(1.24711) \left[ 1 - 0.80788 \exp \left( -1.36801 \left( \frac{dbh_i}{D} \right) \right) \right] 
\]

(6.21)

Average Residual = 0.08 feet
Percent Variation Explained = 91.2

The final equation for the lower coastal plain, fitted with 4782 individual tree measurements, is

\[
H_i = H_D(1.21177) \left[ 1 - 0.90943 \exp \left( -1.60533 \left( \frac{dbh_i}{D} \right) \right) \right] 
\]

(6.22)

Average Residual = 0.09 feet
Percent Variation Explained = 91.9
Stand Table Projection Model

The diameter distribution yield model described above uses only whole stand information such as basal area per acre, trees per acre, stand age, site index, dominant height, and relative spacing to obtain an estimate of the stand table, stock table, and per acre volume (weight) yield. Some users routinely obtain and store an estimate of existing stand tables along with the above mentioned whole stand attributes. When an initial stand table is available as input a stand table projection algorithm originally developed by Clutter and Allison (1974) and revised by Pienaar and Harrison (1988) will be used to obtain future stand and stock tables. This procedure does not rely on an underlying probability distribution function, such as the Weibull, and is very flexible in that any shape stand table, including multi-modal stand tables, can be modeled easily.

Relative size of an individual tree is defined as

\[
\frac{b_i}{b}
\]

where:

\[
b_i = \text{basal area of tree } i, \quad \frac{1}{b} = \text{average basal area of all trees on the plot.}
\]

The following relationship has been shown to be a plausible relationship between present and future relative size (Pienaar and Harrison 1988)

\[
\frac{b_{2i}}{b_2} = \left( \frac{b_{1i}}{b_1} \right)^{A_2} \left( \frac{A_2}{A_1} \right)^\beta
\]

(6.23)
where:

\[ b_{1i} = \text{basal area of tree } i \text{ at age 1}, \]
\[ b_{2i} = \text{basal area of tree } i \text{ at age 2}, \]
\[ b_1 = \text{average basal area of all survivor trees on the plot at age 1}, \]
\[ b_2 = \text{average basal area of all survivor trees on the plot at age 2}, \]
\[ A_1 = \text{age 1}, \]
\[ A_2 = \text{age 2}, \]
\[ \beta \text{ is a parameter estimated from the data}. \]

As Pienaar and Harrison (1988) point out, if \( \beta \) is greater than zero this formulation implies that survivor trees smaller than the average size will become smaller in relation to the average size and survivor trees larger than average size will become larger in relation to the average size as the stand ages. Also, a smaller change in relative size will be realized for a given length of projection as initial age increases. Both of these implications are reasonable for even-aged pine plantations.

Equation 6.23 can be rearranged algebraically to obtain an estimate of basal area at time 2 for tree \( i \) as follows

\[
b_{2i} = b_2 \left( \frac{b_{1i}}{b_1} \right) \left( \frac{A_2}{A_1} \right)^\beta
\]

(6.24)

This algorithm can be applied in two different ways. One way is to project individual trees and use a stochastic individual tree mortality function. The second way is to project midpoint diameter classes of the present stand table and constrain the resulting projected stand table to have the same tpa and basal area per acre as projected by whole stand survival and basal area projection functions. This second approach is preferred for two reasons; 1) it removes the stochastic nature of the individual tree procedure, and 2) it constrains the stand table to be consistent with the whole stand parameters of tpa and BA in which we have fairly high confidence.
To project the midpoint diameters we will use the following revision of equation 6.24 which insures compatibility with per acre basal area

\[ b_{2i} = b_2 n \frac{(b_{1i}/b_1)^{(A_2/A_1)\beta}}{\sum_{i=1}^{n}(b_{1i}/b_1)^{(A_2/A_1)\beta}} \]  

(6.25)

where:

- \( n \) = number of survivor trees,
- and all else is as previously defined.

Now summing equation 6.25 over \( n \) we see

\[ \sum_{i=1}^{n} b_{2i} = b_2 n = BA_2 \]

where:

- \( BA_2 \) = observed or predicted basal area per acre at time 2,
- and all else is as previously defined.

Equation 6.23 was fitted to individual survivor sample trees on remeasured permanent plots. The \( \beta \) parameter was found to be statistically significantly different for the lower coastal plain but no difference was detected between the piedmont and upper coastal plain. The final equation for the piedmont and upper coastal plain, fitted to 3296 individual tree measurements, is

\[ \frac{b_{2i}}{b_2} = \left( \frac{b_{1i}}{b_1} \right)^{(A_2/A_1)^{0.0457}} \]  

(6.26)

Average Residual = -0.003
Percent Variation Explained = 97.6
The equation for the lower coastal plain, fitted to 807 individual trees, is

\[
\frac{b_{2i}}{b_2} = \left( \frac{b_{1i}}{b_1} \right)^{A_2/A_1^{0.1717}}
\]  (6.27)

Average Residual = -0.0012
Percent Variation Explained = 98.0

The implication of equations 6.26 and 6.27 is that stand tables in the lower coastal plain expand more quickly than those in the upper coastal plain and piedmont.

To project a stand table we first project tpa to the future age using equation 4.1 to obtain \( n \), the number of survivors at the projection age. Basal area at time 2 (BA₂) is projected using equation 5.2 or 5.6 depending on the physiographic region your stand is in. The number of trees dying during the projection period (obtained as the difference between \( N₁ \) and the projected \( N₂ \)) is allocated to the initial stand table so that only survivors are projected to the future age. It is assumed that the probability a given tree dies during the projection period is inversely proportional to its relative size. This implies that trees in smaller diameter classes die at a faster rate than trees in larger diameter classes. Pienaar and Harrison (1988) explain the procedure for calculating the number of dead trees expected in each initial dbh class. Once mortality is allocated to the stand table and basal area is projected to the desired age, diameter class midpoints are projected using equation 6.26 or 6.27 depending on the physiographic region the stand is in. To compile the projected diameter class midpoints into a one-inch dbh-class stand table it is assumed that all trees in a given dbh-class have the same dbh growth and are uniformly distributed. Dbh-class limits of the projected stand table are then assumed to fall halfway between the projected dbh-class midpoints. One-inch dbh-classes are then obtained using linear interpolation methodology.

To obtain stock tables the height-dbh function and individual tree volume (weight) equations are used in the same fashion as for the stand table obtained with the Weibull diameter distribution model described above.
Whole Stand Yield Prediction and Projection

In some situations it is not necessary to have stand and stock tables if per acre yield estimates by product class are available. This may be the case when a harvest schedule is being developed using linear programming. Amateis et al. (1986) presented a very flexible whole stand yield model which can be used to obtain yield by product class for various top diameter merchantability limits. The general form of the model is:

\[ Y_m = Y_{exp}[\beta_1(t/D)^{\beta_2} + \beta_3(N)^{\beta_4}(d/D)^{\beta_5}] \]  

(6.28)

where:

- \( Y_m \) = merchantable o.b. or i.b. yield (ft\(^3\)/ac or lbs/ac)
- for trees d inches and above to a t-inch top diameter limit,
- \( Y \) = total o.b. or i.b. yield (ft\(^3\)/ac or lbs/ac),
- \( D \) = quadratic mean dbh (inches),
- \( N \) = number of surviving trees per acre,
- \( t \) = top diameter (o.b.) merchantability limit (inches),
- \( d \) = threshold dbh limit (inches),
- \( \beta_1 - \beta_5 \) are parameters estimated from data.

As Amateis et al. (1986) point out, equation 6.28 is conditioned to set merchantable yield (\( Y_m \)) equal to total yield when \( t \) and \( d \) are set equal to zero. Furthermore, if \( t \) alone is set to zero merchantable volume is defined as total volume of all trees greater than or equal to \( d \)-inches dbh. When \( d \) alone is set to zero merchantable volume is defined as volume of all trees to a top diameter limit of \( t \)-inches.

Note that it is possible to calculate merchantable yields by individual diameter classes or product classes by subtraction. For example, if we want an estimate of the cubic foot volume of trees with dbh greater than 4.5 inches and less than or equal to 9.5 inches to a 4 inch top diameter limit we use the following procedure:

1) Set \( t = 4 \), set \( d = 4.5 \), calculate \( Y_m \) using equation 6.28,
2) Set \( t = 4 \), set \( d = 9.5 \), calculate \( Y_m \) using equation 6.28,
3) Subtract volume predicted in 2 from volume predicted in 1.
Clearly, equation 6.28 provides us with a very simple procedure for obtaining merchantable yields by product class. In order to use equation 6.28 we must have a whole stand total volume (weight) prediction or projection equation. Volume and weight per acre prediction and projection models were developed and fitted to the PMRC data base. Statistically significant differences were found among all physiographic regions. The following model forms are used:

\[
\text{TVOB}_1 = \exp^{a_1} (H_{D1})^{a_2} (N_1)^{a_3} (BA_1)^{a_4}
\]

\[
\text{TVOB}_2 = \text{TVOB}_1 (H_{D2}/H_{D1})^{a_2} (N_2/N_1)^{a_3} (BA_2/BA_1)^{a_4}
\]

\[
\text{TVIB}_1 = \exp^{b_1} (H_{D1})^{b_2} (N_1)^{b_3} (BA_1)^{b_4}
\]

\[
\text{TVIB}_2 = \text{TVIB}_1 (H_{D2}/H_{D1})^{b_2} (N_2/N_1)^{b_3} (BA_2/BA_1)^{b_4}
\]

\[
\text{DWIB}_1 = \exp^{c_1} (H_{D1})^{c_2} (N_1)^{c_3} (BA_1)^{c_4}
\]

\[
\text{DWIB}_2 = \text{DWIB}_1 (H_{D2}/H_{D1})^{c_2} (N_2/N_1)^{c_3} (BA_2/BA_1)^{c_4}
\]

\[
\text{GWOB}_1 = \exp^{d_1} (H_{D1})^{d_2} (N_1)^{d_3} (BA_1)^{d_4}
\]

\[
\text{GWOB}_2 = \text{GWOB}_1 (H_{D2}/H_{D1})^{d_2} (N_2/N_1)^{d_3} (BA_2/BA_1)^{d_4}
\]

where:

\[
\text{TVOB}_i = \text{total volume yield (ft}^3/\text{ac) o.b. at time } i,
\]

\[
\text{TVIB}_i = \text{total volume yield (ft}^3/\text{ac) i.b. at time } i,
\]

\[
\text{DWIB}_i = \text{dry weight (pounds/acre) i.b. at time } i,
\]

\[
\text{GWOB}_i = \text{green weight (pounds/acre) o.b. at time } i,
\]

\[
i = 1, 2,
\]

and all else is as previously defined.
Parameter estimates by region for each yield model are given in table 6.1. All models fit the data very well as evidenced by statistics of fit given in table 6.2.

The total volume breakdown equation (6.28) was fitted for outside and inside cubic foot volume, dry weight inside bark, and green weight outside bark. The final equation form is a variation of Amateis et al's (1986) model with relative spacing (RS) used in place of trees per acre (N in equation 6.28). Statistically significant differences were found among the three physiographic regions. The final model form is:

\[ Y_m = Y \exp[\beta_1(t/D)^{\beta_2} + \beta_3(RS)^{\beta_4}(d/D)^{\beta_4}] \]  

Parameter estimates and statistics of fit for merchantable cubic foot volume outside bark, merchantable cubic foot volume inside bark, merchantable dry weight (pounds) inside bark, and merchantable green weight (pounds) outside bark are given by physiographic region in tables 6.3, 6.4, 6.5, and 6.6 respectively.

Input variables required to use this whole stand yield system are age (current or future), site index (or current dominant height), and trees per acre. With these inputs current yield by product class (for given values of t and d) can be obtained as follows:

1) predict current basal area using the basal area prediction equation for the appropriate physiographic region,

2) obtain an estimate of current quadratic mean dbh (D) using predicted basal area and observed current tpa,

3) predict current total volume using the volume yield prediction equation for the appropriate physiographic region,

4) use the yield breakdown equation for the appropriate physiographic region.
To obtain future yield by product class (for given values of t and d) using the input variables discussed above, we proceed as follows:

1) obtain estimates of current and future basal area using the basal area prediction and projection equations for the appropriate physiographic region,

2) obtain an estimate of future quadratic mean dbh (D) using projected basal area and projected tpa obtained from the survival function,

3) obtain estimates of current and future total volume using the total volume prediction and projection equations for the appropriate physiographic region,

4) use the yield breakdown equation for the appropriate physiographic region.

Note that if current basal area and/or total volume is known use these observed values in the appropriate basal area or total volume projection equations.
Table 6.1. Parameter estimates by physiographic region for volume and weight prediction and projection models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Piedmont</th>
<th>Upper Coastal Plain</th>
<th>Lower Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>0.0</td>
<td>-0.15811</td>
<td>-1.74685</td>
</tr>
<tr>
<td>a2</td>
<td>0.81599</td>
<td>0.80771</td>
<td>1.20281</td>
</tr>
<tr>
<td>a3</td>
<td>-0.08479</td>
<td>-0.06830</td>
<td>0.05221</td>
</tr>
<tr>
<td>a4</td>
<td>1.09915</td>
<td>1.12227</td>
<td>0.96452</td>
</tr>
<tr>
<td>b1</td>
<td>-0.96734</td>
<td>-0.85359</td>
<td>-2.32605</td>
</tr>
<tr>
<td>b2</td>
<td>1.01551</td>
<td>0.93646</td>
<td>1.30390</td>
</tr>
<tr>
<td>b3</td>
<td>-0.07765</td>
<td>-0.06930</td>
<td>0.02839</td>
</tr>
<tr>
<td>b4</td>
<td>1.08475</td>
<td>1.11800</td>
<td>0.98702</td>
</tr>
<tr>
<td>c1</td>
<td>1.56554</td>
<td>1.98942</td>
<td>0.65550</td>
</tr>
<tr>
<td>c2</td>
<td>1.17325</td>
<td>1.10888</td>
<td>1.42148</td>
</tr>
<tr>
<td>c3</td>
<td>-0.03425</td>
<td>-0.09022</td>
<td>0.0</td>
</tr>
<tr>
<td>c4</td>
<td>1.05656</td>
<td>1.09558</td>
<td>1.00336</td>
</tr>
<tr>
<td>d1</td>
<td>3.32881</td>
<td>3.25871</td>
<td>2.19652</td>
</tr>
<tr>
<td>d2</td>
<td>0.99939</td>
<td>0.94741</td>
<td>1.22828</td>
</tr>
<tr>
<td>d3</td>
<td>-0.10128</td>
<td>-0.05347</td>
<td>0.05002</td>
</tr>
<tr>
<td>d4</td>
<td>1.10349</td>
<td>1.10535</td>
<td>0.96649</td>
</tr>
</tbody>
</table>
Table 6.2. Statistics of fit for volume and weight prediction and projection models by physiographic region.

<table>
<thead>
<tr>
<th>Model</th>
<th>PIEDMONT</th>
<th>Upper Coastal Plain</th>
<th>Lower Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVOB1</td>
<td>AR¹</td>
<td>-0.3</td>
<td>-3.9</td>
</tr>
<tr>
<td></td>
<td>PVE²</td>
<td>98.9</td>
<td>99.6</td>
</tr>
<tr>
<td>TVOB2</td>
<td>AR</td>
<td>-21.0</td>
<td>-47.4</td>
</tr>
<tr>
<td></td>
<td>PVE</td>
<td>91.3</td>
<td>91.3</td>
</tr>
<tr>
<td>TVIB1</td>
<td>AR</td>
<td>-0.5</td>
<td>-3.4</td>
</tr>
<tr>
<td></td>
<td>PVE</td>
<td>98.9</td>
<td>99.6</td>
</tr>
<tr>
<td>TVIB2</td>
<td>AR</td>
<td>-18.2</td>
<td>-41.5</td>
</tr>
<tr>
<td></td>
<td>PVE</td>
<td>91.8</td>
<td>91.4</td>
</tr>
<tr>
<td>DWIB1</td>
<td>AR</td>
<td>-329.4</td>
<td>-436.6</td>
</tr>
<tr>
<td></td>
<td>PVE</td>
<td>98.4</td>
<td>99.5</td>
</tr>
<tr>
<td>DWIB2</td>
<td>AR</td>
<td>-659.0</td>
<td>-1370.9</td>
</tr>
<tr>
<td></td>
<td>PVE</td>
<td>91.3</td>
<td>92.1</td>
</tr>
<tr>
<td>GWOB1</td>
<td>AR</td>
<td>-70.1</td>
<td>-213.0</td>
</tr>
<tr>
<td></td>
<td>PVE</td>
<td>99.0</td>
<td>99.6</td>
</tr>
<tr>
<td>GWOB2</td>
<td>AR</td>
<td>-1232.0</td>
<td>-2692.7</td>
</tr>
<tr>
<td></td>
<td>PVE</td>
<td>91.7</td>
<td>91.3</td>
</tr>
</tbody>
</table>

¹ AR - average residual (observed - predicted)

² PVE - percent variation explained
Table 6.3. Parameter estimates and statistics of fit for merchantable cubic foot volume outside bark breakdown equation (6.29) by physiographic region.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Piedmont</th>
<th>Upper Coastal Plain</th>
<th>Lower Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_1$</td>
<td>-0.65632</td>
<td>-0.60851</td>
<td>-0.51428</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>4.65212</td>
<td>4.45592</td>
<td>3.76584</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>-0.23738</td>
<td>-0.21787</td>
<td>-0.33752</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>-0.26185</td>
<td>-0.33502</td>
<td>-0.12110</td>
</tr>
<tr>
<td>$\beta_5$</td>
<td>5.49138</td>
<td>5.49584</td>
<td>5.49547</td>
</tr>
</tbody>
</table>

Statistics of Fit

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AR$^1$</td>
<td>20.9</td>
<td>23.8</td>
</tr>
<tr>
<td>PVE$^2$</td>
<td>96.2</td>
<td>96.2</td>
</tr>
</tbody>
</table>

$^1$ AR - average residual (observed-predicted)

$^2$ PVE - percent variation explained
Table 6.4. Parameter estimates and statistics of fit for merchantable cubic foot volume inside bark breakdown equation (6.29) by physiographic region.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Piedmont</th>
<th>Upper Coastal Plain</th>
<th>Lower Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_1$</td>
<td>-0.70923</td>
<td>-0.64108</td>
<td>-0.56328</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>4.58127</td>
<td>4.43683</td>
<td>3.72169</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>-0.23880</td>
<td>-0.22004</td>
<td>-0.33724</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>-0.25595</td>
<td>-0.32674</td>
<td>-0.11267</td>
</tr>
<tr>
<td>$\beta_5$</td>
<td>5.44005</td>
<td>5.47887</td>
<td>5.49165</td>
</tr>
</tbody>
</table>

Statistics of Fit

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AR$^1$</td>
<td>16.2</td>
<td>18.9</td>
<td>11.8</td>
</tr>
<tr>
<td>PVE$^2$</td>
<td>96.2</td>
<td>96.2</td>
<td>97.8</td>
</tr>
</tbody>
</table>

$^1$ AR - average residual (observed-predicted)

$^2$ PVE - percent variation explained
Table 6.5. Parameter estimates and statistics of fit for merchantable dry weight (pounds) inside bark breakdown equation (6.29) by physiographic region.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Piedmont</th>
<th>Upper Coastal Plain</th>
<th>Lower Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_1$</td>
<td>-0.67155</td>
<td>-0.60970</td>
<td>-0.49474</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>4.67713</td>
<td>4.53141</td>
<td>3.82486</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>-0.24012</td>
<td>-0.21557</td>
<td>-0.33486</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>-0.25345</td>
<td>-0.32606</td>
<td>-0.11052</td>
</tr>
<tr>
<td>$\beta_5$</td>
<td>5.50552</td>
<td>5.53859</td>
<td>5.53416</td>
</tr>
</tbody>
</table>

Statistics of Fit

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AR$^1$</td>
<td>421</td>
<td>535</td>
</tr>
<tr>
<td>PVE$^2$</td>
<td>96.5</td>
<td>96.2</td>
</tr>
</tbody>
</table>

$^1$ AR - average residual (observed-predicted)

$^2$ PVE - percent variation explained
Table 6.6. Parameter estimates and statistics of fit for merchantable green weight (pounds) outside bark breakdown equation (6.29) by physiographic region.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Piedmont</th>
<th>Upper Coastal Plain</th>
<th>Lower Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_1$</td>
<td>-0.70883</td>
<td>-0.64825</td>
<td>-0.56313</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>4.57560</td>
<td>4.43428</td>
<td>3.68481</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>-0.23320</td>
<td>-0.21658</td>
<td>-0.33798</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>-0.26033</td>
<td>-0.33864</td>
<td>-0.12108</td>
</tr>
<tr>
<td>$\beta_5$</td>
<td>5.46273</td>
<td>5.49306</td>
<td>5.47586</td>
</tr>
</tbody>
</table>

Statistics of Fit

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$AR^1$</td>
<td>1095</td>
<td>1245</td>
<td>849</td>
</tr>
<tr>
<td>$PVE^2$</td>
<td>96.1</td>
<td>96.3</td>
<td>97.8</td>
</tr>
</tbody>
</table>

$^1$ AR - average residual (observed-predicted)

$^2$ PVE - percent variation explained
Example Calculations

Suppose we have a 20 year-old loblolly pine plantation in the Georgia piedmont that has 340 tpa, 104 ft² of basal area, and a dominant height of 53 feet. Use the whole stand volume breakdown system to predict the volume outside bark to a 4" top of all trees with 4.5" < dbh <= 9.5". From the example calculations carried out for the Weibull system we know:

\[
\begin{align*}
SI &= 60.2 \\
D &= 7.4888221 \\
RS &= 0.2135643
\end{align*}
\]

Now we calculate total volume outside bark using the following equation

\[
TVOB_1 = H_{D_1}^{0.81599} N_1^{-0.08479} BA_1^{1.09915}
\]

Thus

\[
TVOB_1 = 53^{0.81599} 340^{-0.08479} 104^{1.09915}
\]

\[
TVOB_1 = 2566.67 \text{ ft}^3/\text{acre}.
\]

Now we calculate outside bark volume to a 4" top for all trees greater than 4.5" dbh with equation 6.29

\[
Y_{4,4.5} = TVOB_1 \exp[-0.65632(4/D)^{4.65212} - 0.23738(RS)^{-0.26185}(4.5/D)^{5.49138}]
\]

\[
Y_{4,4.5} = 2566.67 \exp[-0.65632(4/7.4888221)^{4.65212} \\
- 0.23738(0.2135643)^{-0.26185}(4.5/7.4888221)^{5.49138}]
\]

\[
Y_{4,4.5} = 2424.02 \text{ ft}^3/\text{acre}.
\]
Now we calculate outside bark volume to a 4" top for all trees greater than 9.5" with equation 6.29

\[ Y_{9,9.5} = 2566.67 \exp[-0.65632(4/7.4888221)^{4.65212} - 0.23738(0.2135643)^{-0.26185}(9.5/7.4888221)^{5.49138}] \]

\[ Y_{9,9.5} = 666.27 \text{ ft}^3/\text{acre}. \]

Outside bark volume to a 4" top for trees 4.5" < dbh <= 9.5" is calculated as

\[ Y_{4.4.5} - Y_{4,9.5} = 2424.02 - 666.27 = 1757.74 \text{ ft}^3/\text{acre}. \]
CHAPTER 7

COMPARISON AND VALIDATION OF YIELD PREDICTION AND PROJECTION SYSTEMS

The three yield prediction and projection systems vary in type of required input data and resolution of output information. An important question is which system is most precise or accurate for a given situation. To help shed some light on this question, the three systems were compared under two sets of assumptions. These two sets of assumptions are dictated by the various combinations of input data and output resolution desired.

One set of comparisons is for yield prediction. The systems which can be used for yield prediction are the Weibull parameter recovery system and the whole stand volume breakdown system. The error index developed by Reynolds et al. (1988) was used to compare these two systems. This error index is the sum of absolute differences between observed and predicted diameter or product class values (tpa, BA, volume, or value). The error index should be relatively small when all classes are predicted well. For the yield prediction comparison we use both the Weibull system and the whole stand volume breakdown system to predict merchantable volume in the following three product classes:

- **Pulpwood**: $4.5 < \text{dbh} \leq 9.5$; 4" outside bark top,
- **Chip-N-Saw**: $9.5 < \text{dbh} \leq 12.5$; 4" outside bark top,
- **Sawtimber**: $12.5 < \text{dbh}$; 6" outside bark top.

Note that for both systems it was assumed that stand age, dominant height, and trees per acre were available as input. The error index was calculated for both systems for each plot and was then averaged across all physiographic regions and within each physiographic region. These average error index values show that both yield prediction systems are similar in predictive ability for product classes as defined above (table 7.1). Thus, the decision as to which system to use for yield prediction should be based entirely on the output resolution desired since both systems are very similar in accuracy.
A second comparison of interest is the ability of the various systems to project yields from current conditions into the future. If an estimate of the current stand table is available then all three systems can potentially be used for projecting yields. For the comparison reported here, it was assumed that current age, dominant height, and trees per acre were available as input into the systems. Furthermore, it was assumed that the current stand table was available and thus current basal area and current volume were also available as input information. The error index was calculated for each plot using the three projection systems to project yields by the product classes previously defined. Average error index was calculated across all physiographic regions as well as by physiographic region. These average error index values show that all yield projection systems behave similarly (table 7.2). However, it should also be noted that the stand table projection system has a lower average error index in all cases except for lower coastal plain plots. Furthermore, the standard error is consistently lower for the stand table projection system. This implies that yields are being projected more precisely using the stand table projection system than using the other two systems. This is intuitively appealing since the stand table projection system uses the most information to make the yield projection and is similar to the findings of Patterson and Borders (1990). Thus, it becomes clear that if a stand table is available as input then the stand table projection system should give more precise projections. However, there is not a great difference between any of the systems and users who choose to use the more simple whole stand volume breakdown system will not give up a large degree of precision.

Comparison of the three systems discussed above was carried out with data used to fit the models. This gives us information to choose among the various models but does not indicate how these models will perform when used to predict or project data from independent sources. An independent data base, obtained from Union Camp Corporation, was used to validate the models presented above. These data come from a regionwide spacing study that most recently has been reported on by Borders and Bailey (1985). The study consists of 114 loblolly pine installations distributed across the southeastern United States. Each installation consists of variable sized plots, each containing 50 trees and ranging in density from 100 to 900 trees per acre (tpa). One installation has densities up to 1800
Table 7.1. Error index for the Weibull (WEIB) and whole stand volume breakdown (WHST) yield prediction systems.

<table>
<thead>
<tr>
<th>Physiographic Region</th>
<th>Model</th>
<th>Error Index</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Standard Error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All regions</td>
<td>WEIB</td>
<td>451.2</td>
<td>15.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>WHST</td>
<td>450.3</td>
<td>15.6</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Lower Coastal Plain</td>
<td>WEIB</td>
<td>610.5</td>
<td>32.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WHST</td>
<td>615.3</td>
<td>34.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Coastal Plain</td>
<td>WEIB</td>
<td>385.0</td>
<td>18.4</td>
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<tr>
<td></td>
<td>WHST</td>
<td>380.0</td>
<td>19.0</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Piedmont</td>
<td>WEIB</td>
<td>335.3</td>
<td>21.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WHST</td>
<td>333.4</td>
<td>21.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Table 7.2. Error index for the Weibull (WEIB), whole stand volume breakdown (WHST), and stand table projection (STP) yield projection systems.

<table>
<thead>
<tr>
<th>Physiographic Region</th>
<th>Model</th>
<th>Error Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>All regions</td>
<td>WEIB</td>
<td>500.9</td>
</tr>
<tr>
<td></td>
<td>WHST</td>
<td>516.1</td>
</tr>
<tr>
<td></td>
<td>STP</td>
<td>471.7</td>
</tr>
<tr>
<td>Lower Coastal Plain</td>
<td>WEIB</td>
<td>640.6</td>
</tr>
<tr>
<td></td>
<td>WHST</td>
<td>628.2</td>
</tr>
<tr>
<td></td>
<td>STP</td>
<td>671.5</td>
</tr>
<tr>
<td>Upper Coastal Plain</td>
<td>WEIB</td>
<td>420.4</td>
</tr>
<tr>
<td></td>
<td>WHST</td>
<td>453.0</td>
</tr>
<tr>
<td></td>
<td>STP</td>
<td>347.7</td>
</tr>
<tr>
<td>Piedmont</td>
<td>WEIB</td>
<td>428.3</td>
</tr>
<tr>
<td></td>
<td>WHST</td>
<td>455.1</td>
</tr>
<tr>
<td></td>
<td>STP</td>
<td>383.3</td>
</tr>
</tbody>
</table>
Plots were measured at age 2 and every 3 years thereafter. Currently, the oldest plots are 23 years old. Further details of these data can be found in Borders and Bailey (1985).

The two yield prediction systems (the weibull and whole stand systems) were used to predict per acre basal area and volume given inputs of current age, tpa, and dominant height. The number of plots used in this test by age and physiographic region is shown in table 7.3. Average residual (observed - predicted values) by model and physiographic region shows that the models performed very well (Table 7.4). Residual plots showed no trends with regard to any input variable.

The three yield projection systems (the weibull, whole stand, and stand table projection systems) were used to project basal area per acre, volume per acre, trees per acre, and dominant height from inputs of current and future age, current dominant height and current trees per acre. In addition to these inputs, current basal area was also input for the stand table projection system. Three projection periods were used for this analysis: 8-11 years, 11-14 years, and 14-20 years. The number of plots by projection period and physiographic region are given in table 7.3. Average residuals show that all models are performing relatively well (table 7.5) and residual plots showed no trends with regard to input variables. There is a slight under prediction occurring for basal area per acre and volume per acre. This is attributed to the relatively large underprediction of dominant height which resulted from having to arbitrarily calculate dominant height for this data since crown class was not available in the data base. The definition used to calculate dominant height was the average height of all trees greater than the average height per plot. Obviously, this is an arbitrary call and it is not surprising that a consistent over or underprediction occurs. The under prediction of basal area per acre for the stand table projection system was relatively large. This may be because the plots used in this study were all very small and thus are not really suited to give good representation of stand tables, a key component of the stand table projection system.
Table 7.3. Number of plots used for model prediction and projection validation.

<table>
<thead>
<tr>
<th>Age</th>
<th>Piedmont</th>
<th>Upper Coastal Plain</th>
<th>Lower Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>32</td>
<td>307</td>
<td>288</td>
</tr>
<tr>
<td>14</td>
<td>17</td>
<td>196</td>
<td>64</td>
</tr>
<tr>
<td>17</td>
<td>3</td>
<td>136</td>
<td>30</td>
</tr>
<tr>
<td>20</td>
<td>-</td>
<td>39</td>
<td>16</td>
</tr>
<tr>
<td>23</td>
<td>-</td>
<td>16</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Age Interval</th>
<th>Piedmont</th>
<th>Upper Coastal Plain</th>
<th>Lower Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-11</td>
<td>32</td>
<td>321</td>
<td>319</td>
</tr>
<tr>
<td>11-14</td>
<td>17</td>
<td>203</td>
<td>73</td>
</tr>
<tr>
<td>14-20</td>
<td>-</td>
<td>39</td>
<td>16</td>
</tr>
</tbody>
</table>
Table 7.4. Average residuals (observed-predicted values) for basal area per acre and volume per acre for two yield prediction systems used on independent data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Piedmont</th>
<th>Upper Coastal Plain</th>
<th>Lower Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>-35.7</td>
<td>-4.1</td>
<td>-214.5</td>
</tr>
<tr>
<td>Basal Area</td>
<td>0.3</td>
<td>3.4</td>
<td>-7.8</td>
</tr>
</tbody>
</table>

**Physiographic Region**

**Weibull Model**

**Whole Stand Model**

| Volume          | -3.6     | 43.1                | -201.1              |
| Basal Area      | 0.3      | 3.4                 | -7.8                |
Table 7.5. Average residuals (observed-predicted values) for basal area per acre, volume per acre, trees per acre, and dominant height for three yield projection models used on independent data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Piedmont</th>
<th>Upper Coastal Plain</th>
<th>Lower Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Weibull Model</td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td>100.8</td>
<td>246.2</td>
<td>478.6</td>
</tr>
<tr>
<td>Basal area</td>
<td>5.9</td>
<td>11.1</td>
<td>13.3</td>
</tr>
<tr>
<td>Trees/acre</td>
<td>-5.1</td>
<td>-10.8</td>
<td>-12.1</td>
</tr>
<tr>
<td>Height</td>
<td>2.5</td>
<td>3.4</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whole Stand Model</td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td>166.6</td>
<td>351.9</td>
<td>488.5</td>
</tr>
<tr>
<td>Basal area</td>
<td>5.9</td>
<td>11.1</td>
<td>13.3</td>
</tr>
<tr>
<td>Trees/acre</td>
<td>-5.1</td>
<td>-10.8</td>
<td>-12.1</td>
</tr>
<tr>
<td>Height</td>
<td>2.5</td>
<td>3.4</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stand Table Projection</td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td>95.0</td>
<td>110.6</td>
<td>522.1</td>
</tr>
<tr>
<td>Basal area</td>
<td>9.3</td>
<td>8.1</td>
<td>22.6</td>
</tr>
<tr>
<td>Trees/acre</td>
<td>-5.1</td>
<td>-10.8</td>
<td>-12.1</td>
</tr>
<tr>
<td>Height</td>
<td>2.5</td>
<td>3.4</td>
<td>9.1</td>
</tr>
</tbody>
</table>
LITERATURE CITED


