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[1] Contributed paper, not presented at the workshop.

# RESEARCH PAPERS

## Biomass Functions in the Eastern United States: Regression Models and Application to Timber Inventories

Moderator: Virgil C. Baldwin, Jr.

"A SUMMARY OF EQUATIONS FOR PREDICTING BIOMASS OF PLANTED SOUTHERN PINES"

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Publications containing regression equations for predicting green or dry weight of whole trees or components of planted southern pine species were reviewed. Their results are summarized with emphasis on the equation databases (sample selection processes, sample size, representiveness), and prediction models utilized. The parameter fitting processes, the measures of precision reported, and the expressed or implied usefulness of the equations are also discussed.

## Introduction

Research involving the measurement of whole tree or tree component weight has progressed very rapidly in the South. With some exceptions, green- and dry-weight prediction equations are available for the bole weights of nearly all commercially important softwood and hardwood species. In many instances, branch and foliage weight prediction equations are also available for these species. Baldwin (1984), summarizing statements of earlier researchers, indicated that this work has progressed because of the more widespread use of weight scaling, the utilization of non-bole components in the forest products industry, and the need for biomass as a supplemental energy source.

Forest biomass researchers have responded to meet the need for prediction equations and many have been published. However, because of the great cost involved in developing these equations, there is quite a disparity with respect to which tree components can be weight-predicted. Also, some equations were derived from data sets quite restricted in their representiveness of each species' population and therefore have narrow utility.

The purpose of this paper is to identify, catalog, and describe the data sets, models, and fitted regression equations that have been developed for planted southern pines. This will be an update to, but have a slightly different emphasis than, an earlier review published by Baldwin (1982) and should serve as a guide to the applicability of existing functions for predicting the biomass of southern pine plantations. The published equations and supporting statistics, if reported, will not be given here because of space limitations; however, the references and all essential background information about the publications are given in Table 1. The reader should go directly to the last page of this table first when referring to it to become familiar with the table-heading codes.

## Biomass prediction models

Biomass prediction equations generally have utilized one of the following three basic model forms:

Linear (additive error):

$$Y = \beta_0 + \beta_1 X_1 + \ldots + \beta_j X_j + \varepsilon, \qquad (1)$$

Non-linear (additive error):

$$Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} \ldots X_j^{\beta_j} + \varepsilon, \qquad (2)$$

Non-linear (multiplicative error):

$$Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} \ldots X_j^{\beta_j} \varepsilon, \qquad (3)$$

where $Y$ = dependent variables,

$X_j$ = independent or predictor variables,

$\beta_j$ = parameters to be estimated,

and $\varepsilon$ = error term.

Model 1 produces multiple linear regressions that can be fitted by standard least squares estimation procedures. Some commonly used variables are diameter at breast height (dbh), diameter squared, total height, diameter squared times total height, age, and live crown ratio.

Model 2 produces nonlinear regression equations that require use of iterative procedures for parameter estimation. Commonly used variables are the same as above.

Model 3 nonlinear regression equations are usually transformed into linear (additive error) regression equations by taking the logarithm of both sides of the equation. In this form the equation parameters can easily be estimated by least squares procedures. However, all common goodness-of-fit statistics will relate to the transformed equation only, and are not directly comparable with the same statistics produced through use of either models 1 or 2 unless further steps are taken. Furthermore, the "intercept" parameter must be corrected to obtain precise prediction when retransforming these equations back into the original units (Baskerville 1972, Yandle and Wiant 1981). Variables commonly used are the logarithmic transformations (to either base e or base 10) of those listed above.

Prediction Equations Available

The earliest green-weight equations for plantation southern pines were developed by McGee (1959) for old-field slash pines in the sandhills of North and South Carolina. The regression equations and any supporting statistics are not given in the paper, but derived tables for bole green weight (including bark) for 4-, 3-, and 2-inch top merchantability limits are presented. McGee's sample consisted of 250 randomly selected merchantable (dbh $\geq$ 5 inches) trees from 150 plantations.

Romancier (1961) produced green-weight and volume tables for plantation-grown loblolly pine for the lower piedmont of Georgia. His sample of 116 trees, representing all crown classes, came from 12 plantations ranging from 19 to 24 years old, 5 to 12 inches dbh, and 30 to 65 feet tall. Equations (from model 1) and tables are for merchantable bole weight or volume predictions only. No goodness-of-fit statistics are given in the paper.

Three other noteworthy studies were done during the early 1960's from which tree component biomass equations were developed (Vaidya 1961, Baker 1962, Rogerson 1964). Foliage-weight equations were developed in all three cases, and in two of the studies branch-weight equations were developed in addition to bole-weight equations. The applicability of these equations is restricted though because the number of sample trees was small, and trees were selected from a single plantation or plantations located in a comparatively small geographic area.

The first of these studies, Vaidya (1961), utilized 12 shortleaf pine trees from 12 plantations and natural stands on the Duke Forest, North Carolina. All trees were dominants or codominants, although they were chosen to represent a broad range of site quality, age, and stand density. The three equations developed from these data, stem dry weight, branch dry weight, and foliage dry weight, were fitted using model 3 form. Standard error of the mean (SE) and coefficient of determination ($R^2$) statistics are given for each equation.

Baker (1962) sampled 27 dominant and codominant loblolly pine trees from 15 plots on the Duke Forest. They ranged in dbh from 1 to 10 inches, in age from 3 to 31 years, and in site index (base age 50) from 30 to 110 feet. He used model 3 to develop equations to predict stem dry weight, branch dry weight and foliage dry weight as functions of dbh, total height, site index, and percentage of stocking. $R^2$ and SE statistics are presented for each fitted equation.

Rogerson (1964) fitted loblolly pine foliage data to model 3, with the final equation predicting the weight of loblolly pine foliage as a function of dbh. He also tried projected crown area, tree basal area , and crown length, alone and in combination, in the equation but found that they did not significantly add to the predictions obtained using dbh alone or dbh and basal area. His 28 sample trees came from one plantation in northern Mississippi. His final equation $R^2$ was 0.81; SE was not given.

The first large whole-stem dry-weight study published for plantation southern pines was that of Collicott et al. (1968). They sampled 177 slash pine trees from the southwest Georgia area and present merchantable bole, top-volume and dry-weight tables for trees 5 - 12 inches dbh. Their trees were sampled from 54 one-quarter acre plots. The type 1 model form was used. Correlation coefficient (r) and SE values are given for each equation.

The publication by Burkhart and Clutter (1971) reports various aspects of Burkhart's biomass research for his doctoral dissertation which involved 702 loblolly pines sampled from 234 old-field plantations in the Georgia Piedmont. Three trees were sampled from each plantation - - 608 of the trees were > 5 inches dbh. Equations and tables are given for green- and dry-weight of the total and merchantable bole with and without bark. Equation form followed the type 1 model and $R^2$ values were presented. Burkhart followed this publication with Burkhart et al, (1972) wherein he presented similar bole-weight equations and tables for plantation loblolly pine sampled from the Virginia Piedmont Region and the Coastal Plains of Virginia, Deleware, Maryland, and North Carolina. They sampled 378 trees from 189 temporary plots which were randomly located within selected unthinned plantations. Equations developed from these data were also type 1 but no goodness-of-fit statistics were given for the weight or volume equations. In both of these studies samples were obtained across as wide a range as practical of tree heights and diameters, plantation ages, sites and densities.

Hasness and Lenhart (1972), Hicks et al. (1972), Hyink et al. (1972), Lenhart (1973), and Lenhart and Hyink (1973) are a series of publications that were based on a data set for plantation loblolly pine that was obtained in east Texas, Arkansas, and Louisiana. Wood only, wood plus bark, and green and dry weight, plus cubic-foot volume tables and prediction equations are given for the tree bole. The equations were based on a sample of 632 trees from 158 unthinned old-field plantations ranging in age from 9 to 30 years, in density from 174 to 1,518 trees per acre, and in site index (base age 25) from 37 to 85 feet. Equations were all from model 1, with both $R^2$ and SE statistics presented for each equation.

Prediction equations for estimating bole green and dry weight and cubic-foot volume of plantation slash pine in the West Gulf Region were developed by Moehring et al. (1973) and King and Moehring (1974). Their data set was obtained from 379 sample trees felled in 110 plantations established on old fields or previously cutover longleaf (_P. palustris_ Mill.) pinelands. Tables are presented with or without a form-class variable for the total and merchantable stem with or without bark. The model 1 form was followed,

$R^2 \geq 0.96$ for all equations, and the addition of a form-class variable in the equations reduced SE in all cases.

Several papers during the 1970's reported research in pine plantations on primary productivity and nutrient content. During this research, trees were felled and weighed, and equations were developed to describe the growth or yield in terms of the various tree components. Although the main thrust of the work was incidental to forest-management-related growth and yield work, the data and equations might prove useful for this purpose under certain circumstances. The following six paragraphs briefly describe these studies:

(1) Swank and Schreuder (1973) sampled 39 white pine (Pinus strobus L.) trees from the Coweeta Watershed in western North Carolina over a period of 5 years to determine temporal changes in biomass, surface area, and net production. Equations using a weighted model 1 form to reduce heterosckedasticity were developed to predict foliage, branch, and stem weights at different time periods. Also presented are $R^2$ and SE statistics.

(2) Annual primary productivity in a loblolly pine plantation was researched by Ralston (1973). He sampled 26 trees in 3 annual collections from 1 study plot in the Piedmont of North Carolina. Equations predicting weight of tree boles, branches, needles, and roots are provided; they are based on model 3. Variance and $R^2$ supporting statistics are given for each equation.

(3) Nemeth (1973) studied dry matter production in young loblolly and slash pine plantations on the Coastal Plain of North Carolina. Tree component prediction equations using model 3 form were developed from data measurements of 41 loblolly and 15 slash pine trees sampled from 28 permanent plots. Data from both species were combined in the fitting process, and a qualitative variable was included to differentiate the species. However, this species-variable was only significant in the regressions predicting main stem bark, bole needles, and dead branches. Variance of the mean and $R^2$ values are also included.

(4) Biomass production and nitrogen recovery after fertilization of young loblolly pines in central Mississippi were the topics of Baker et al.'s (1974) research project. They sampled a total of 85 trees 3 to 6 years old. Biomass prediction equations, which are presented in Baker's doctoral dissertation (Baker 1971), were developed for trees in each fertilization treatment. He utilized the model 3 form and provided the correlation coefficient as a goodness-of-fit measure.

(5) Wells et al. (1975) felled 16 trees in a 16-year-old thinned loblolly pine plantation on the North Carolina Piedmont. Biomass prediction equations were developed but were not published; they are available from the authors.

(6) Nelson and Switzer (1975) present prediction equations and tables for green and dry weight of loblolly pines, based on the data from other studies conducted at the Mississippi Agricultural and Forestry Experiment Station (e.g. Baker 1971). The data were originally collected for other study objectives. Their publication presents separate equations (using model 3 form) and tables for estimating aboveground components of plantation loblolly pines at ages 3, 5, 6, 10, and 15. In all, 133 trees were used to develop these equations. Included is the goodness-of-fit measure, $R^2$.

Weight and volume equations for southeast coastal plain plantations of loblolly pine were developed by Flowers (1978). He sampled 762 trees from plantations 10 to 30 years old having site indices (base age 25) ranging from less than 45 to more than 84 feet. Similarly, green- and dry-weight equations for southeast coastal plain slash pine are presented in Queen and Pienaar (1977). Their sample also covered a wide range of stand ages, sites, and densities. In both of these publications, results are given for total wood and bark and for "merchantable" portions of the bole only. The equations were developed from model 3 for total cubic foot volume or total green or dry weight. Merchantable volume or weights are predicted using a ratio equation that predicts the proportion of the total volume or weight contained in the merchantable portion of the stem. Those equations are also presented in two recent articles describing growth and yield prediction systems for plantation loblolly and slash pine (Clutter et al. (1984) and Bailey et al. (1982), respectively). $R^2$ and SE were the support statistics used in these publications.

Edwards and McNab (1979, 1981) sampled trees from young even-aged stands of loblolly, longleaf, shortleaf, and slash pines in central Georgia and developed total tree dry-weight equations for each species. The sample trees ranged in age form 2 to 20 years, in groundline diameter from less than 1 to 6 inches, and in height from about 1 to 29 feet. Equations were of model 3 form. There is no specific reference in the publications stating that these trees came from plantations. They are mentioned here because there is little information available about sapling-size shortleaf and longleaf pines in either natural or planted stands. The goodness-of-fit statistics provided are correlation coefficient and variance of the estimate.

The most recent biomass studies have usually reflected the increased interest in total tree utilization. The resulting publications usually report green- and dry-weight equations for all of the aboveground components, but only one major mensurational study predicts pine plantations stump/root system weights as well as aboveground component weights (Gibson et al. 1984).

Madgwick and Kreh (1980) provided equations to estimate the component biomass of Virginia pine (Pinus virginiana Mill.) trees and stands. They fitted data from 506 trees (182 from plantations) felled from 13 plots in 10 stands on the Virginia Piedmont. The sample included five open-grown trees. The equations developed were from model 3. Also presented are SE values.

Rockwood et al. (1980) produced equations to predict the green and dry weight of dense plantations of Choctawhatchee sand pine (P. clausa var. immuginata Ward) in the Florida sandhills. Only equations for prediction of green and dry stem weight are given, although all the components were weighed separately; presumably, total tree and/or other component equations could be fitted from the data if needed. The authors anticipate that the main utilization of the species will be for fuelwood. The equation form used was from model 1; $R^2$ is the only support statistic given. These samples consisted of 28 trees from 3 plantations on the Chipola Experimental Forest.

To study the impact of attacks by the Nantuckett pine tip moth on young loblolly pine, Hedden et al. (1981) looked closely at the effects the defoliation had on the biomass of the tree components. Twenty trees, 10 each from untreated and insecticide-treated plots were felled after a sufficient time of insect attack, and component biomass equations were developed for each 10-tree data set. Model 3 form was used for developing equations. The authors also provided $R^2$ and SE statistics.

Bower and Clason (1981) reported results of a biomass study utilizing managed plantation loblolly pine in the West Gulf Region. This was a cooperative effort between Louisiana State University and the Weyerhaeuser Company. Component biomass (including root system) models were developed from combined data sets supplied by the two cooperators. The generalized results are reported in the publication, although no prediction equations are provided. The study is one of the first weight-yield studies done in thinned southern pine plantations.

Green-weight, dry-weight, and cubic-foot volume for the aboveground components of unthinned longleaf pines growing in the West Gulf Region can be predicted utilizing equations developed by Baldwin and Saucier (1982, 1983). They sampled 111 trees 1 to 21 inches dbh from 10 plantations in Louisiana and east Texas. Site index (base age 50) ranged from 60 to 119, plantation age from 10 to 44 years, and planting densities from 250 to 1,815 trees per acre. The data were fitted to the model 3 form. Stem weights and volumes to desired top diameters are obtained by predicting weight or volume ratios and then obtaining the proportionate weight from the total weight estimate. Goodness-of-fit statistics included $R^2$ and SE in logarithmic units, fit index, SE in actual units, coefficient of variation, and percent error.

The most intensive study of crown component biomass yet undertaken in southern pine plantations is reported in Hepp and Brister (1982). They measured and weighed crown components of 364 trees from 182 plots in site-prepared loblolly pine plantations distributed throughout the lower Coastal Plain of the Carolinas. Total crown, branch, and foliage dry-weight equations are given in the publication. They used model 3 for equation development and included crown ratios, age, and basal area in them. SE and $R^2$ statistics are also included with the equations.

Shelton et al. (1984) developed equations to predict the weight and volume of plantation-grown loblolly pine trees in the interior flatwoods of Mississippi. They sampled 104 trees ranging in age from 6 to 20 years. Regression equations from the various tree components were developed using models 1 and 2. Ratio equations for estimating the merchantable portion of the main stems are also provided. In addition, they provide support statistics of fit index, SE, and coefficient of variation.

Biomass and nutrient content of a 41-year-old, twice-thinned loblolly pine plantation on a poor site on the upper Piedmont of South Carolina were recently studied by VanLear et al. (1984). Sixteen trees were felled and regression equations, using model 3 form, were developed from the measurement data for aboveground component biomass. The sample included representative trees from each of the four crown classes found in the plantation. SE and $R^2$ statistics are also provided.

Gibson et al. (1984) presented preliminary results of an interesting study in which they compared the biomass of planted loblolly, longleaf, shortleaf, and slash pine trees in unthinned plantations on wet, intermediate, and dry sites in northern Louisiana. The stands were long-term study areas in which all four species had been maintained and periodically measured since planting. The stands were 25 years old at the time of sampling. Thirty-six trees of each of the four species were sampled--12 trees on each of the 3 sites. Regression equations (model 3) with $R^2$ and SE values to predict total-tree green and dry biomass are presented for each species at each location.

Bailey et al. (1985) and Pienaar and Grider (1984) present model 3 equations to predict green weight with bark and dry weight without bark of site-prepared loblolly pine tree boles. Ratio equations are also provided to predict the corresponding merchantable bole weights. $R^2$ and SE statistics are provided for each equation. These equations were developed from a 472-tree sample taken from 157 well distributed plots on the Piedmont and upper Coastal Plain of Alabama, Georgia, and South Carolina. The trees ranged in size from 1 to 12 inches in dbh, 15 to 70 feet in height, and 40 to 80 feet in site index (base age 25).

Direct-seeded and planted trees were sampled in Lohrey's (1985) study of component biomass of slash pine trees. He sampled 468 trees (201 planted and 267 direct-seeded) from stands throughout central Louisiana. The trees ranged in age from 12 to 48 years. Many of the planted trees were from thinned plantations. Lohrey provides model 3 green- and dry-weight prediction for all aboveground tree components and ratio equations for prediction of green or dry merchantable stem weight. Equations are presented for direct-seeded trees and plantation trees. The following goodness-of-fit statistics are provided for each equation: fit index, SE in actual units, and coefficient of variation in actual units.

McNab et al. (1985) felled 83 Choctawhatchee sand pine trees in 8 northwestern Florida plantations. They developed model 3 equations to predict the green- and dry-weight and cubic-foot volume of the aboveground components. Their site index range was quite narrow--49 to 53 feet (base age 25)--but the tree ages ranged from 7 to 27 years, dbh from 2 to 12 inches, and total height from 11 to 63 feet. They also used ratio equations to predict merchantable weights or volumes of the bole. The support statistics provided are $R^2$ and SE.

Baldwin (1986) sampled 130 trees from 12 loblolly pine plantations or study areas in central Louisiana to provide green- and dry-weight prediction equations (model 3) for all aboveground tree components. The data indicated a difference in bole form or taper between trees from unthinned stands and trees from thinned stands, so separate weight-ratio equations are given for these two classes of trees. The trees ranged in age from 9 to 55 years, in dbh from 2 to 21 inches, and in total height from 18 to 94 feet. The goodness-of-fit statistics given are fit index, SE in actual units, coefficient of variation in actual units, and mean percent error.

This author is aware of only three other completed studies that will produce biomass prediction equations within the next year or two for publication. These studies were all accomplished within the Utilization of Southern Timber Research Work Unit of the Southeastern Forest Experiment Station, Athens, Georgia.[1] Equations will be provided to predict aboveground components of trees from unthinned slash pine plantations on the coastal plain of south Georgia and north Florida; of trees from unthinned loblolly pine plantations on the Piedmont region of South Carolina, Georgia, and Alabama; and of aboveground and belowground (taproot) components of loblolly pines from northwest Georgia and slash pines from northwest Florida. These will supplement the work of Queen and Pienaar (1977) and Pienaar and Grider (1984) by providing predictions for the non-bole components of trees from those regions.

Sampling Discussion

Henceforth, our discussion will only be concerned with those studies that the author perceives were designed to develop biomass equations for general mensurational use (e.g., growth and yield estimation, stand inventories) rather than for uses incidental to that objective. That leaves us with two groups of papers based on somewhat arbitrary groupings of the work done in the Southern United States:

| | |
|---|---|
| (1) The Southeastern States Group - (Virginia, North and South Carolina, Georgia, Alabama, and Florida) | Burkhart et al. (1972), Madgwick and Kreh (1980), McGee (1959), Romancier (1961), Collicott et al. (1968), Burkhart and Clutter (1971), Flowers (1978), Queen and Pienaar (1977), Edwards and McNab (1979,1981) Rockwood et al. (1980), Hepp and Brister (1982), Pienaar and Grider (1984), NcNab et al. (1985). |
| (2) The Mid-South States Group - Mississippi, Louisiana, Arkansas, and Texas) | Nelson and Switzer (1975), Shelton et al. (1984), Hicks et al. (1972) Hyink et al. (1972, Moehring et al. (1973), King and Moehring (1974), Bower and Clasen (1981), Baldwin and Saucier (1983) Lohrey (1985), Baldwin (1986). |

Within the Southeastern States Group, the large growth and yield weight/volume studies tended to have broadly based sampling plans wherein a few trees were taken from many plantations over a wide area within a particular geographic region (e.g., upper or lower Coastal Plain for only the most valuable tree component, the bole, and in some cases only trees $\geq$ 4.6 inches ee dbh were sampled. The emphasis was on unthinned plantations of loblolly and slash pine on either old-field or mechanically prepared cutover sites. Within these categories the work is relatively complete.

However, there are some notable deficiencies, most of which can only be corrected by more research. Except for the work of Hepp and Brister (1982) and Madgwick and Kreh (1980), branch and foliage components have been largely ignored until recently. The three Southeastern Forest Experiment Station studies mentioned earlier[2] will provide prediction equations for aboveground and belowground components of slash and loblolly pines to help in this area. There is also a noticeable absence of data from thinned stands and from older stands. Apparently, there are no equations to predict weights of mature planted longleaf pines in the Southeast.

Within the Mid-South States Group, the larger growth and yield weight/volume studies roughly fall into two subgroups--the Texas studies and the Louisiana-Mississippi studies. The former subgroup was most like the Southeastern States studies, e.g., broadly based, a few trees sampled from many plantations, only bole equations developed for trees $\geq$ 4.6 inches dbh, and mostly old-

1/ Personal communication, Alexander Clark III USDA-Forest Service

2/ Ibid.

field plantations. However, the latter subgroup emphasized tree rather than stand diversity, and developed equations for aboveground tree components. For example, in the Louisiana studies trees were selected across a range of diameter, height, and crown ratio classes within age and site location classes, within thinned and unthinned plantations, and within unthinned and precommercially thinned direct-seeded stands.

Thus, in the Mid-South States Group of studies, indepth complete aboveground tree component weight equations have been developed for loblolly, longleaf, and slash pines over somewhat limited geographical areas within Louisiana and Mississippi. Tree bole weight equations are available for loblolly and slash pines sampled from mostly old-field plantations in eastern Texas, western Louisiana, and southern Arkansas.

A problem with the limited area studies is that the extent of their overall applicability in the Mid-South States is unknown quantitatively. There is no statistical basis to support use of regression equations developed from these studies outside of the plantations from which their data were collected. Indeed this problem is inherent to some degree in all of the studies reviewed. Therefore, all of these equations should be validated for accurate use outside of the populations sampled, and this is true for the entire South. With the exception of the paper by Phillips and Saucier (1979), there is apparently no published information with respect to validation with independent data sets of any of the equations discussed in this paper.

In addition to validation, the possible development of southwide equations for the major pine species should be undertaken, and regional as well as southwide equations still need to be developed for shortleaf pine.

## Modeling Discussion

All three basic model forms have been employed by southern researchers in the development of the biomass equations presented. The relative merits of one model over another have been presented elsewhere (e.g., Crow and Laidly 1980, Payandeh 1981, Schlaegel 1982) and are not discussed here. One major problem paramount in all but the most recent studies, however, has been the negligence of researchers in calculating and reporting statistics much more useful than the coefficient of determination ($R^2$) or the standard error of the estimate ($S_{y.x}$) in order to evaluate goodness-of-fit. Reporting of just a few more useful statistics would also enable readers to make quantitatively based comparisons between published equations. The paper by Schlaegel (1982) addressed this topic. He suggested publication of the following statistics along with all equations:

(1) Fit index (FI) - a statistic analogous to $R^2$ (which is identical to $R^2$ for untransformed equations).

(2) Standard error of the estimate ($S_e$) - for transformed equations this statistic needs to be calculated in original units of measure and presented in the untransformed units.

(3) Coefficient of variation (CV) - based on the untransformed $S_e$.

(4) Furnival's Index (I) - a statistic similar in form and information to $S_e$ except that transformed and untransformed equations can be compared on a common basis (Furnival 1961).

(5) Percent standard error (S(%)) - a goodness-of-fit statistic that describes the mean error of all residuals in a percentage form.

(6) Percent error (P) - a statistic useful in the comparison of one equation with another.

(7) The mean ($\bar{x}$) and the sum of squares ($\Sigma x^2$) - required for a user to be able to construct confidence limits about his predictions obtained from the the equation presented.

Another desirable feature of tree component regression equations is that predictions for the components sum to the prediction for the total tree. This is easily accomplished if the same (model 1) form is used for the equations fitted to predict all components (Kozak 1970). However, there are procedures to accomplish this additivity feature even if different model forms are used for different components (Jacobs and Cunia 1980; Cunia and Briggs 1985a, 1985b; Chiyenda and Kozak 1984). Researchers in the South have not indicated their use of these techniques in any of the publications presented in this paper. Additivity of bole components has been achieved in many of the more recent papers through the use of the ratio equation in conjunction with a total bole weight equation to obtain partial bole weights. Generally, a prediction equation for the total tree weight is not fitted; total tree weight is estimated by summing the predictions for the component parts.

## Summary and Conclusions

This review provides an update with a slightly different emphasis than an earlier review on this subject by Baldwin (1982). Since that time, about 678 more loblolly, 36 more longleaf, 36 more shortleaf, 504 more slash pine, and 83 more sand pine sample trees have been felled, measured, weighed, and analyzed for the development of tree component biomass equations. Most of the studies were done in the Mid-South States Region as defined earlier, but the largest sample of trees from one region (472 loblolly pines) was obtained from the Southeastern States Region.

Numerous equations have been developed as a result of all this work. Existing model forms were categorized into three basic types for the purpose of this paper, and the fitted equations published in all the papers were reviewed, classified, and discussed according to the characteristics of each model form. Generally, the authors of these papers have provided little supplemental information with their equations. In many cases (particularly with model 3) a user cannot adequately evaluate an equation's precision or accuracy. Also, there is insufficient information for quantitative equation comparisons.

In general, studies that were broadly based on large areas tended to emphasize sampling of comparatively few trees from many plantations, with the researchers only collecting data sufficient to develop bole weight equations. The studies with less scope in area emphasized sampling of many more trees from fewer plantations, and data were collected for the development of complete tree-component weight equations. For plantations, most of the former work was done in the Southeastern States Region, and the latter work was mostly done in the Mid-South States Region.

The four remaining greatest needs in pine plantation biomass research are (1) development of southwide prediction equations for loblolly and slash pines, (2) development of complete aboveground tree component equations for shortleaf pine, (3) development of more thinned-stand equations in all species, and (4) published validations of new and existing equations.

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Table 1.--A summary of published biomass data, functions, and tables, by species, for southern pine plantation trees

| Reference | Location | Sample size | Age | Data range: Dbh | Data range: Height | Data range: Site index | Data range: Density | Tree component [1/]: S/R | TW | TS | MS | BR | F | B | Weight [2/]: Green | Dry | Prediction equation model [3/] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | State | No. | Yr | In | Ft. | Ft. | Trees/acre | | | | | | | | | | |
| **LOBLOLLY PINE** | | | | | | | | | | | | | | | | | |
| Romancier 1961 | GA Piedmont | 116 | 19-24 | 5-12 | 30-65 | - | - | | | | x | | | | x | | 1 |
| Baker 1962 | NC Piedmont | 27 | 3-31 | 1-10 | 5-69 | 30-110 (base age 50) | 430-1,816 (at cut) | | x | x | | x | x | | | x | 3 |
| Rogerson 1964 | MS | 28 | 25 | 5-11 | 37-66 | 69-97 (base age 50) | - | | | | | | x | | | x | 3 |
| Baker 1971<br>Baker et al. 1974 | Central MS | 85 | 3-6 | 0-3 | 2-19 | 80 (base age 50) | 910 (planted) | | x | x | | x | x | x | | x | 3 |
| Burkhart & Clutter 1971 | GA Piedmont | 702 total<br>608 >5 in dbh | 9-32 | 3-12 | 15-80 | 25-80 (base age 25) | 300-1,675 (at cut) | | | x | x | | | x | x | x | 1 |
| Burkhart et al. 1972 | VA Piedmont & Coastal Plain of VA,DE, MD, NC | 378 | 9-35 | - | - | 47-84 | 300-2,900 | | | x | x | | | x | x | x | 1 |
| Hicks et al.1972<br>Hyink et al.1972<br>Lenhart& Hyink 1973 | Interior coastal plain of east TX, ARK, LA | 632 | 9-30 | 5-19 (99% were 5-13) | 25-85 (97% were 30-70) | 37-85 (base age 25) | 174-1,518 | | | x | x | | | x | x | x | 1 |
| Nemeth 1973 | NC Coastal Plain | 41 | 4-11 | - | - | - | 546 (at cut) | x | x | x | x | x | x | x | | x | 3 |
| Ralston 1973 | NC Piedmont | 26 | 13-15 | - | - | - | 681(planted)<br>606 (at cut) | x | x | x | x | x | x | | | x | 3 |

See footnotes at end of table.

Table 1.--A summary of published biomass data, functions, and tables, by species, for southern pine plantation trees (continued)

| Reference | Location | Sample size | Age | Data range: Dbh | Data range: Height | Data range: Site index | Data range: Density | Tree component[1/]: S/R | TW | TS | MS | BR | F | B | Weight[2/]: Green | Dry | Prediction equation model[3/] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | State | No. | Yr | In | Ft | Ft | Trees/acre | | | | | | | | | | |
| | | | | | | LOBLOLLY PINE | | | | | | | | | | | |
| Nelson & Switzer 1975 | Central MS | 133 | 3-15 | 1-11 | 4-56 | 65-105 (base age 50) | - | | x | x | | x | x | x | x | x | 3 |
| Wells et al. 1975 | NC | 16 | 16 | 6.5 (avg.) | 49 (avg.) | 68 (base age 25) | 907 (at cut) | (equations not published; available from authors) | | | | | | | | | |
| Flowers 1978 Clutter et al.1984 | Coastal Plain North FL | 762 | 10-30 | 2-14 | 15-75 | <45 to 84> | | | | x | x | | | x | x | x | 2,3 |
| Edwards & McNab 1979, 1980 | GA Piedmont | 25 | 2-8 | 1-4 (4/) | 2-19 | - | - | | x | | | | | | | x | 3 |
| Hedden et al.1981 | MD | 20 | 10 | 4-10 | 14-27 | | 4,840 (planted) | | x | x | | x | x | | x | x | 3 |
| Gibson et al.1984 | LA | 36 | 25 | 2-9 | 23-66 | - | 1,210 (planted) | | x | | | | | | x | x | 3 |
| Pienaar & Grider 1984 Bailey et al.1985 | AL GA SC | 472 | 10-25 | 1-12 | 15-70 | 40-80 (base age 25) | 300-1,500 | | | x | x | | | | x | x | 2,3 |
| Shelton et al.1984 | MS | 104 | 6-20 | 1-14 | 8-76 | 70-82 (base age 25) | 486-1,740 | x | x | x | x | x | x | x | x | x | 1,2 |

See footnotes at end of table.

Table 1.--A summary of published biomass data, functions, and tables, by species, for southern pine plantation trees (continued)

| Reference | Location | Sample size | Age | Data range | | | | Tree component[1/] | | | | | | | Weight[2/] | | Prediction[3/] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Dbh | Height | Site index | Density | S/R | TW | TS | MS | BR | F | B | Green | Dry | equation model |
| | State | No. | Yr | In | Ft | Ft | Trees/acre | | | | | | | | | | |
| | | | | | | LOBLOLLY PINE | | | | | | | | | | | |
| VanLear et al. 1984 | SC | 16 | 41 | 5-15 | 76 (avg.) | - | 177 | | x | | x | x | x | x | | x | 3 |
| Baldwin 1986 | LA | 130 | 9-55 | 2-21 | 18-94 | 40-76 (base age 25) | 13-1,133 | | | x | x | x | x | x | x | x | 2,3 |
| | | | | | | SLASH PINE | | | | | | | | | | | |
| McGee | NC & SC | 250 | 9-25 | 5-12 | 20-75 | - | - | | | | x | | | | x | | (only tables published) |
| Collicott et al. 1968 | GA | 177 | 17 | 5-12 | - | - | - | | | x | x | | | | | x | 1 |
| Moehring et al. 1973 | East TX | 379 | - | 5-14 | 30-85 | - | - | | | x | x | | | | x | | 1 |
| Nemeth 1973 | NC Coastal Plain | 15 | 4-11 | - | - | - | 545 (at cut) | x | x | x | x | x | x | x | | x | 3 |
| King & Moehring 1974 | East TX | 220 | - | 5-23 | 27-87 | - | - | | | x | x | | | | | x | 1 |
| Queen & Pienaar 1977<br>Bailey et al 1982 | GA<br>FL | 686 | 11-28 | 3-12 | 20-75 | 41-81 (base age 25) | 250-650 | | | x | x | | | | x | x | 2,3 |
| Edwards & McNab 1979, 1981 | Central GA | 29 | 3-8 | 1-6 | 2-19 | - | - | | x | | | | | | | x | 3 |
| Gibson et al. 1984 | LA | 36 | 25 | 2-9 | 23-66 | - | 1,210 | | x | | | | | | x | x | 3 |
| Lohrey 1985 | LA | 468 | 12-48 | 1-19 | 12-110 | 30-78 (base age 25) | 51-3,580 | | | x | x | x | x | x | x | x | 2,3 |

See footnotes at end of table.

Table 1.--A summary of published biomass data, functions, and tables, by species, for southern pine plantation trees (continued)

| Reference | Location | Sample Size | Age | Data range: Dbh | Data range: Height | Data range: Site index | Data range: Density | Tree component[1/]: S/R | TW | TS | MS | BR | F | B | Weight[2/]: Green | Dry | Prediction[3/] equation model |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | State | No. | Yr | In | Ft | Ft | Trees/acre | | | | | | | | | | |
| | | | | | | LONGLEAF PINE | | | | | | | | | | | |
| Edwards & McNab 1979, 1980 | Central GA | 24 | 2-16 | 1-4 | 1-29 | - | - | | x | | | | | | | x | 3 |
| Baldwin & Saucier 1982, 1983 | Central LA & East TX | 111 | 10-44 | 1-21 | 12-83 | 60-119 (base age 50) | 250-1,815 | | x | x | x | x | x | x | x | x | 2,3 |
| Gibson et al. 1984 | LA | 36 | 25 | 2-9 | 23-66 | | 1,210 | | x | | | | | | x | x | 3 |
| | | | | | | SHORTLEAF PINE | | | | | | | | | | | |
| Vaidya 1961 | NC | 12 | - | 1-9 | 8-66 | - | - | | | x | x | x | | | | x | 3 |
| Edwards & McNab 1979 | Central GA | 22 | 4-20 | 1-4 | 3-17 | - | - | | x | | | | | | | x | 3 |
| Gibson et al. 1984 | LA | 36 | 25 | 2-9 | 23-16 | - | 1,210 | | x | | | | | | x | x | 3 |
| | | | | | | WHITE PINE | | | | | | | | | | | |
| Swank & Schreuder 1973 | Western NC | 39 | 10-15 | 1-9 | 11-45 | - | 1,760-1,790 (at cut) | | | x | | x | x | | | x | 1 |

See footnotes at end of table.

Table 1.--A summary of published biomass data, functions, and tables, by species, for southern pine plantation trees (continued)

| Reference | Location | Sample size | Age | Data range: Dbh | Data range: Height | Data range: Site index | Data range: Density | Tree component[1/]: S/R | Tree component[1/]: TW | Tree component[1/]: TS | Tree component[1/]: MS | Tree component[1/]: BR | Tree component[1/]: F | Tree component[1/]: B | Weight[2/]: Green | Weight[2/]: Dry | Prediction equation model[3/] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | State | No. | Yr | In | Ft | Ft | Trees/acre | | | | | | | | | | |
| | | | | | | SAND PINE | | | | | | | | | | | |
| Rockwood et al. 1980 | FL sandhills | 28 | 6-17 | 1-5 | 9-45 | - | 3,630-5,808 (planted) | | x | x | x | x | x | x | x | x | 1 |
| McNab et al.1985 | FL | 83 | 7-27 | 2-12 | 11-63 | 49-53 (base age 25) | 225-955 | | x | x | x | x | x | x | x | x | 2,3 |
| | | | | | | VIRGINIA PINE | | | | | | | | | | | |
| Madgwick & Kreh 1980 | VA Piedmont | 182 | 8 | 2-3 | 13-16 | 83 (base age 50) | 619 (at cut) | | x | x | | x | x | x | | x | 3 |

1/ Code indicating the tree components measured:
S/R = all or part of the stump-root system
TW = total tree weight
TS = total stem (bole) weight
MS = merchantable stem weight
BR = branches
F = foliage
B = bark

2/ Study emphasized either green or dry weight as indicated.

3/ Model 1 is $Y = \beta_0 + \beta_1 X_1 + \dots + \beta_j X_j + \varepsilon$,

Model 2 is $Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} \dots X_j^{\beta_j} + \varepsilon$,

Model 3 is $Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} \dots X_j^{\beta_j} \varepsilon$ transformed to $\ln(Y) = \beta_0' + \beta_1 \ln(X_1) + \beta_2 \ln(X_2) + \dots + \beta_j \ln(X_j) + \varepsilon'$

4/ Ground-line diameter.

# SUMMARY OF BIOMASS EQUATIONS AVAILABLE FOR SOFTWOOD AND HARDWOOD SPECIES IN THE SOUTHERN UNITED STATES[1]

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Abstract--Published equations for estimating biomass of entire trees and tree components for softwoods and hardwoods $\geq$ 1.0 inches d.b.h. are summarized by species, geographic location, and dependent and independent variables. References containing 244 sets of equations for 11 softwood and 52 hardwood species are listed. Regression models commonly used to estimate total-tree and component biomass are also reviewed.

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Researchers in the South have developed a large number of tree biomass prediction equations for individual species and species groups. Timber owners, foresters, and researchers need these equations to estimate biomass of forest stands for forest management and utilization decisions. To obtain these biomass estimates, they need to know what species equations are available, what their independent and dependent variables are, and in what geographic areas the equations were developed. Several reviews of the biomass literature (Keays 1971, Stanek and State 1978, Madgwick 1976, Art and Marks 1971, Young 1976, Hitchcock and McDonnell 1979, Tritton and Hornbeck 1982, Clark 1982, Phillips 1982, Baldwin 1982, McNab et al. 1982, and USDA Forest Service, 1984) summarize the many studies conducted to develop biomass equations for entire trees and tree components. This paper updates these literature reviews of biomass research in the South and summarizes the biomass equations available for softwood and hardwood species 1.0 inch d.b.h. and larger growing in natural stands. In this review, the South is defined as the area extending from Virginia and West Virginia in the east to eastern Oklahoma and Texas in the west.

## Tree Biomass Prediction Equations

Researchers have collected biomass data on thousands of softwood and hardwood trees in the South to develop equations for predicting green and dry weights and volumes of entire trees and their components. The biomass equations developed for southern hardwoods are summarized in table 1 by species and location. Table 2 summarizes the equations developed for softwoods by species and location. These tables also show the number of trees sampled, the independent and dependent variables used in the equations, and the investigator or author.

Table 1 lists 180 sets of hardwood equations developed to estimate the biomass of 52 hardwood species and Table 2 lists 64 sets of softwood equations developed to estimate the biomass of 11 softwood species. These species account for over 92 percent of the volume on commercial forest lands in the South and make up over 65 percent of the commercial species listed by the USDA Forest Service's Renewable Resource Survey Unit in the Mid-South and Southeast.

No southwide hardwood species equations have been developed. However, regional weight equations for hardwoods are available for the Gulf and Atlantic Coastal Plains (Clark et al. 1985b), the Piedmont Plateau (Clark et al. 1986b), the Southern Appalachian Mountains (Clark and Schroeder 1986), and the Upland-South[2] (Clark et al. 1986c). Biomass data for hardwood species sampled in Alabama, Georgia, Florida, South Carolina, and western North Carolina have been pooled for the development of southeastern hardwood species equations (Clark et al. 1986a). Only statewide or local sampling has been conducted in east Texas, Louisiana, and Mississippi, and no regional hardwood species equations are available for the Deep South.

Statistical comparisons for southern hardwood species, similar to those reported by Jacobs and Monteith (1981) for species in the Northeast, have not been published. However, to illustrate the differences in total-tree green weight that exist between geographic regions, equations for several important hardwood species were applied to trees with identical d.b.h. and total height (Clark 1982a, 1982b). Results indicate differences of up to 20 percent for southern red oak, white oak, and hickory in comparisons between the Southeast and east Texas and Oklahoma.

The within-species geographic variations in specific gravity (dry weight per cubic foot), moisture content, and green weight of wood and bark per cubic foot of wood have been statistically compared for eight southern hardwood species (Clark et al. 1986d). The species examined include yellow-poplar, sweetgum, red maple, white oak, scarlet oak, hickory, blackgum, and ash. The results indicate that stemwood specific gravity of the species sampled in the Coastal Plains, Piedmont, Southern Appalachian Mountains, and Upland-South differ significantly (P=0.05) among geographic regions. However, there was no indication of a consistent geographic trend except for red maple, whose wood specific gravity decreased from north to south.

For each species except for blackgum, wood moisture content varied significantly among geographic regions. The green weight of wood and bark per cubic foot of wood or weight-scaling factor also varied significantly among geographic regions for all species except hickory.

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[1]Paper presented at the Tree Biomass Regression Functions and their Contribution to the Error of Forest Inventory Estimates Workshop, Syracuse, NY, May 27-30, 1986.

[2]Upland-South includes north Alabama, Mississippi, eastern Arkansas, southern Kentucky, and Tennessee.

However, the weight-scaling factors for sweetgum, red maple, and white oak did not differ significantly between the Piedmont and Coastal Plains. Differences in weight-scaling factors among geographic regions within a species were as high as 16 percent. Because of the magnitude of the within-species regional differences in wood specific gravity, moisture content, and green weight per cubic foot, regional, rather than specieswide, green and dry weight prediction equations and weight-scaling factors should be used for marketing hardwood timber. Species-wide equations are suitable for resource surveys of the Southeast or Mid-South.

Numerous equations have been generated for southern softwoods in natural stands. Equations are available for the four major southern pines, white pine, Virginia pine, sand pine, pond pine, eastern hemlock, eastern redcedar, and pond cypress. Equations for the four major southern pine species have been developed for individual states, such as Georgia (Saucier at al. 1981) and east Texas (Walters 1982), and for geographic regions, such as the Piedmont or Coastal Plain of the Southeast (Saucier et al. 1985) or a group of states (Clark 1986). No southwide pine biomass equations have been developed, however.

As with the hardwoods, there have been no published statistical comparisons of results of equations developed for softwood species at different locations. However, graphs of plotted data for trees at different locations but with identical d.b.h. and total heights show smaller differences for softwoods than that reported for hardwoods. The four major southern pines do increase in weight per cubic foot from north to south across their natural ranges (Clark 1982a), however.

McNab and others (1982) compared results from five equations developed for loblolly pine from Texas to Georgia and found only a 3 to 6 percent difference among them. Clark (1982a) compared predictions for slash pine from Georgia, Alabama, and Mississippi and found a maximum difference of 10 percent. The maximum difference among the four major pines was reported for shortleaf pine. For it, samples in northern Mississippi differed by 10 to 17 percent from samples in Georgia, Texas, and Oklahoma (McNab et al. 1982).

For regional resource surveys, the available state or Southeast area equations for major southern pine species appear to be sufficient. However, these equations need to be tested locally before they are used to predict market yields for southern pines.

## Regression Models Used to Estimate Biomass

Researchers have used a variety of regression models for estimating total-tree and tree-component biomass in the South. The three most common models are the linear, weighted linear, and log-log. The linear models are the single-variable

$$Y = a + b(D^2H) + \varepsilon \qquad (1)$$

or the two-variable

$$Y = a + b(D^2) + c(H) + \varepsilon \qquad (2)$$

where: Y = predicted component weight or volume
D = tree diameter at breast height in inches
H = tree-total height, height to 4-inch d.o.b. top, or saw-log merchantable height in feet
ε = experimental error
a,b,c = regression coefficients.

The variance of total-tree and total-stem weight is heterogeneous. That is, when plotted over D2H, variance increases with increasing D2H. A weighted or log-log transformation, therefore, is commonly used to obtain a more homogeneous variance. The form of the weighted linear model is:

$$\frac{Y}{(D^2H)^K} = \frac{a}{(D^2H)^K} + b(D^2H)\ (D^2H)^K + \varepsilon \qquad (3)$$

where: K = weighting factor.

The weighting factor (K) is computed using the procedure reported by McClure et al. (1983). The logarithmic transformation is another common method for obtaining a relatively homogeneous variance. The log-log model is:

$$\text{Log } Y = a' + b \text{ Log } (D^2H) + \varepsilon' \qquad (4)$$

where: a' = log a
ε' = log

When developing biomass equations from hardwood tree data collected on 25 1/10 acre plots in the Coastal Plain, we found a single log-log equation resulted in biased estimates when fitted to trees 1 to 20 inches d.b.h. It overestimated the weight of trees < 10 inches and underestimated the weight of trees > 12 inches. This bias probably occurred because of the large number of observations in the smaller diameter classes caused by the area sampling procedures used to select sample trees. We used a segmented log-log equation to correct for this bias (Clark et al. 1985a). The segmented procedure used two equations--one for trees < 11.0 inches d.b.h. and one for trees ≥ 11.0 inches d.b.h. The procedure outlined in Draper and Smith (1981) for fitting two linear equations with known point of intersection was used. The equation for trees < 11.0 inches d.b.h. was:

$$\text{Log } Y = a + b \text{ Log } (D^2H) + \varepsilon \qquad (5)$$

The equation for trees ≥ 11.0 inches d.b.h. was:

$$\text{Log } Y = a + b \text{ Log } (11^2H) + c \text{ Log}(D^2/11^2) + \varepsilon \qquad (6)$$

Researchers have used each of the models described at different times and no one model is best for all species and tree components. However, some researchers favor one model over another (McClure 1983, Clark et al., 1985).

The minimum top diameter at which trees are cut during harvest varies significantly and is dictated by local practice and logging conditions. To meet the needs of all users it is necessary for a researcher to develop a series of independently fitted equations to estimate stem weight to several top diameters (2-, 4-, 7-, 9-inch top). This approach is cumbersome and often leads to what is called crossover (Williams 1982). Crossover occurs when the line for predicted weight to a 7-inch top crosses the line for predicted weight to a 4-inch top for the same d.b.h. and height tree. This result leads to the illogical conclusion that stems cut at a 7-inch top weigh more than those logged to a 4-inch top.

To avoid this problem, researchers (Burkhart 1977, Van Deusen et al. 1981) have suggested predicting the weight of the total stem and then predicting the ratio of the stem weight to a specified top:total stem weight. We have found the exponential form of Burkharts' model, shown below, to be the best model for natural pine and hardwoods.

$$R = e^{a(d)^{b}(D)^{c}} \tag{7}$$

where: R = ratio of stem weight to specified top to weight of total stem
d = specified top diameter
D = tree d.b.h.
e = base of natural log.

This ratio model can be used to estimate stem ratios to any specified top diameter when cruising by d.b.h., d.b.h. and total height, or height to 4-inch top. These three tree dimensions are good predictors of total stem weight. Sawtimber trees, particularly hardwoods, are cruised by d.b.h. and saw-log height to estimate saw-log stem weight as accurately as possible with biomass equations. The total stem ratio model (7) is not applicable to trees cruised by d.b.h. and saw-log height. The following nonlinear model (Clark et al. 1985b) is suggested for predicting the ratio of weight to a specified top diameter:saw-log stem weight:

$$R_s = e^{a\left[(Mh)^{b}\left(\left(1-\left(\frac{d}{.78D}\right)^{2}\right)^{2}\right)^{c}\right]} \tag{8}$$

where: Rs = weight of stem to top diameter/weight of saw-log stem ratio
Mh = saw-log merchantable height
d = specified top diameter
D = d.b.h. and 0.78D estimates the d.o.b. at the top of the first 16-foot saw log

Model (8) can be used to estimate the weight of the stem in saw-log trees to any specified diameter without crossover, assuming d is less than 0.78D.

## Summary

A review of the literature shows that weight equations for entire trees and tree components are available for 11 southern softwood species and 52 southern hardwood species occurring in natural stands. The species for which equations are available make up over 92 percent of the commercial volume in the South. No specieswide or southwide biomass equations have been developed, but species equations are available for the Upland-South, the Southern Appalachian Mountains, the Piedmont, the Gulf and Atlantic Coastal Plains, and the Southeastern United States. Because of possible geographic differences in weight, only regional or locally developed and tested species equations should be used when estimating tree biomass for marketing purposes.

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Table 1.--Summary of total tree and tree component weight equations for southern hardwoods ≥ 1.0 inches d.b.h. by species and location

| Species and location | Sample size | D.b.h. range | Independent variables[1] | Dependent variables[2] | Investigator |
|---|---|---|---|---|---|
| | Number | Inches | | | |
| Ash, green (*Fraxinus pennsylvanica* Marsh.) | | | | | |
| S. and S.E. Coastal Plain | 158 | 1-18 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1985b |
| Mississippi Delta | 70 | 1-30 | DTh | TT,ST | Schlaegel, 1984d |
| Ash, white (*Fraxinus americana* L.) | | | | | |
| Northeast Georgia | 31 | 5-18 | DH4,DMh | TT,SST,ST4 (G) | Clark & McNab, 1982 |
| North Georgia and Western North Carolina | 52 | 5-22 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark & Schroeder, 1986 |
| S.E. West Virginia | 15 | 2-16 | D | TT (G&D) | Brenneman et al., 1978 |
| S.E. West Virginia | 13 | 2-16 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| Basswood, American (*Tilia americana* L.) | | | | | |
| Western North Carolina | 18 | 6-16 | D,DTh,DH4 | TT,ST/R (G&D) | Clark & Schroeder, 1986 |
| S.E. West Virginia | 13 | 6-19 | D | TT (G&D) | Benneman et al., 1978 |
| S.E. West Virginia | 19 | 5-19 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| Beech, American (*Fagus grandifolia* Ehrh.) | | | | | |
| S.E. West Virginia | 56 | 2-15 | D | TT (G&D) | Brenneman et al., 1978 |
| S.E. West Virginia | 24 | 5-15 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| Birch, sweet (*Betula lenta* L.) | | | | | |
| S.E. West Virginia | 8 | 4-15 | D | TT (G&D) | Brenneman et al., 1978 |
| Western North Carolina | 21 | 6-18 | D,DTh,DH4 | TT,ST/R (G&D) | Clark & Schroeder, 1986 |
| S.E. West Virginia | 21 | 6-16 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| Birch, yellow (*Betula alleghaniensis* Britton) | | | | | |
| S.E. West Virginia | 24 | 2-16 | D | TT (G&D) | Brenneman et al., 1978 |
| Blackgum (*Nyssa sylvatica* var. *biflora* (Walt.) Sarg.) | | | | | |
| S. and S.E. Coastal Plain | 135 | 1-20 | D,DTh,DH4,DMh | TT,ST/R,SST (G&D) | Clark et al., 1985b |
| S.E. United States | 135 | 1-20 | DTh,DH4,DMh | TT,ST/R,SST (G) | Clark et al., 1986a |
| Central Georgia | 20 | 1- 6 | BD | TT (D) | Edwards, 1976 |
| Blackgum (*Nyssa sylvatica* Marsh.) | | | | | |
| Western North Carolina | 18 | 6-18 | D,DTh,DH4 | TT,ST/R (G&D) | Clark & Schroeder, 1986 |
| Western North Carolina | 18 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Tennessee | 15 | 1- 2 | DTh,Th,DBTh | TT (G&D) | Hitchcock, 1978 |
| Boxelder (*Acer negundo* L.) | | | | | |
| Mississippi Delta[3] | 49 | 1-14 | DTh | TT,ST4,CR (G&D) | Schlaegel, 1982 |

Continued

Table 1.--Summary of total tree and tree component weight equations for southern hardwoods ≥ 1.0 inches d.b.h. by species and location--Continued

| Species and location | Sample size | D.b.h. range | Independent variables[1/] | Dependent variables[2/] | Investigator |
|---|---|---|---|---|---|
| | Number | Inches | | | |
| Buckthorn, Carolina (*Rhamnus caroliniana* Walt.) | | | | | |
| Tennessee | 15 | 1- 2 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |
| Cherry, black (*Prunus serotina* Ehrh.) | | | | | |
| Northern West Virginia | 21 | 2-16 | D | TT,ST4,CR (G&D) | Wiant et al., 1977 |
| Northern West Virginia | 21 | 2-16 | DTh | TT,ST4,CR (G&D) | Wiant et al., 1979 |
| S.E. West Virginia | 24 | 5-16 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| S.E. West Virginia | 26 | 3-16 | D | TT (G&D) | Brenneman et al., 1978 |
| Tennessee | 17 | 1- 2 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |
| Cherry, pin (*Prunus pensylvanica* L. f.) | | | | | |
| S.E. West Virginia | 20 | 7-12 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| Cottonwood, eastern (*Populus deltoides* Bartr. ex Marsh.) | | | | | |
| Alabama | 48 | 1-11 | D | TT (D) | Carter & White, 1971 |
| Dogwood, (*Cornus florida* L.) | | | | | |
| Western North Carolina | 12 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Piedmont Georgia | 12 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Western North Carolina | 24 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Piedmont Southeast | 24 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Tennessee | 16 | 1- 2 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |
| Central Georgia | 20 | 1- 6 | BD | TT (D) | Edwards, 1976 |
| Elm, American (*Ulmus americana* L.) | | | | | |
| Piedmont of Southeast | 16 | 1-11 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1986b |
| Eucalyptus, grandis (*Eucalyptus grandis*) | | | | | |
| South Florida | 28 | 2-12 | DTh | TT,ST/R,CR (G&D) | Saucier, 1986b |
| Eucalyptus, robusta (*Eucalyptus robusta*) | | | | | |
| South Florida | 28 | 2-12 | DTh | TT,ST/R,CR (G&D) | Saucier, 1986b |
| Hickory, mockernut (*Carya tomentosa* (Poir.) Nutt.) | | | | | |
| Central Alabama | 18 | 4- 9 | DTh | TT,ST4,CR (G&D) | Sirois, 1983 |
| North Georgia | 27 | 5-19 | DH4,DMh | TT,SST,ST4 (G) | Clark & McNab, 1982 |
| Hickory, shagbark (*Carya ovata* (Mill.) K. Koch) | | | | | |
| S.E. West Virginia | 14 | 3-17 | D | TT (G&D) | Brenneman et al., 1978 |
| S.E. West Virginia | 13 | 7-17 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| Hickory, species (*Carya sp.*) | | | | | |
| S. and S.E. Coastal Plain | 42 | 1-18 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1985b |
| Piedmont of Southeast | 22 | 1-18 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1986b |
| S. Appalachian Mountains | 54 | 5-23 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark & Schroeder, 1986 |
| Mid-South | 37 | 1-18 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1986c |

Continued

Table 1.--Summary of total tree and tree component weight equations for southern hardwoods ≥ 1.0 inches d.b.h. by species and location--Continued

| Species and location | Sample size | D.b.h. range | Independent variables[1] | Dependent variables[2] | Investigator |
|---|---|---|---|---|---|
| | Number | Inches | | | |
| Hickory, species (*Carya sp.*) (con't.) | | | | | |
| S.E. United States | 64 | 1-19 | DTh,DH4,DMh | TT,SST,ST/R (G) | Clark et al., 1986a |
| Eastern Oklahoma | 22 | 1-14 | DTh | TT,ST4 (G&D) | Matney, 1977 |
| Eastern Tennessee | 37 | 2-28 | D | TT,SST,CR (G&D) | Schnell, 1978 |
| Northern West Virginia | 19 | 2-16 | DTh | TT,ST4,CR (G&D) | Wiant et al., 1979 |
| Northern West Virginia | 19 | 2-16 | D | TT,ST,CR (G&D) | Wiant et al., 1977 |
| Western North Carolina | 12 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Piedmont Georgia | 11 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Western North Carolina | 24 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Piedmont Southeast | 22 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Tennessee | 16 | 1- 3 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |
| Loblolly-bay (*Gordonia lasianthus* (L.) Ellis) | | | | | |
| North Florida | 19 | 2- 9 | D | ST (G) | Swindel et al., 1982 |
| Locust, black (*Robinia pseudoacacia* L.) | | | | | |
| S. Appalachian Mountains | 18 | 6-16 | D,DTh,DH4 | TT,ST/R (G&D) | Clark & Schroeder, 1986 |
| Eastern Kentucky | 1,371 | 1- 5 | DTh | TT (D) | Rowell & Carpenter, 1983 |
| Magnolia, cucumber (*Magnolia acuminata* L.) | | | | | |
| S.E. West Virginia | 6 | 8-16 | D | TT (G&D) | Brenneman et al., 1978 |
| Maple, red (*Acer rubrum* L.) | | | | | |
| S. and S.E. Coastal Plain | 85 | 1-15 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1985b |
| Piedmont of Southeast | 32 | 1-16 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1986b |
| S. Appalachian Mountains | 30 | 5-17 | D,DTh,DH4 | TT,ST/R (G&D) | Clark & Schroeder, 1986 |
| Western Virginia | 95 | 1-16 | DTh,DH4 | TT,ST4 (G) | Ford, 1976 |
| Northern West Virginia | 20 | 2-16 | DTh | TT,ST4,CR (G&D) | Wiant et al., 1979 |
| Northern West Virginia | 20 | 2-16 | D | TT,ST4,CR (G&D) | Wiant et al., 1977 |
| S.E. West Virginia | 27 | 2-17 | D | TT (G&D) | Brenneman et al., 1978 |
| S.E. West Virginia | 13 | 5-17 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| Western North Carolina | 12 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Piedmont Georgia | 12 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Western North Carolina | 24 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Piedmont Southeast | 23 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Tennessee | 16 | 1- 3 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |
| Maple, sugar (*Acer saccharum* Marsh.) | | | | | |
| S.E. West Virginia | 119 | 2-15 | D | TT (G&D) | Brenneman et al., 1978 |
| S.E. West Virginia | 38 | 5-15 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| Oak, black (*Quercus velutina* Lam.) | | | | | |
| Western North Carolina | 40 | 12-26 | DMh | SST (G) | Phillips et al., 1974 |
| S. Appalachian Mountains | 26 | 6-22 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark & Shroeder, 1986 |
| Tennessee | 26 | 12-35 | D | TT,SST,CR (G&D) | King & Schnell, 1972 |
| Northern West Virginia | 22 | 2-16 | DTh | TT,ST4,CR (G&D) | Wiant et al., 1979 |
| Northern West Virginia | 22 | 2-16 | D | TT,ST4,CR (G&D) | Wiant et al., 1977 |
| Oak, blackjack (*Quercus marilandia* Muenchh.) | | | | | |
| Oklahoma | 15 | 1-12 | DTh | TT,ST4,CR (G&D) | Matney, 1977 |

Continued

Table 1.--Summary of total tree and tree component weight equations for southern hardwoods ≥ 1.0 inches d.b.h. by species and location--Continued

| Species and location | Sample size | D.b.h. range | Independent variables[1/] | Dependent variables[2/] | Investigator |
|---|---|---|---|---|---|
| | Number | Inches | | | |
| Oak, chestnut (*Quercus prinus* L.) | | | | | |
| S. Appalachian Mountains | 50 | 6-22 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark & Schroeder, 1986 |
| Piedmont of Southeast | 37 | 1-15 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1986b |
| Western Virginia | 125 | 1-17 | DTh,DH4 | TT,ST4,CR (G) | Ford, 1976 |
| Northern West Virginia | 21 | 2-16 | D | TT,ST4,CR (G&D) | Wiant et al., 1977 |
| Northern West Virginia | 21 | 2-16 | DTh | TT,ST4,CR (G&D) | Wiant et al., 1979 |
| S.E. West Virginia | 13 | 3-13 | D | TT (G&D) | Brenneman et al., 1978 |
| S.E. West Virginia | 12 | 5-13 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| Western North Carolina | 11 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Western North Carolina | 24 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Tennessee | 15 | 1- 2 | DTh,Th,BDTh | TT (G&D) | Hitchcock, 1978 |
| Oak, laurel (*Quercus laurifolia* Michx.) | | | | | |
| S. and S.E. Coastal Plain | 47 | 1-17 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1985b |
| Oak, laurel and water combined (*Q. laurifolia* Michx. and *Q. nigra* L.) | | | | | |
| S.E. United States | 148 | 1-20 | DTh,DH4,DMh | TT,SST,ST/R (G) | Clark et al., 1986a |
| Oak, live (*Quercus virginiana* Mill.) | | | | | |
| Northwest Florida | 37 | 3-30 | D,DTh,DH4,DMh | TT,SST,ST/R (G) | Saucier & McNab, 1986 |
| Oak, nuttall (*Quercus nuttallii* Palmer) | | | | | |
| Mississippi Delta | 56 | 3-38 | DTh | TT,ST4 (G&D) | Schlaegel & Willson, 1983 |
| Oak, overcup (*Quercus lyrata* Walt.) | | | | | |
| Mississippi Delta | 88 | 1-34 | DTh | TT,ST4,CR (G&D) | Schlaegel, 1984a |
| Oak, post (*Quercus stellata* Wangenh.) | | | | | |
| Piedmont Southeast | 12 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Mid-South | 26 | 5-21 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1986c |
| Oak, northern red (*Quercus rubra* L.) | | | | | |
| S. Appalachian Mountains | 71 | 6-24 | D,DTh,DH4,DMh | TT,SST,ST4,CR(G&D) | Clark et al., 1980b |
| S. Appalachian Mountains | 71 | 6-24 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark & Schroeder, 1986 |
| Northern West Virginia | 22 | 2-16 | DTh | TT,ST4,CR (G&D) | Wiant et al., 1979 |
| Northern West Virginia | 22 | 2-16 | D | TT,ST4,CR (G&D) | Wiant et al., 1977 |
| S.E. West Virginia | 24 | 4-21 | D | TT (G&D) | Brenneman et al., 1978 |
| S.E. West Virginia | 23 | 5-21 | DTh | TT,ST4 (G) | Brenneman & Daniels, 1982 |
| Oak, scarlet (*Quercus coccinea* Muenchh.) | | | | | |
| Piedmont Southeast | 32 | 5-18 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1986b |
| S. Appalachian Mountains | 27 | 6-22 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark & Schroeder, 1986 |
| Mid-South | 42 | 5-20 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1986c |
| Central Tennessee | 28 | 5-20 | D,DTh,DH4,DMh | TT,SST,ST4,CR(G&D) | Clark et al., 1980a |
| Western Virginia | 43 | 2-20 | DTh,DH4 | TT,ST4 (G) | Ford, 1976 |
| Northern West Virginia | 20 | 2-16 | DTh | TT,ST4,CR (G&D) | Wiant et al., 1979 |
| Northern West Virginia | 20 | 2-16 | D | TT,ST4,CR (G&D) | Wiant et al., 1977 |

Continued

Table 1.--Summary of total tree and tree component weight equations for southern hardwoods ≥ 1.0 inches d.b.h. by species and location--Continued

| Species and location | Sample size | D.b.h. range | Independent variables1/ | Dependent variables2/ | Investigator |
|---|---|---|---|---|---|
| | Number | Inches | | | |
| Oak, scrub (*Quercus sp.*) | | | | | |
| Sand Hills Georgia | 124 | 1- 7 | D,DTh | TT,ST (G) | McNab, 1981 |
| Oak, southern red (*Quercus falcata* Michx.) | | | | | |
| Central Alabama | 25 | 3-12 | DTh | TT,ST,CR (G&D) | Sirois, 1983 |
| Piedmont Southeast | 48 | 2-19 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1986b |
| Oklahoma | 16 | 1-18 | DTh | TT,ST4,CR (G&D) | Matney, 1977 |
| Central Tennessee | 29 | 5-22 | D,DTh,DH4,DMh | TT,SST,ST4,CR(G&D) | Clark et al., 1980c |
| East Texas | 33 | 2-21 | DTh | TT,ST4,CR (G&D) | Lenhart, 1981 |
| Mid-South | 60 | 5-22 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1986c |
| Piedmont Georgia | 13 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Piedmont Southeast | 25 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Oak, southern red and scarlet combined (*Q. alba* L. and *Q. coccinea* Muenchh.) | | | | | |
| S.E. United States | 98 | 5-22 | DTh,DH4,DMh | TT,SST,ST/R (G) | Clark et al., 1986a |
| Oak, water (*Quercus nigra* L.) | | | | | |
| S. and S.E. Coastal Plain | 112 | 1-20 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1985b |
| North Florida | 10 | 3-13 | D | ST (G) | Swindel et al., 1982 |
| Oak, white (*Quercus alba* L.) | | | | | |
| Central Alabama | 14 | 4- 9 | DTh | TT,ST,CR (G&D) | Sirois, 1983 |
| S.E. United States | 128 | 1-22 | DTh,DH4,DMh | TT,SST,ST/R (G) | Clark et al., 1986a |
| S. and S.E. Coastal Plain | 38 | 6-20 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1985b |
| Piedmont Southeast | 44 | 2-21 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1986b |
| S. Appalachian Mountains | 28 | 5-22 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark & Schroeder, 1986 |
| Mid-South | 51 | 1-20 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1986c |
| Oklahoma | 32 | 1-18 | DTh | TT,ST4,CR (G&D) | Matney, 1977 |
| Western Virginia | 70 | 1-20 | DTh,DH4 | TT,ST4 (G) | Ford, 1976 |
| Northern West Virginia | 21 | 2-16 | DTh | TT,ST4,CR (G&D) | Wiant et al., 1979 |
| Northern West Virginia | 21 | 2-16 | D | TT,ST4,CR (G&D) | Wiant et al., 1977 |
| S.E. West Virginia | 29 | 3-14 | D | TT (G&D) | Brenneman et al., 1978 |
| S.E. West Virginia | 28 | 5-14 | DTh | TT,ST4 (G) | Brennemen & Daniels, 1982 |
| Western North Carolina | 12 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Piedmont Georgia | 12 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Western North Carolina | 18 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Piedmont Southeast | 23 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Tennessee | 16 | 1- 3 | DTh,Th,BDTh | TT (G&D) | Hitchcock, 1978 |
| Oak, willow (*Quercus phellos* L.) | | | | | |
| Mississippi Delta | 79 | 2-37 | DTh | TT,ST4, (G&D) | Schlaegel, 1981 |
| Sugarberry (*Celtis laevigata* Willd.) | | | | | |
| Mississippi Delta | -- | -- | DTh | TT,ST4,CR (G&D) | Schlaegel, 1984b |
| Sweetbay (*Magnolia virginiana* L.) | | | | | |
| North Florida | 6 | 2- 9 | D | ST (G) | Swindel et al., 1982 |
| Persimmon (*Diospyros virginiana* L.) | | | | | |
| Tennessee | 19 | 1- 3 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |

Continued

Table 1.--Summary of total tree and tree component weight equations for southern hardwoods $\geq$ 1.0 inches d.b.h. by species and location--Continued

| Species and location | Sample size | D.b.h. range | Independent variables[1] | Dependent variables[2] | Investigator |
|---|---|---|---|---|---|
| | Number | Inches | | | |
| Sassafras (*Sassafras albidum* (Nutt.) Nees.) | | | | | |
| Tennessee | 17 | 1- 3 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |
| Serviceberry (*Amelanchier sp.*) | | | | | |
| Tennessee | 12 | 1- 2 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |
| Sourwood (*Oxydendrym arboreum* (L.) DC) | | | | | |
| Western North Carolina | 11 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Tennessee | 17 | 1- 3 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |
| Sumac sp. (*Rhus sp.*) | | | | | |
| Tennessee | 16 | 1- 2 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |
| Sweetgum (*Liquidambar styraciflua* L.) | | | | | |
| Central Alabama | 15 | 4-10 | DTh | TT,ST,CR (G&D) | Sirois, 1983 |
| Coastal Plain | 313 | 1-20 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1985b |
| Piedmont Southeast | 236 | 1-21 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1986b |
| Mid-South | 39 | 2-17 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1986c |
| Mississippi Delta | 54 | 1-32 | DTh | TT,ST/R (G&D) | Schlaegel, 1984c |
| Mississippi | 60 | 1-20 | DTh | TT,SST,ST4,CR(G&D) | Reans et al., 1982 |
| East Texas | 30 | 4-12 | DTh | TT,SST,ST4,CR(G&D) | Lenhart, 1981 |
| S.E. United States | 263 | 1-21 | DTh,DH4,DMh | TT,SST,ST/R (G) | Clark et al., 1986a |
| S.E. United States | 263 | 1-21 | DTh,DH4,DMh | TT,SST,ST/R (G) | Saucier & Clark, 1985 |
| Piedmont Georgia | 12 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Piedmont Southeast | 24 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Central Georgia | 20 | 1- 6 | BD | TT (D) | Edwards, 1976 |
| Sycamore (*Platanus occidentalis* L.) | | | | | |
| Central Georgia | 103 | 4-10 | DTh | ST (G&D) | Belanger, 1973 |
| Piedmont Southeast | 29 | 2-20 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1986b |
| Tupelo, water (*Nyssa aquatica* L.) | | | | | |
| Coastal Plain Alabama | -- | 1-20 | D,DTh,DH4,DMh | TT,SST,ST4,CR(G&D) | Glover, 1980 |
| S. and S.E. Coastal Plain | 79 | 1-20 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1985b |
| Yellow-poplar (*Liriodendron tulipifera* L.) | | | | | |
| S. and S.E. Coastal Plain | 26 | 5-21 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1985b |
| S. Appalachian Mountains | 62 | 6-26 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark & Schroeder, 1986 |
| Piedmont Southeast | 78 | 3-20 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark et al., 1986b |
| Mid-South | 19 | 5-19 | D,DTh,DH4 | TT,ST/R (G&D) | Clark et al., 1986c |
| Western North Carolina | 39 | 6-28 | DTh | TT,SST,ST4,CR(G&D) | Clark & Schroeder, 1977 |
| Western North Carolina | 47 | 12-28 | DMh | SST,ST4 (G&D) | Clark et al., 1974 |
| Northern West Virginia | 21 | 2-16 | DTh | TT,ST4,CR (G&D) | Wiant et al., 1979 |
| Northern West Virginia | 21 | 2-16 | D | TT,ST4,CR (G&D) | Wiant et al., 1977 |
| S.E. West Virginia | 12 | 6-15 | D | TT (G&D) | Brenneman et al., 1978 |
| S.E. United States | 117 | 1-22 | DTh,DH4,DMh | TT,SST,ST/R (G) | Saucier & Clark, 1985 |
| S.E. United States | 117 | 1-22 | DTh,DH4,DMh | TT,SST,ST/R (G) | Clark et al., 1986a |

Continued

Table 1.--Summary of total tree and tree component weight equations for southern hardwoods ≥ 1.0 inches d.b.h. by species and location--Continued

| Species and location | Sample size | D.b.h. range | Independent variables1/ | Dependent variables2/ | Investigator |
|---|---|---|---|---|---|
| | Number | Inches | | | |
| Yellow-poplar (*Liriodendron tulipifera* L.) (con't.) | | | | | |
| Western North Carolina | 12 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Piedmont Georgia | 12 | 1- 5 | DTh | TT (G&D) | Phillips, 1977 |
| Western North Carolina | 24 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Piedmont Southeast | 24 | 1- 5 | D,DTh | TT (G&D) | Phillips, 1981 |
| Tennessee | 17 | 1- 2 | DTh,BDTh,Th | TT (G&D) | Hitchcock, 1978 |

1/D = tree stem diameter at breast height; Th = tree height; H4 = height to 4-inch d.o.b. top; Mh = height to saw-log merchantable height; BD = basal diameter.

2/TT = total tree above stump; SST = saw-log stem; ST4 = stem from butt to 4-inch d.o.b. top; ST = stem from butt to top; ST/R = stem from butt to top with ratio equations; CR = crown, G = green weight; D = dry weight.

3/Metric units.

Table 2.--Summary of total tree and tree component weight equations for southern softwoods ≥ 1.0 inches d.b.h. by species and location

| Species and location | Sample size | D.b.h. range | Independent variables1/ | Dependent variables2/ | Investigator |
|---|---|---|---|---|---|
| | Number | Inches | | | |
| Pine, loblolly (*Pinus taeda* L.) | | | | | |
| Georgia | 448 | 6-18 | DTh | TT,ST/R (G) | Saucier et al., 1981 |
| Central Alabama | 41 | 6-20 | DTh | TT,SST,ST4,CR (G&D) | Taras & Clark, 1975 |
| Central Georgia | 18 | 6-17 | D | CR (D) | Wade, 1969 |
| Central Georgia | 60 | 5-18 | DMh,DH4 | TT,SST,ST4 (G&D) | McNab, 1983 |
| Central Mississippi | 36 | 2-20 | DTh | TT,ST4,CR (G&D) | Nelson & Switzer, 1975 |
| Eastern Oklahoma | 81 | 1-24 | DTh | TT,ST4,CR (G&D) | Matney, 1977 |
| Southern South Carolina | 48 | 10-20 | DMh | SST (G) | Taras et al., 1974 |
| Southern South Carolina | 9 | 1-20 | D | CR (D) | Storey et al., 1955 |
| East Texas | 38 | 2-24 | DTh | TT,ST4,CR (G&D) | Lenhart, 1981 |
| Eastern Virginia | 721 | 1-18 | DTh | ST4 (G&D) | Burkhart et al., 1972 |
| S.E. United States | 913 | 1-24 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark, 1986 |
| Piedmont Georgia | 25 | 1- 4 | BDTh | TT (D) | Edwards & McNab, 1979 |
| Georgia | 100 | 1- 5 | D,DTh | TT (G&D) | Phillips & McNab, 1986 |
| East Texas | 359 | 5-23 | DTh,DH4 | ST/R (G) | Walters, 1982 |
| Pine, loblolly and shortleaf (*Pinus taeda* L. and *P. echinata* Mill.) | | | | | |
| Piedmont Southeast | 1026 | 1-20 | DTh,DH4,DMh | TT,SST,ST/R (G) | Saucier & Clark, 1985 |
| Pine, loblolly, shortleaf, and virginia (*Pinus taeda* L., *P. echinata* Mill., *P. virginia* Mill.) | | | | | |
| Piedmont Georgia | 200 | 1- 5 | D,DTh | TT (G) | Phillips & McNab, 1982 |

Continued

Table 2.--Summary of total tree and tree component weight equations for southern softwoods ≥ 1.0 inches d.b.h. by species and location--Continued

| Species and location | Sample size | D.b.h. range | Independent variables[1/] | Dependent variables[2/] | Investigator |
|---|---|---|---|---|---|
| | Number | Inches | | | |
| Pine, shortleaf (*Pinus echinata* Mill.) | | | | | |
| Georgia | 228 | 6-18 | DTh | TT,ST/R (G) | Saucier et al., 1981 |
| Northern Mississippi | 34 | 6-20 | DTh | TT,SST,ST4,CR (G&D) | Clark & Taras, 1976 |
| Northern Mississippi | 57 | 10-20 | DMh | SST,ST4, (G) | Phillips & Schroeder, 1975 |
| Southeast Missouri | 182 | 6-16 | D | CR (D) | Loomis et al., 1966 |
| Eastern Oklahoma | 81 | 1-24 | DTh | TT,ST4,CR (G&D) | Matney, 1977 |
| Eastern Tennessee | 10 | 2-11 | D | CR (D) | Whittaker, 1963 |
| East Texas | 38 | 2-24 | DTh | TT,TST,CR (G&D) | Lenhart et al., 1981 |
| S.E. United States | 467 | 1-20 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark, 1986 |
| Piedmont Georgia | 22 | 1- 4 | BDTh | TT (D) | Edwards & McNab, 1979 |
| Georgia | 100 | 1- 5 | D,DTh | TT (G&D) | Phillips & McNab, 1986 |
| East Texas | 242 | 1-20 | DTh,DH4 | ST/R | Walters, 1982 |
| Pine, slash (*Pinus elliottii* Engelm. var. *Elliottii*) | | | | | |
| Georgia | 208 | 6-18 | DTh | TT,SST,ST/R (G) | Saucier et al., 1981 |
| Southern Alabama | 43 | 6-20 | DTh | TT,SST,ST4,CR (G&D) | Taras & Phillips, 1978 |
| Southern Alabama | 43 | 9-20 | DMh | SST,ST4 (G) | Clark & Taras, 1975 |
| North Florida | 128 | 2-14 | D | TT,TST,CR (G) | Swindel et al., 1979 |
| North Florida | 132 | 1-14 | D | TST (G) | Swindel et al., 1982 |
| South Georgia | 16 | 5-11 | D | CR (D) | Johansen & McNab, 1977 |
| S.E. United States | 435 | 1-21 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark, 1986 |
| Coastal Plain Georgia | 29 | 1- 4 | BDTh | TT (D) | Edwards & McNab, 1979 |
| Georgia | 80 | 1- 5 | D,DTh | TT (G&D) | Phillips & McNab, 1986 |
| Pine, longleaf (*Pinus palustris* Mill.) | | | | | |
| South Georgia | 273 | 6-18 | DTh | TT,ST/R (G) | Saucier et al., 1981 |
| South Alabama | 48 | 10-20 | DMh | SST (G) | Schroeder et al., 1975 |
| South Alabama | 47 | 6-18 | DTh | TT,SST,ST4,CR (G) | Taras & Clark, 1976 |
| S.E. United States | 552 | 1-19 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark, 1986 |
| Coastal Plain Georgia | 24 | 1- 4 | BDTh | TT (D) | Edwards & McNab, 1979 |
| Georgia | 80 | 1- 5 | D,DTh | TT (G&D) | Phillips & McNab, 1986 |
| East Texas | 169 | 1-20 | DTh,DH4 | ST/R | Walters, 1982 |
| Pine, loblolly, slash & longleaf (*Pinus taeda* L., *P. elliottii* Engelm, var. *elliottii*, *P. palustris* Mill.) | | | | | |
| Coastal Plain Southeast | 1285 | 1-24 | DTh,DH4,DMh | TT,SST,ST/R (G&D) | Sauicer & Clark, 1985 |
| Coastal Plain Georgia | 200 | 1- 5 | D,DTh | TT (G) | Phillips & McNab, 1982 |
| Pine, virginia (*Pinus virginiana* Mill.) | | | | | |
| North Georgia | 25 | 6-14 | DTh | TT,ST/R (G&D) | Saucier et al., 1981 |
| Central Virginia | 324 | -- | DTh | TST,CR (D) | Madgwick & Kreh, 1980 |
| Southwest Virginia | 14 | -- | Th | TST,CR (D) | Madgwick et al., 1977 |
| North Georgia | 25 | 6-14 | DTh,DH4 | TT,ST/R (G&D) | Clark, 1986 |
| Georgia | 80 | 1- 5 | D,DTh | TT (G&D) | Phillips & McNab, 1986 |
| Pine, virginia, white, & shortleaf (*Pinus virginiana* Mill., *P. strobus* L., *P. echinata* Mill.) | | | | | |
| S. Appalachian Mountians | 100 | 1- 5 | D,DTh | TT (G) | Phillips & McNab, 1982 |
| Pine, sand (*Pinus clausa* var. *immuginata* Ward.) | | | | | |
| Northwest Florida | 36 | 4-15 | DTh | TT,SST,ST4,CR (G&D) | Taras, 1980 |

Continued

Table 2.--Summary of total tree and tree component weight equations for southern softwoods ≥ 1.0 inches by species and location--Continued

| Species and location | Sample size | D.b.h. range | Independent variables[1] | Dependent variables[2] | Investigator |
|---|---|---|---|---|---|
| | Number | Inches | | | |
| Pine, pond (*Pinus serotina* Michx.) | | | | | |
| Eastern North Carolina | 20 | 3-15 | DTh | CR (D) | Wendel, 1960 |
| Pine, eastern white (*Pinus strobus* L.) | | | | | |
| North Georgia | 36 | 6-18 | DH4,DMh | TT,SST,ST/R (G) | McNab & Clark, 1982 |
| North Georgia | 36 | 6-18 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark & McNab, 1986 |
| North Georgia | 40 | 1- 5 | D,DTh | TT (G&D) | Phillips & McNab, 1986 |
| Hemlock, eastern (*Tsuga canadensis* (L.) Carr.) | | | | | |
| North Georgia | 36 | 6-18 | DH4,DMh | TT,SST,ST/R (G) | McNab & Clark, 1982 |
| North Georgia | 36 | 6-18 | D,DTh,DH4,DMh | TT,SST,ST/R (G&D) | Clark & McNab, 1986 |
| Western North Carolina | 12 | 1-10 | D | TT,TST,CR (D) | Santee, 1978 |
| S.E. West Virginia | 21 | -- | D | TT (G&D) | Brenneman et al., 1978 |
| Red cedar, eastern (*Juniperus virginiana* L.) | | | | | |
| Eastern Tennessee | 31 | 6-17 | D | TT,TST,CR (G&D) | Schnell, 1976 |
| Pondcypress (*Taxodium distichum* var. *nutans* (Ait.) Sweet) | | | | | |
| Central Florida | 65 | 5-18 | DTh | TT,TST (G&D) | McNab et al., 1984 |
| North Florida | 51 | 1-18 | D | TST (G) | Swindel et al., 1982 |
| Central Florida | 10 | 3-16 | DTh | TT,TST,CR (D) | Mitsch & Ewel, 1979 |

[1]D = tree stem diameter at breast height; Th = tree height; H4 = height to 4-inch d.o.b. top; Mh = height to saw-log merchantable height; BD = basal diameter.

[2]TT = total tree above stump; SST = saw-log stem; ST4 = stem from butt to 4-inch d.o.b. top; ST = stem from butt to top; ST/R = stem from butt to top with ratio equations; CR = crown, G = green weight; D = dry weight.

# METHODS FOR ESTIMATING THE FOREST BIOMASS IN TENNESSEE VALLEY REGION

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Species-specific weight prediction equations utilizing a segmented log-log form were applied to U.S. Forest Service plot- and tree-level data from State inventories in the 201-county Tennessee Valley region to produce the detailed biomass estimates essential for regional resource management and industrial development. The forest biomass inventory; annual growth, removals, and net change of merchantable growing stock biomass; and the biomass potentially available each year for use as energywood were estimated. The total oven-dry weight of aboveground woody biomass is estimated to be 1,223.3 million tons or 40.2 tons per acre of commercial forest land.

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## Introduction

Following a general realization in the 1970s of the implications of their dependence on other countries as energy suppliers, Americans began a search for alternative energy sources. One of the first alternatives to be utilized was America's original, abundant, renewable resource--biomass fuels--primarily wood. The forests of the Tennessee Valley region, having recovered from near devastation in the early part of the century were believed to be ready to meet part of future energy demands.

When foresters were asked to quantify the available resource for energy, it was soon realized that insufficient information existed for estimating the weight of trees; and a major effort was directed toward developing accurate methods of estimating forest biomass. The results of this effort are only now becoming fully available.

The methods presented here combined with the most recent and complete data were used to produce the detailed forest biomass estimates essential to comprehensive, regional resource management and TVA's industrial development program. These estimates are available in customized reports for any group of counties in the Tennessee Valley region and a surrounding buffer zone through the Forest Resources Information System (FRIS).

## Geographic Area

The 201-county Tennessee Valley region consists of the 125 counties in the Tennessee River Drainage Basin plus 76 counties outside the Basin served by TVA power. These counties include the entire State of Tennessee plus portions of the States of Alabama, Georgia, Kentucky, Mississippi, North Carolina, and Virginia.

## Methods

### Data Sources

Plot- and tree-level forest inventory data were obtained through cooperative agreements with the U.S. Forest Service Experiment Stations serving the Tennessee Valley region. The Southeastern Forest Experiment Station provided the data for Georgia (1982), North Carolina (1984), and Virginia (1977). The Southern Forest Experiment Station provided data for Alabama (1982), Tennessee (1980), and Mississippi (1977). Data for Kentucky (1975) were provided by the Northeastern Forest Experiment Station. These were the most recent forest inventories available. The average inventory date for the Tennessee Valley region is 1980.

County-level data were summarized from the plots within each county inventoried by the Southeastern and Southern Forest Experiment Stations. For the Kentucky counties, data from the new-ground plots were used to derive county-level estimates based on survey-unit partitioning techniques.

### Biomass Estimation

Species-specific weight prediction equations were used to estimate green and oven-dry weights of wood and wood and bark in the bole, crown, total stem, and total tree (Clark et al., in press-a; Clark et al., in press-b; Clark, personal communication, 1985). These equations utilize a segmented log-log equation form. Two equations were fit simultaneously using a known point of intersection (11.0 inches dbh for hardwoods and 9.0 inches dbh for softwoods). Statistical comparison indicated that a segmented log-log method of deriving equations was much more accurate than use of a single log-log equation. The logarithmic forms of the equations were converted to original units by applying a correction factor to the antilogarithm to remove the bias incurred by estimating the geometric mean rather than the arithmetic mean. An exponential ratio equation was used to estimate the proportion of predicted total stem weight to a specified top diameter outside bark.

Tree weight equations were available for species comprising 83 percent of the cubic foot volume of hardwood species and 92 percent of the softwood species in the region. For the remaining species, equations were not available. Substitutions of existing equations were made based on specific gravity and crown form.

The segmented equations which utilize merchantable height and diameter at breast height (dbh) were applied to each tree. Weight estimates were derived for growing stock, rough and rotten trees, small (understory) trees, and growth and removals of growing stock. Net change was computed by subtracting removal weight from growth weight.

Total tree weight

In this paper, biomass is defined as the weight of all wood and bark (exluding foilage) above a 1-foot stump in all live trees that are 1.0 inch or greater in diameter at breast height (4.5 feet aboveground) and located on commercial forest land.

The following equations were used to estimate total tree weight for growing stock, rough and rotten trees, and understory trees:

For trees less than 5.0 inches dbh and greater than 1.0 inch dbh:

(1) $TTW = a * (DBH^2 * Ht)^b$

where:

TTW = Total tree weight

a and b = Species-specific coefficients for green or oven-dry wood or wood and bark

Ht = Total height

DBH = Diameter at breast height

For hardwoods less than 11.0 inches dbh and greater than or equal to 5.0 inches dbh and softwoods less than 9.0 inches dbh and greater than or equal to 5.0 inches dbh:

(2) $TTW = c * (DBH^2 * H4)^d$

where:

TTW = Total tree weight

c and d = Species-specific coefficients for green or oven-dry wood or wood and bark

H4 = Height to a 4.0 inch top outside bark

DBH = Diameter at breast height

For hardwoods greater than or equal to 11.0 inches dbh and softwoods greater than or equal to 9.0 inches dbh:

(3) $TTW = f * (DBH^2)^g * H4^i$

where:

TTW = Total tree weight

f, g, and i = Species-specific coefficients for green or oven-dry wood or wood and bark

H4 = Height to a 4-inch top outside bark

DBH = Diameter at breast height

Bole and sawlog weight

To obtain the bole weight of an individual tree, equations (2) and (3) were applied using appropriate coefficients to solve for total stem weight. The results were multiplied by a bole-stem ratio to give the weight of the merchantable bole to a 4-inch top. If the tree qualified as a sawlog, the total stem weight was multiplied by a sawlog-stem ratio to yield the sawlog weight.

The following equation form was used to calculate bole-stem and sawlog-stem ratios:

(4) $R_x = e^{(j * DOB^k)} * DBH^m$

where:

$R_x$ = Bole-stem ratio or sawlog-stem ratio

$e$ = Base of natural logarithm (2.71828)

j, k, and m = Species specific coefficients for green or oven-dry wood or wood and bark

DOB = Diameter outside bark

DOB = 4.0 inches for all boles
7.0 inches for softwood sawlogs
9.0 inches for hardwood sawlogs

DBH = Diameter at breast height

Thus bole weight was obtained by:

(5) $BW = TSW * R_B$

where:

BW = Bole weight

TSW = Total stem weight

$R_B$ = Bole-stem ratio

and sawlog weight (where trees qualified) was calculated by:

(6) $SLW = TSW * R_S$

where:

SLW = Sawlog weight

TSW = Total stem weight

$R_S$ = Sawlog-stem ratio

Crown and pulpwood weight

Once the values of total tree and bole were known, crown and pulpwood weights were calculated by subtraction as follows.

(7) $CW = TTW - BW$

and

(8) $PW = BW - SLW$

where:

CW = Crown weight

TTW = Total tree weight

BW = Bole weight

PW = Pulpwood weight

SLW = Sawlog weight

Growth weight

Growth weights were obtained by first computing the weight per cubic foot for the bole of each tree and then multiplying this weight by the cubic foot growth volume to give the growth weight in the bole.

(9) $GWB = (BW/CBV) * GVOL$

where:

GWB = Growth weight of the bole

BW = Bole weight

CBV = Current bole volume

GVOL = Growth volume

Total tree growth weight was then calculated based on a ratio of bole growth weight to total bole weight.

(10) $TTGW = (GWB/BW) * TTW$

where:

TTGW = Total tree growth weight

GWB = Growth weight of the bole

BW = Bole weight

TTW = Total tree weight

Total stem growth weight was calculated in the same manner by substituting total stem weight for total tree weight in equation (10). Sawlog growth weight was computed by replacing total stem weight with total stem growth weight in equation (6). Likewise the respective growth weights were substituted in equations (7) and (8) to obtain crown and pulpwood growth weights.

Removal weight calculation

Removal weights were calculated using the past dbh and past height to a 4-inch top in equation (2) or (3) to yield past weight of the total tree and past weight of the total stem. Current total stem weight was then calculated using a past weight to past volume ratio times the current volume.

(11) TSW = (PTSW/PVOL) * CVOL
where:
TSW = Total stem weight
PTSW = Past total stem weight
PVOL = Past volume
CVOL = Current volume

The current bole-stem ratio was determined by using current dbh in equation (4). This ratio was used with the result of (11) in equation (5) to produce current bole weight of removal trees. Total tree weight was computed by replacing past total stem weight in equation (11) with past total tree weight. Crown and pulpwood weights were derived as they were for growing stock trees with equations (7) and (8). Sawlog weights were computed using the appropriate sawlog ratio from (4).

Potential annual energywood

The weight of wood and bark available for energywood can be described as the sum of three components.

1. The weight of net change available (including crowns) minus the weight of sawlogs (reserved for conventional forest products).

2. The portion of rough and rotten inventory including crowns, which could be removed in conjunction with the conventional harvest of net change.

3. Logging residues from current harvests (crowns).

The estimate of potential annual energywood can be considered as the sum of future energywood harvests plus logging residues from current harvests. The components of future energywood harvests are the total weight of pulpwood size trees (5.0 inches dbh up to sawlog size), the portion of sawtimber tree boles above the sawlog plus the crowns of sawlog trees, and the total weight of rough and rotten or cull trees harvested. The sawlog portion of sawtimber trees is excluded since it likely could be marketed for a higher return. Only the portion of the rough and rotten inventory which would be removed in connection with the harvest of the available net change is included in the energywood estimates. This quantity is estimated by multiplying the growing stock net change rate of the major species group by the rough and rotten inventory.

Assuming a market for energy wood exists, loggers currently harvesting timber for other products could remove the tops of trees which they are currently leaving in the woods. These are logging residues from current harvests. While logging residues are defined as including remaining rough and rotten trees, crowns, and other residual material, only the crowns are considered here resulting in a more conservative estimate.

The weight of potential annual energywood can be expressed mathematically as follows:

(12) PAEW = ((G - R) - (SG - SR)) + (RR * ((G-R)/GSI)) + LR
= (GSNC - SNC) + (RR * GSNC) + LR
= NCA + RRA + LR

where:
PAEW = Potential Annual Energywood
G = Annual Growth of Growing Stock
R = Annual Removals of Growing Stock
SG = Annual Sawlog Growth
SR = Annual Sawlog Removals
RR = Rough and Rotten Inventory
GSI = Growing Stock Inventory
LR = Logging Residues
GSNC = Growing Stock Net Change
SNC = Sawlog Net Change
NCA = Net Change Available
RRA = Rough and Rotten Available

Standard Errors

Standard errors were computed by source (growing stock, rough and rotten, understory) and major species group (hardwood, softwood, total) for each county and for all counties in a State using the standard error function in a statistical computing package where N was the number of plots in a county or State. These were then expressed as a percent of the mean.

Due to the sampling techniques used in Kentucky, standard errors were computed using a slightly different method. The total number of new ground plots was determined for each county. The variance for each variable for a survey unit was calculated and divided by the number of plots in each county in the unit to give the county variance. The square root of the county variance was expressed as a percent of the county. The standard error for all Kentucky counties in the region was similarly computed.

These methods gave standard errors comparable to those in traditional forest inventory. Contribution to the error by the equations used to compute biomass was ignored. Table 1 shows the standard errors in percent for the Tennessee Valley region.

Table 1. Standard Errors for Oven-dry Aboveground Woody Biomass by Source and Major Species Group for the Tennessee Valley Region.

| Species group | Growing stock | Rough and rotten | Understory | Total |
|---|---|---|---|---|
| | Percent | | | |
| Softwood | 2.0 | 3.5 | 3.5 | 2.0 |
| Hardwood | 3.1 | 2.5 | 3.4 | 3.0 |
| Total | 2.9 | 2.5 | 3.3 | 2.8 |

## Results

The total oven-dry weight of aboveground woody biomass in the Tennessee Valley region is estimated to be 1,223.3 million tons (±2.8 percent) covering 30.4 million acres of commercial forest land or 51 percent of the total land area. This is equivalent to 40.2 oven-dry tons per acre of commercial forest land.

The following are key statistics for the region:

- Growing stock trees contribute 894.0 million oven-dry tons. Rough and rotten or cull trees add 161.6 million oven-dry tons, and understory trees add 167.7 million oven-dry tons to the total.
- The majority of the standing inventory (1005.6 million oven-dry tons or 82 percent) consists of hardwoods. Softwoods account for 217.7 million oven-dry tons or 18 percent of the inventory.

Table 2. Oven-dry Weight of Aboveground Woody Biomass by Source and Major Species Group for the Tennessee Valley Region.

| Species group | Growing stock | Rough and rotten | Understory | Total |
|---|---|---|---|---|
| | Million tons | | | |
| Softwood | 185.8 | 7.2 | 24.7 | 217.7 |
| Hardwood | 708.2 | 154.4 | 143.0 | 1005.6 |
| Total | 894.0 | 161.6 | 167.7 | 1223.3 |

- The greatest softwood per acre weights occur in the Mississippi, Alabama, and Georgia portion of the region, while hardwood per acre highs are in North Carolina and Virginia.
- Private landowners hold 75 percent of the total biomass inventory. Forest industry owns 8 percent and national forests and other public holdings contain 17 percent.
- Annual growth exceeds removals in merchantable growing stock--increasing inventory at a rate of 2.2 percent per year.
- There are 18.8 million tons (0.62 ton per acre) of oven-dry energywood potentially available in the Tennessee Valley region each year. This is the energy equivalent of 0.27 quads or more than one third of the energy derived in 1985 from coal at TVA's steam plants (Mills In press).
- Softwood energy wood totals 2.8 million tons (0.09 ton per acre) while hardwoods contribute 16.0 million tons (0.53 ton per acre).
- The greatest amounts of potential annual energywood are located in the Virginia counties (0.84 ton per acre) while Alabama counties have the least (0.41 ton per acre).

## Summary

Species-specific weight prediction equations utilizing a segmented log-log form can be applied traditional forest inventory data to produce regional biomass estimates across U.S. Forest Service Experiment Station boundaries. Customized reports for any group of counties in the Tennessee Valley region and a surrounding buffer zone are available through the Forest Resources Information System.

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# AREAS OF BIOMASS RESEARCH

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Biomass research is classified into areas according to the major forms of biomass heterogeneity produced by the spatial and temporal discreteness of trees. It is suggested that, at present, ecologically-oriented areas deserve equal or higher priority than the technical aspects of biomass studies.

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## Introduction

Although biomass research has been the major accomplishment in forest science during the last two decades, its potential contribution far exceeds the present achievements which are largely confined to the estimation of existing biomass. In order to answer some practically urgent problems, future biomass studies should address, along with development of more efficient methods for accurate biomass estimations, the problems of predicting the natural course of biomass dynamics and the effects of management activities.

The wide and expanding scope of biomass studies makes it necessary to look at the organization of our efforts and to classify them into more or less uniform research areas. Such a classification establishes a framework for the discussion of previous works and the guidance of future studies. To be meaningful and convenient, a classification should be based on some of the important attributes of forest biomass.

One of these pivotal attributes is biomass variability. Biomass estimation would have been quite simple if biomass had covered the Earth with a complete and homogeneous layer of a fixed depth. Actual biomass distribution differs from this simplest uniformity in many forms. Of them, three major forms, described below, should be considered as separate areas of biomass research.

Much of biomass variability can be traced to the fact that living matter exists in the form of discrete individuals and not as an undivided whole. Discovery of other, hidden units of matter discreteness (cell, gene, atom, etc.) required a great deal of effort and profoundly affected the corresponding branches of science and our knowledge as a whole. Feynman et al. (1963, p. 1-2) wrote at the beginning of "The Feynman lectures on physics": "If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact, or whatever you wish to call it) that all things are made of atoms - little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied."

In contrast, the existence of discrete organisms is too apparent to be acknowledged and is usually overlooked in the lists of ecological concepts, principles and laws (McIntosh 1980). Yet the discreteness on the organism level might be as fruitful as that on other levels of matter organization and, in particular, helpful in structuring biomass research and better understanding forest ecosystems.

Organism discreteness means that there are two basic variables for overall description of living creatures: their mass and their number per unit area. Accordingly, in addition to ecological taxonomy, there are two main branches of ecology: production ecology and population ecology (Harper 1977) which emphasize, respectively, the mass and the number. The relationship between these variables links together the branches and belongs to neither of them; it constitutes the core of ecology. This relationship determines the change in biomass of closed stands: as trees grow, biomass per unit area increases too, despite the decline of the number of trees.

Organisms are discrete not only in space but in time as well. Fallen trees create gaps which cannot be instantly covered by neighbors' growth. Affected by growth and density-dependent mortality of individual trees, as well as by various disturbances, forest canopy is always patchy and often incomplete. This density variation, a direct result of spatial and temporal discreteness in biomass, is a second source of variability in biomass distribution. In even-aged stands the proportion of canopy closure predictably decreases with age after the thicket stage. One of the mechanisms responsible for this trend is that the size of a gap created by the fall of a single tree increases as trees become older and larger, while the ability of the neighbors to close the gap decreases with age. Stand density is of great practical concern: manipulation of tree number, which is the most manageable stand variable, is a chief method in the maximization of the end product of foresters' activities, usable tree mass.

The third kind of biomass diversity has evolved in forest communities where organism discreteness has unleashed competition for light which in turn has resulted in the highly heterogeneous structure of each tree. Tree biomass consists of several components with drastically different properties. Crown occupies the entire aboveground space alloted to a tree but constitutes only about one-fifth of its mass. Roots are also widely spread and constitute an even smaller proportion of biomass than crowns. Stem, on the other hand, is the densest tree part which accounts for about two-thirds of tree mass with practically no utilized space of own. Investigation of relations between the components, which vary with site, species, age, density and many other factors, might greatly improve biomass estimations.

The lack of the simplest uniformity does not mean that biomass distribution is chaotic. There are certain patterns in the relationships between size and number of trees, tree structure, and gap dynamics. Investigation of these patterns can provide the basis for estimation, prediction and manipulation of forest biomass.

Along with the three mentioned ecologically-oriented areas, sampling techniques, methods of measurements and computational procedures should always remain a subject of biomass research.

Thus the following four areas capture the major directions in biomass research:

(1) tree morphology;
(2) stand density;
(3) size and number of trees;
(4) field and computational methods.

## Tree Morphology

While present biomass models have been developed for the practical purpose of predicting the mass of trees or their portions, they often fail to consider the mechanical and ecological considerations affecting tree form. These factors can be helpful in biomass modeling. For instance, fundamental principles of mechanics immediately reveal that the product of squared diameter and height, a commonly used variable in biomass equations, is not a good predictor of crown mass because crown mass (as any load atop a column of equal resistance) is inversely related to tree height while it is directly proportional to the diameter. In relation to trees this fact has been often documented when crown dimensions were regressed on both diameter and height (Briegleb 1952; Madgwick and Kreh 1980; Moeur 1981; Schmitt and Grigal 1981; Alban and Laidly 1982; Ouellet 1983, 1985; Harding and Grigal 1985; Lohrey 1985). This example shows that deductive inference can be useful in biomass research which currently relies mostly on approximations without clear biological or mechanical meaning.

Ecological investigations could produce interpretations of the coefficients of biomass models in terms of ecological variables like species tolerance, crown class, stand density, and so on and, as a result, facilitate the estimation of the coefficients. Using the immense amount of biomass data collected during the last two decades, it is also possible to scrutinize some tenets of silvicultural textbooks such as the connections between tolerance, crown length and crown density (crown mass per unit of crown volume.)

## Stand Density

Estimation and prediction of forest biomass can be made on the basis of relatively stable and consistent factors such as species composition and site quality. At the same time biomass is affected by numerous accidental forces such as natural disturbances which reduce stand density. The actual density of stands is always below the maximum or potential value due to the time lag between the practically instant creation of gaps by natural factors or management activities and the filling of them. Therefore, prior to investigation of the intrinsic relationship between size and number of trees, one has to take into account stand density.

Relative measures of stand density are more useful than absolute ones because the same absolute value, depending on specific conditions, might represent quite different levels of density. Relative density is the ratio of the existing biomass (or related variables) to its maximum possible on a given site. Determining this maximum value is crucial for the solution of two central forestry problems, the problem of density and stocking and the problem of site quality evaluation.

So far these problems have been either avoided by choosing variables insensitive to density (height of dominant trees) or substituted for by measuring the most dense "fully stocked" areas outside of the given stand. These indirect approaches are not always adequate. The chief example of this avoidance is site index classification. It is based on the height of dominant trees which, although less sensitive than other variables, still changes with density. Additionally, the correspondence between height and biomass is not exact. The drawbacks of the substitution approach are that there is no guarantee that the fully stocked areas are indeed maximally dense, and that the site quality of these areas and the studied stand is identical.

Therefore, what is needed now is to develop a direct approach for the estimation of the biomass limit which is required as a reference level for the calculation of relative density of stands and evaluation of site quality. The point is to determine the limit for a given stand within the stand itself, that is, to develop an intrinsic measure of density stress. This can be done by analyzing the distribution of a suitable absolute density measure estimated from plots within a given stand. This distribution must be negatively skewed because it is bounded by the density limit. When a distribution function, which reflects this asymmetry and contains a coefficient representing the limit, is fitted to the actual data, the limit can be computed even when none of the plots is fully stocked.

## Size and Number of Trees

The relationship between the size of trees and their number per unit area is another area of biomass research essential for the efficient estimation of stand biomass. Two well-known models, the Reineke (1933) equation and the 3/2 power law of self-thinning (Yoda et al. 1963), provide a background for the further development necessitated by some limitations of the models. Among these limitations are the restricted set of variables, the trend in coefficients which are supposed to be constant (this indicates the deficiency of the models' form), and, particularly for the law, low accuracy.

According to the self-thinning law, biomass of trees is a function of one variable, the number of trees per unit area, and the relative rate of self-thinning with respect to biomass growth is a universal constant. The law could be true in two cases: (1) when all factors of stand dynamics unaccounted for by the law (in particular, change in plant form and change in crown closure) are nonexistent; (2) when the effects of the unaccounted factors on the rate of self-thinning cancel each other. Investigation of the actual effects of these neglected factors is a worthy subject of biomass research. It seems (Zeide 1985) that developmental changes in plant form and in crown closure indeed oppositely affect the rate of self-thinning. In general, however, these factors rarely balance each other and the rate predictably changes with age, species, and site quality, and does not merely fluctuate about a constant value. The limiting line of self- thinning does not have any constant slope (on the log-log scale); generally, this line is a curve. A more realistic model of self-thinning should be more inclusive and in particular it should reflect the change in crown closure, or gap dynamics. This problem deserves special attention since knowledge of this process might lead to optimization of a major forestry operation, management thinning. The analysis of the law suggests the use of tree size as a predictor of their number, the utilization of the fact that diameter is better correlated with crown width and tree number than tree mass, and the development of a more adequate form of expressing allometric relationships than the elementary power function.

## Field and Computational Methods

This indispensible area is the most developed one since it is the only one traditionally considered as a proper area of biomass studies. Still, there are serious doubts about the accuracy of biomass estimates and the reliability of methods used in biomass studies. Numerous discrepancies and contradictions were reported in the literature. It is not uncommon in biomass studies to find that a tree portion is greater than the entire tree or that the whole is not equal to the sum of its parts. Different field methods frequently produce different estimates of the same stand. Reviewing the existent techniques used for biomass estimation, Parde (1980) writes that they lead to alarming inconsistencies even when the methods are close and the experimentation is careful. Another noted researcher, Cunia (1979, p. 662) expressed a similar concern: "A review of the presently used methodology of selecting sample trees for biomass tables construction shows that seldom, if ever, the samples of trees were representative of the population of interest. Most of the time, a subjective opinion of what seems representative, random and efficient superseded statistical considerations. For this reason, serious doubts are cast over the applicability of most if not all presently constructed tree biomass tables."

Instead of routine application of known methods and regressions, perhaps, new ecologically meaningful models should be formulated which would allow the drafting of appropriate inferences and predictions amendable for testing, analysis, and exclusion of alternatives which in their turn should become a subject of continuous doubt, checking, and developing. In other words, explicit and consistent application of the scientific method is required in biomass measurements just as in any other branch of science. As soon as we stop questioning our approaches and methods, we can be pretty confident that it won't take long to go astray and produce erroneous and misleading results.

## Priorities

So far the rapid progress in biomass studies has substantially increased the amount of information about forest stands but contributed little to their understanding. In biomass studies, physical efforts (cutting and weighing of trees) far exceed mental exploits which are usually limited to regressing the weights on accessible variables, chiefly, stem diameter at breast height. Except for a few ecological investigations, the studies do not set forward any hypotheses to be tested. Selection of regression equations is based on narrow statistical considerations rather than on biological reasoning. Discussions of the values of coefficients, their correspondence to theoritical expectations and relationship to species characteristics and environmental conditions are rare.

This problem is further aggravated because, with few exceptions, it is not recognized among foresters involved in biomass estimations. A notable exception to this rule is H. A. I. Madgwick, one of the most respected and experienced students of forest biomass, who wrote in his preface to the English edition of Forest Biomass (Satoo 1982): "Lord Rutherford has said that all science is either physics or stamp collecting. On that basis the study of forest biomass must be classified with stamp collecting and other such pleasurable pursuits".

The crucial issue of biomass studies is not a deficiency in a particular weighing technique, sampling method, or regression model. The issue is more general: it is our approach to research, the current imbalance between measurement and thinking. We keep accumulating redundant and often incorrect data instead of learning from our own experience. Therefore, at present, the ecologically-oriented areas deserve equal or higher priority that the technical aspects of biomass studies.

To support the thesis that "with different forms of measurement as well as with improvement measurement [sic] our scientific knowledge will increase", Young and Ribe (1983, p. 158) cite the famous words by Lord Kelvin in which science is virtually equated with measuring. This was a popular idea in the latter part of the past century, but today, a remark by Lord Rutherford, Kelvin's successor at Cambridge, is more appropriate. He is said to have interrupted one of his students with the comment: "All the time I see you measuring something. It's good. But when do you take time and think?"

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