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Tree profile equations for black walnut (*Juglans nigra* L.) and green ash (*Fraxinus pennsylvanica*) in Mississippi

By

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Tree profile equations for black walnut (*Juglans nigra* L.) and green ash (*Fraxinus pennsylvanica*) in Mississippi

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Black walnut (*Juglans nigra* L.) is a valued, Mississippi tree species with very little published mensurational data. Tree profile equations are effective tree volume predictors but are typically developed from measurements on destructively sampled trees, an impractical method on valuable species. This study developed black walnut and green ash (*Fraxinus pennsylvanica)* profile equations from non-destructive measurements using a Barr & Stroud FP15 optical dendrometer. Accuracy of the dendrometer was validated by taking both optical dendrometer and felled, direct measurements on green ash trees. Two profile models were evaluated for measured tree data. Separate equations were created from optical dendrometer tree profile data for black walnut and green ash and felled tree profile data for green ash. The Barr & Stroud allowed tree profile equations to be developed from standing tree measurements with acceptable accuracy, thus providing useful tools towards the valuation and management of southeastern black walnut and green ash.

DEDICATION

I would like to dedicate this research to my late grandfather, Thomas C. Howard.

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I would like to thank Dr. Emily Schultz and Dr. Thomas Matney for their immeasurable support in my development as a graduate student. I cannot imagine progressing as far and quickly as I have without their guidance. I would also like to thank Dr. Zhaofei Fan for his assistance and guidance in the statistical analysis of my data.

Cade Booth deserves a large acknowledgment for the blood, sweat and eye strain from countless viewings through the Barr & Stroud. Without his help and experience, it would not have been possible to accommodate the time frame in which we worked. I would also like to acknowledge Paul Jeffreys for his help in the field and office, as he provided both laughter and advice to me.

In addition, I would like to acknowledge the many landowners who made this work possible; without their cooperation, it is likely that our data for black walnut would have been severely limited. I would also like to thank the Forest and Wildlife Research Center at Mississippi State University and the John and Jane Player Walnut Foundation for providing funding for this project.

I would also like to thank my mother, Lara, and father, Kenny, for teaching me the value of education and for providing support in all that I do. I would not be the man I am today without their love and guidance.

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CHAPTER I

INTRODUCTION

1.1 Problem Statement

Black walnut (*Juglans nigra* L.) is a highly valued, native Mississippi hardwood tree species typically managed for quality sawlogs and veneer. United States Forest Service, Forest Inventory and Analysis (FIA) data estimated the presence of more than 660,000 instances of black walnut throughout the State (USDA FS, 2013). Schultz and DeLoach (2004) found Mississippi black walnut trees on bottomland fronts, flats and ridges and upland toe slopes. Very little published mensurational data is available for black walnut in the southeastern United States (Mize and Gutierrez-Espeleta, 1989). This is especially true in regard to profile equations designed for black walnut exclusively. Profile equations which are constructed for stem volume calculations are predominately developed using felled tree measurements. The data required for the regression fitting of profile equation model parameters include diameter and height value pairs along the entire length of the tree stem; profile data collected for this purpose is a representation of the region and/or species for which the final profile equation may be applicable (Larson, 1963). Upper stem diameters and bark thicknesses can easily be measured directly on felled trees; however, the procedure is destructive. Profile equations may be also developed from measures taken along the length of standing tree boles. Volume quantification of standing trees is desirable in many situations. This methodology is applied in the study of highly valued specimens but requires an investment of time and expense, especially if ladder and climbing procedures are to be used in the data collection. Optical dendrometers, however, provide a practical alternative to more costly standing tree measurements methods.

1.2 Justification

Given the high value of black walnut wood products, the development of a profile equation for this species should be an important improvement to volume and value estimates. Landowners, however, are unlikely to participate in research projects involving the destructive sampling of their trees. Given the limited distribution of the species in the State of Mississippi and the preclusion of landowner willingness to forfeit black walnut trees to destructive research, profile equation development from destructive measurements is not feasible. Mississippi black walnut is primarily found as a naturally occurring species along minor stream bottoms and toe slopes (Schultz and DeLoach, 2004) and is typically not artificially regenerated; therefore, profile equation development should focus on natural, woods-grown black walnut. A non-destructive approach to the development of a Mississippi black walnut profile equation could be realized from using optical dendrometer profile data given appropriate measurement accuracy.

1.3 Research Considerations

The accuracy and efficiency of an equation developed using an optical dendrometer could be determined from the involvement of a parallel study regarding profile equations for a surrogate species. Standing tree measurements would be recorded from the surrogate sample trees using instrumentation and methodology identical to the black walnut procedure. Subsequent destructive sampling of these surrogate study trees would allow development of a profile equation from observed, direct data. The standing tree measures would serve as a predicted species profile equation and the felled measures would serve as an observed species profile equation. The relation between the two equations would describe the efficiency of the optical dendrometer instrumentation to accurately measure profile data.

Analysis of residuals between the optical dendrometer measurements and the felled measurements for the surrogate species would indicate the accuracy of the optical dendrometer-only black walnut profile equation. This validation method does not require the primary and surrogate species to be similar but a surrogate species, green ash (*Fraxinus pennsylvanica* L.), was selected based on its availability and closeness in form to black walnut. The development of black walnut and green ash profile equations would provide improved volume estimates for those species in Mississippi, as compared to traditional volume models based solely on geometric forms, and would thus benefit stand management and valuation while serving as an example for future models involving primary/surrogate relationship measurements.

CHAPTER II

LITERATURE REVIEW

2.1 Yield Projections

Growth and yield predictions represent an important area of study in forestry. The ability to interpret the future outcome of a stand places a tool in the hand of the forester that allows for management objectives and outcomes to be obtained during the evaluation and redirection of the stand in silvicultural practice. These volume predictions of the stand are inherently based on forest mensurational data. “Growth is the increase (increment) over a given amount of time and yield is the total amount available for harvest at a given time.” as defined by Avery and Burkhart (2002, p.353). Thus, yield is the summation of all prior growth.

Growth and yield are primarily influenced by three factors: point of time in stand development, site quality, and the degree to which the site is occupied. These factors may be quantitatively expressed within an even aged stand as stand age, site index and stand density, respectively (Avery and Burkhart, 2002). Yield, or volume obtainable from a stem/stand, is a factor in several decision making processes involved in silviculture and other forestry disciplines. In order to measure yield, there are several routes of calculation available. In the past, the calculation of yield was largely based on a number of volume tables created for this purpose. Today, volumes may be obtained either from a volume table or prediction equations.

In general, for all processes available with regard to tree volume estimation, two broad classifications have been established. These are regarded to as single-entry and multiple-entry equations (Avery and Burkhart, 2002), which are delineated in respect to the number of variables necessary for user entry. Avery and Burkhart (2002) extend the classification of volume estimation procedures into those dealing with single species and composite applications; composite refers to those involving the computation and consideration of multiple species forms within a single equation (Avery and Burkhart, 2002). Volume equations may also include a tree form quotient component, often like the Girard form class (Avery and Burkhart, 2002). Girard form class is a form class quotient described by the percent of the established ratio between scaling diameter and diameter at breast height; the higher the value of the ratio, the greater the amount of volume to be estimated from the tree stem. Scaling diameter is considered to be stem diameter inside bark at the top of the first log. In the United States, this expression of form has received the most attention from foresters (Avery and Burkhart, 2002), which has led to its inclusion in some profile equations.

2.2 Tree Profile Equations

Growth and yield estimates necessitate the determination of standing tree volumes for a basis of comparison. Avery and Burkhart (2002) explain the greatest proportion of volume variation between individual trees can be accounted for by differences in diameter of the bole relative to a point of height without regard to age of the stem. This implies, primarily, that growth is not a necessary function in the calculation of yield. Tree profile equations use statistical functions built to predict the diameter at any point of height along the bole of a tree. Profile modeling has been and remains a very active area of research in forestry given the flexibility and utility that is afforded by the various existing models (Westfall and Scott, 2010).

2.2.1 Utility of Tree Profile Equations

Why are profile equations so valuable to the practicing forester? With complex stand inventories being performed by agencies and individuals, accurate estimates of volume are necessary in order to meet the desired level of accuracy for timber estimation during marketing decisions (Rupsys and Petrauskas, 2010). The ability to quickly and accurately predict volume of a stem, be it a segment or the entirety, is an economically and scientifically desired goal for the forester. During an inventory, a forester can easily record diameter at breast height and merchantable height to a variable point; fitted profile equations can then incorporate these values to accurately predict the outside and inside standing diameter of desired merchantable points along the bole of a tree (Matney and Parker, 1992).

2.2.2 Upper Stem Profile Data

Stem profile equations provide foresters with an efficient means for determining variables including merchantable tree height, and both total and merchantable stem volume (Max and Burkhart, 1976). Stem profile equations are an effective predictor of taper as well. Taper is the rate of change of diameter in respect to height. The taper rate varies due to factors including species, age, diameter at breast height, and site (Husch et al., 1982). Avery and Burkhart (2002) report the common requisite of upper stem diameters for the study of tree form, taper, and volume. Direct measurement of these upper stem values on felled, destructively sampled trees has been standard practice in tree profile data collection. This practice is time consuming and often cost limited. In addition, when performed in fragile ecosystems, the potential for disturbance caused by the felling of trees can easily prove to be a limiting factor during data collection (Parker and Matney, 1999). Despite these drawbacks, sampling of stem profile data along a felled tree provides reliable data that is one of the most accurate methods of direct volume quantification, aside from the use of a xylometer and water displacement. After the profile data has been collected from the desired range of tree forms/species, it only requires organization for analysis of fit to a desired profile equation model.

2.2.3 Max and Burkhart (1976) Profile Equation Model

There are several stem profile equation model forms in existence. Max and Burkhart (1976) developed a well-known profile equation for loblolly pine (*Pinus taeda*) involving a segmented polynomial regression approach, which delineates the bole of a tree into three sectors based on generalized relative geometric form (Equation 2.1). This is done under the assumption that in mathematical evaluation, a segmented model will best approximate the stem form. Sharma and Burkhart (2003) explain that a segmented polynomial profile model is created by grafting three submodels at two join points referred to as inflection points.

$$y_i = \beta_{41}(x_i - 1) + \beta_{42}(x_i^2 - 1) + \beta_{43}(\alpha_{41} - x_i)^2 I(\alpha_{41} - x_i) + \beta_{44}(\alpha_{42} - x_i)^2 I(\alpha_{42} - x_i) + e_i \tag{2.1}$$

Where,

y_i = predicted relative diameter,

x_i = relative height,

α_{41} and α_{42} = inflection point parameters to be estimated,

β_{41}, β_{42}, β_{43}, and β_{44} = parameters estimated from profile data,

I (Argument) = indicator function, where,

I (Argument) = 1, Argument ≥ 0,

= 0, Otherwise.

These segmented geometric forms are joined at inflection points within the stem based on a set of estimated parameters obtained from the regression analysis of collected profile data. The collected profile data set is a representation of the estimated parameters; the fitted equation will be applicable to individual trees from regions and forest types similar to those collected for estimation of the parameters. Any particular timber type desired for involvement with the profile equation should thus be considered during the collection of stem profile data for entry during the analysis of fit to the model parameters.

In evaluations of profile equation models (Clark et al., 1991), Max and Burkhart's (1976) model is favored because of its accuracy in predicting diameter and user accessibility. Max and Burkhart (1976) claim that their segmented polynomial regression model with three quadratic submodels is superior to a single, nonsegmented model for profile prediction; however, the complexity of their model precludes application to small data sets with limited diameter and height ranges (Matney and Parker, 1992; Parker, 1997). Parker (1997) suggests the use of a non-segmented, third degree polynomial for small data sets with limited diameter and height ranges, and authored a computer program for calculating both non-segmented and single and multiple segmented tree profile equations. His equations were based on optical dendrometer, standing tree measurements of upper stem diameters.

2.2.4 Clark, Souter, and Schlaegel (1991) Profile Equation Model

Souter (2003) developed a segmented profile for southern tree species for predicting a 1) diameter to a specified height; 2) cubic-foot volume, board-foot volume, and stem weight of wood and bark between two specified heights; 3) height for a specified diameter; and 4) auxiliary variables. Previously, Souter had collaborated with Clark and Schlaegel (Clark et al., 1991) to produce a form-class segmented profile model for height (H_x) to a 4-, 7-, or 9-inch diameter outside bark top (Equation 2.2). This model incorporates the form quotient of the Girard form class to produce a robust model that describes stem structure partially based on the relative measurements involved with the quotient.

$$d = \left[I_S \left\{ D^2 \left(1 + \frac{\left(c + \frac{e}{D^3}\right)\left(\left(1 - \frac{h}{H_x}\right)^r - \left(1 - \frac{4.5}{H_x}\right)^r\right)}{\left(1 - \left(1 - \frac{4.5}{H_x}\right)^r\right)} \right) \right\} + I_B \left\{ D^2 - \frac{\left(D^2 - F^2\right)\left(\left(1 - \frac{4.5}{H_x}\right)^p - \left(1 - \frac{h}{H_x}\right)^p\right)}{\left(\left(1 - \frac{4.5}{H_x}\right)^p - \left(1 - \frac{17.3}{H_x}\right)^p\right)} \right\} \right.$$
$$\left. + I_T \left\{ F^2 - \left(F^2 - D_x^2\right)\left(1 - \left(\frac{(H_x - h)}{(H_x - 17.3)}\right)^q\right) \right\} \right]^{0.5} \tag{2.2}$$

Where,

d = diameter (inches) at a particular height (h) (feet) above ground,

D = diameter at breast height (DBH) (inches),

H_x= tree height (feet) to a variable top diameter (x) (inches),

F = diameter at Girard form class height (inches),

r, c, and e = parameters to be estimated for the stem section below DBH,

p = parameter to be estimated for the stem section between DBH and Girard form class height,

q = parameter to be estimated for the stem section above Girard form class height,

$I_S = 1 \; if \; h < 4.5,$

$= 0 \; otherwise,$

$I_B = 1 \; if \; 4.5 \leq h \leq 17.3,$

$= 0 \; otherwise,$

$I_T = 1 \; if \; h > 17.3,$

$= 0 \; otherwise.$

The Max and Burkhart (1976) profile model is an example of a non-form class equation because it does not incorporate a form quotient in its regression. While the addition of a form quotient to a regression calculation can improve the stability of the model, one drawback is that entry of field data post model fitting will require the collection of the appropriate form class quotient in order to match the entry values to the model. This means more time for collecting inventory data but exactly how much more time has not been quantified. For data collection involving an optical or laser dendrometer, this should not prove difficult.

2.2.5 Non-Destructive Profile Data Collection

Parker (1997) studied the Tele-Relaskop optical dendrometer and whether non-destructive optical dendrometer measurements could produce data accurate enough for profile equation development. The results of this study showed that an optical dendrometer is capable of providing volume estimates comparable to those obtained by standard volume calculation procedures using felled tree, direct measurements. Parker and Matney (1999) later compared the accuracy of different dendrometer instruments, including the Criterion 400 Laser, Tele-Relaskop, and Wheeler Pentaprism on loblolly pine trees.

Based on the above studies, the associated benefits of standing tree measurements support the employment of optical instrumentation for recording tree profile data. Parker and Matney (1999) state, however, that an impracticality of using optical dendrometers is the difficulty of recording diameters below breast height, given the variable presence of forest vegetation. This impracticality may be slightly reduced through the removal of understory vegetation within the instrument's field of view to the lower stem; it is possible that this may not always serve a feasible option given the understory vegetation distribution status (threatened or endangered species) or study site ownership. Parker and Matney (1999), however, counter this problem with the suggestion to interpret the lower stem sector as a cylinder, or relative geometric shape.

2.2.6 Comparison of Max and Burkhart (1976) and Clark, Souter, and Schlaegel (1991) Profile Equation Models

Clark, Souter, and Schlaegel (1991) compared their form-class segmented profile model with Max and Burkhart's (1976) segmented polynomial equation and found the form-class segmented profile model provided more accurate volume estimations. Given the determined efficacy and accuracy of the Clark, Souter, and Schlaegel (1991) model, it provides a useful design for standing tree measurement profile equations.

2.3 Black Walnut

Black walnut is well recognized as a highly valuable species. Its scattered occurrence, shade intolerance, and short-distance seed dispersal characteristics are suited for artificial regeneration and plantation management through which it can provide a valuable specialty crop to landowners (Schultz and DeLoach, 2004).

2.3.1 Mississippi Black Walnut

In spite of black walnut's ability to be managed for plantation timber production, plantations do not typically occur in the State of Mississippi. Mississippi black walnut is most often found as scattered pockets on deep, well drained, naturally forested bottomland soil types; it is not uncommon for the species to be located near a perennial stream. Black walnut less frequently occurs on the toe slopes of upland sites where soils are deep, moist, but well-drained (Schultz and DeLoach, 2004). Information on black walnut growth habits and site requirements in the southeastern United States is very limited as is growth and mensurational data. Schultz and DeLoach (2004) studied the growth habits and site and soil characteristics of native Mississippi black walnut. Because of its high value and scattered occurrence, informed landowners will generally protect and manage local trees. Landowner concerns over possible damage to black walnut stems pose a handicap to the collection of profile data in particular and the subsequent development of profile equations to support reliable volume estimations and stem/stand valuations (Schultz and DeLoach, 2004).

2.3.2 Existing Black Walnut Mensurational Research

Very little development has occurred in any region of the United States for black walnut profile equations. At Iowa State University, Gutierrez-Espeleta and Mize (1986) constructed an interactive computer program for growth and yield modeling of the species. However, their project involved the use of destructive sampling, an option that is not feasible in the State of Mississippi. Black walnut is widely distributed throughout the State of Iowa and this fact allowed them to secure forty one trees for destructive sampling within the Shimek, Yellow River, Stephens and Holst State Forests located in southeastern, northeastern, south central and central Iowa, respectively (Gutierrez-Espeleta and Mize, 1986). Gutierrez-Espeleta and Mize (1986) describe the selection protocol as favoring measurement of woods-grown walnut, with DBH of sample trees ranging from 7.9 to 19.2 inches. Despite the abundance of black walnut, Gutierrez-Espeleta and Mize (1986) also cited an evident lack of black walnut mensurational data available for the State of Iowa. There is a distinct need for black walnut profile data and the investigation of stem profiles would fill an obvious gap based on published literature for this favored tree species.

CHAPTER III

METHODS

3.1 Sampled Trees

Black walnut trees were located throughout the State of Mississippi (Figure 3.1) by contacting landowners who participated in an earlier site suitability study (Schultz and DeLoach, 2004) and by requesting new study participants through Mississippi Forestry Commission service foresters, county agents, and forest industry employers. Records for each landowner included: name, phone number, address, email, land use, and geographic coordinate (latitude and longitude) location of tree(s). Only woods-grown trees were utilized in the study as verified during the site visit; open-grown and yard trees were excluded. Woods-grown trees that have recently been converted to open-grown settings were evaluated for inclusion in the study based on resulting stem habit. Presence of branching on the lower stem was the primary determinant in this decision.

Green ash trees were located in areas of the Mississippi State University John Starr Memorial Forest where destructive measurements by felling were possible (Figure A.1). The minimum diameter at 4.5 feet above ground for trees of both species was ten inches or greater in order to be valid for sampling. A minimum of 60 individual walnut trees and 40 individual green ash trees was set for measurement and profile function construction. These sample sizes were considered to be sufficiently large to estimate stable profile functions for estimating volumes. These criteria are considered important to the study procedure as previous studies have indicated the significance of tree selection criteria and sample size to the accuracy of a fitted profile equation (Kitikidou and Chatzilazarou, 2008; Subedi et al., 2011).

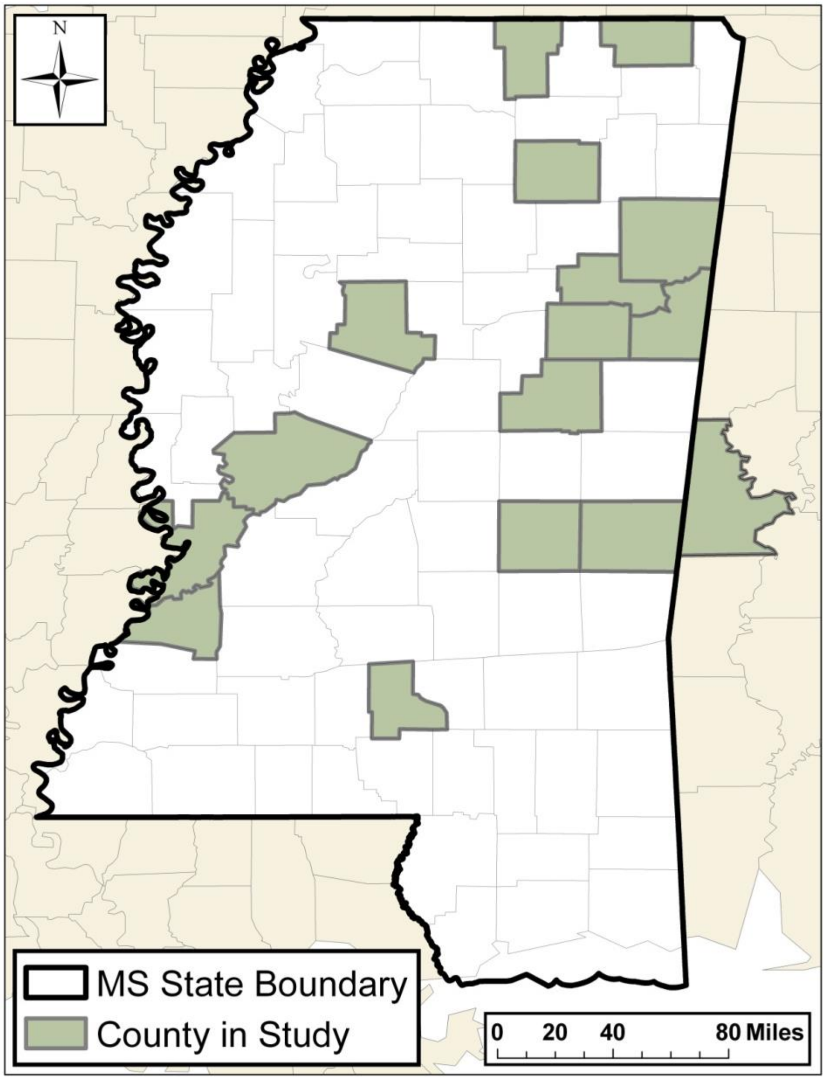

Figure 3.1 Mississippi (MS) and Alabama counties containing standing black walnut sample tree site locations.

3.2 Experimental Design

Both felled tree and optical dendrometer data were collected upon which to base: 1) non-destructive development of a black walnut profile equation, 2) non-destructive development of a green ash profile equation, and 3) destructive development on the identical sample of green ash trees to produce a separate profile function. By using the same instrumentation for both black walnut and green ash non-destructive data collection, profile equations developed from the data could be visually compared to assess the similarity of growth habit between the two species. Destructive and non-destructive green ash equations could also be visually compared to determine the accuracy of the non-destructive (optical dendrometer) instrumentation. Through the evaluation of the instrument accuracy, the expected accuracy of the standing black walnut profile equation could be determined. At the conclusion of this study, three separate profile equations will have been created for the purpose of evaluating the possibility of producing an accurate profile equation for black walnut by means of utilizing standing tree measurements exclusively.

3.3 Field Data Collection

Measurements varied depending on whether they were for the target species (black walnut) or the surrogate species (green ash). Both black walnut and green ash measurements included collection parameters for use with the Barr & Stroud FP-15 optical dendrometer.

3.3.1 Barr and Stroud FP15 Optical Dendrometer

The Barr & Stroud dendrometer is a specialized fixed-base rangefinder designed to measure diameters along the bole of a tree at user-selected heights (Figure A.2). Three measures are produced by the device: convergence, divergence, and the vertical angle for height measurement. These measures are involved with post field work processing to obtain records of diameter and height. Convergence and divergence are used for diameter calculations and are measured in gradians of angle viewed to the stem. They are the angles read by the device for the width of the linked image of the bole and the split image of the bole, respectively, in accordance to dual-prisms. The difference of width between these two prism-images, in addition to the relationship of this distance to the fixed base value of the dendrometer, allows the calculation of diameter from geometric calculations. Convergence and divergence are complemented by a record of height obtained by a built-in inclinometer.

The inclinometer measures the sine of the viewed angle and reports the value with an addition of one to the measured unit, in order to bring all the possible sine angles measureable by the device into a positive range. The inclinometer records height in respect to the angle optics of the Barr & Stroud and was used in relating the recordings of all points along the bole to six known heights (0.5, 1.5, 2.75. 4.5, 6.0, and 17.3 feet) measured with a 25 foot height pole (Figure A.3). In doing so, accurate estimations of height for each point can be obtained for the data set. These device values of diameter and height are then used in the Profile Data Calculator (Beard et al., In Press) to produce organized data for parameter estimates.

3.3.2 Other Instrumentation

The dendrometer was calibrated according to manufacturer specifications to ensure accurate measures of height and diameter to the degree possible. A 25-foot height pole was used for optical height validation. A loggers tape was used to obtain diameter at breast height. Calipers and Swedish bark gauge measures were used to take diameters on felled trees and bark thicknesses, respectively. Black walnut trees underwent standing measurements only, while green ash trees received both standing and subsequent felled or direct measurements. Green ash trees were marked with spray paint on the face of the tree measured with the Barr and Stroud optical dendrometer (Figure A.4) so that caliper diameter measurements could be taken on the same face. Green ash trees were also numbered with spray paint to avoid any possible errors relating standing and felled data for the same tree. Trees were cut at a 0.5-foot stump using a chainsaw. Direct measurement of the stem occurred immediately after felling in order to minimize shrinking and swelling of wood (Figure A.5).

3.3.3 Field Work Timing

Data collection occurred between deciduous canopy leaf-fall and deciduous canopy leaf-out. Presence of various canopy strata foliage has the potential to prevent measurements or reduce accuracy of the Barr & Stroud given its high sensitivity to picking up object edges in the viewfinder. Given that maximum light filtering occurs in the winter, stem edge detection would be most appropriate during this time period. In addition, proper environmental conditions were required to record accurate data. Sunny, cloudless skies and wind free days were chosen as much as possible. Sunny days provided a greater accuracy of stem edge detection. The absence of wind ensured the bole remained stationary during optical measurement reducing errors in divergence and convergence measurements especially in the upper stem where wind disturbance is greatest.

3.4 Profile Data Measurement Protocol

3.4.1 Standing Tree Measurement Protocol

Identical optical dendrometer methodologies were used for measuring both black walnut and green ash trees. A vantage point was selected for each study tree where a clear sighting of the terminal leader of the main stem of the tree was available. At this location, the Barr & Stroud optical dendrometer was set up on a tripod and leveled to record measurements for calculating diameters along the bole. Barr & Stroud measurements were taken at six specified heights on every sampled tree stem, at 0.50 feet, 1.50 feet, 2.75 feet, 4.50 feet, 6.00 feet, and 17.30 feet. The ocular record of diameter at 17.30 feet was used in calculations to obtain Girard form class for each tree. Diameter inside bark (DIB) for the Girard form class height was calculated by multiplying the average ratio of DIB to diameter outside bark (DOB) at breast height (4.5 feet) and at 6.0 feet by the DOB at form class height (17.3 feet) (Equation 3.1).

$$\mathrm{DIB}_{\mathrm{GFC\ Height}} = \left(\frac{\mathrm{DIB}_{4.5'} + \mathrm{DIB}_{6.0'}}{\mathrm{DOB}_{4.5'} + \mathrm{DOB}_{4.5'}}\right) * \mathrm{DOB}_{\mathrm{GFC\ Height}} \tag{3.1}$$

The six specified heights were directly determined using a 25-foot height pole placed adjacent and parallel to the stem of the tree. Direct measurement of heights using a height pole has been studied and shown to provide accurate measurements when used in conjunction with an optical dendrometer (McClure, 1968). Additional measurements were taken along the bole at 4.5 foot intervals, with typical recordings made at 10.50 feet, 15.00 feet, 19.50 feet, 24.00 feet, and so forth. A generalized diagram of these points along the stem may be seen in Figure 3.2. Measurements every 4.5 feet were continued into the upper stem as feasible, until reaching a top diameter of 3.0 inches for a final stem recording using the optical dendrometer.

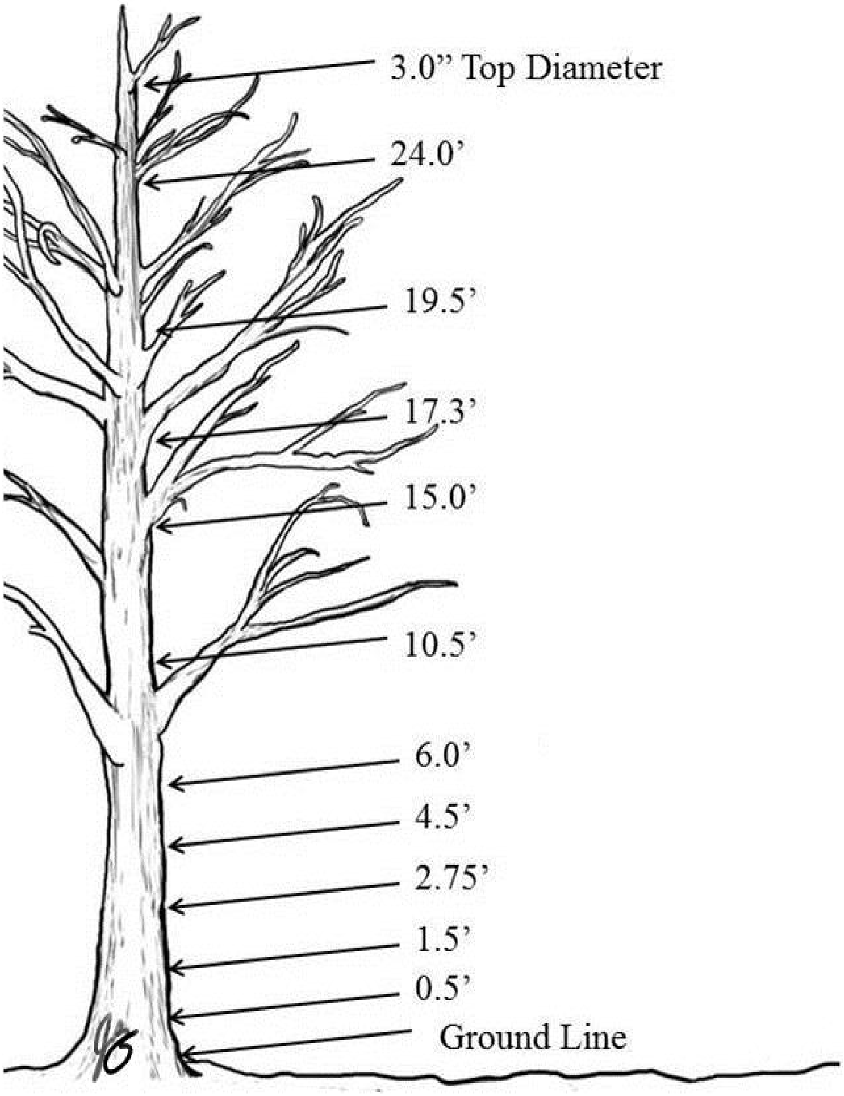

Figure 3.2 Heights measured during standing tree evaluation as located along the tree bole.

In the event that another vantage point is necessary for accurately reading upper stem measurements, the Barr & Stroud was moved provided that diameter at breast height was visible, and recorded, at the new station. At least one measured vantage point should include recordings of all the required variables, including a measurement of diameter at breast height with a logger's tape. By having a measured recording of diameter at breast height from each vantage point station, the profile equation data calculator (Beard et al., In Press) was able to calibrate the vantage point data groups together. At each recorded height along the bole, the Barr & Stroud optical dendrometer produced convergence, divergence, and inclinometer values. The distance between these two image gradian angle values and the relationship of the values to the fixed base of the dendrometer allowed calculation of diameter by the instrument's gradian angle gauge. A digital laser hypsometer was used to record total tree height and horizontal distance from each Barr & Stroud vantage point station to the pith center of the tree.

Caliper and logger tape recordings of diameter outside bark and Swedish bark gauge measurements for bark thicknesses were taken at ground line, 0.50 feet, 1.50 feet, 2.75 feet, 4.50 feet, and 6.00 feet. The logger tape was used only to record diameter at breast height, whereas the caliper was employed at all six heights. Two bark thicknesses located on alternate sides of the stem are recorded for each of the six heights using the Swedish bark gauge. Finally, each black walnut tree was mapped by collecting latitude and longitude coordinates using a backpack GPS and recorded by tree number. Given the destructive nature of the green ash sampling methodology, it was not necessary to retain geographic location for any future study involving these trees.

3.4.2 Felled Tree Measurement Protocol

Felled tree or direct measurements were obtained for green ash trees only following optical dendrometer measurements. Green ash trees were felled at approximately 0.5 feet and the bole was cleared of branches to facilitate linear measurements of the stem. Where stem breakage occurred within the upper portion of the bole, branches and bole were fit back together as carefully as possible, in order to have an accurate portrayal of the complete stem. Total stem length was recorded for the tree by running a tape measure along the length of the main apical branch.

Stump height was recorded, and diameter outside bark measured along the bole at relative heights of 2.00 feet, 3.50 feet, 4.50 feet, 6.00 feet, 8.00 feet and 17.30 feet. After 8.00 feet, heights and diameters were measured at 4.0-foot intervals to a 3.0 inch diameter outside bark (Figure 3.3). At each recorded diameter point along the felled stem, bark thickness was measured twice, using the Swedish bark gauge, on alternate tree face sides and were summed to calculate double bark thickness.

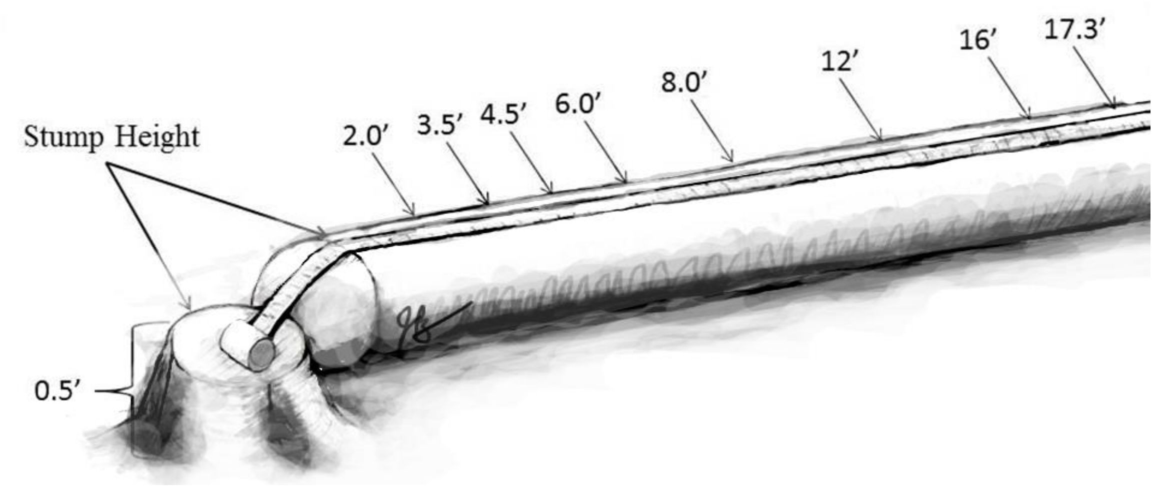

Figure 3.3 Points of felled tree measurements located along the cleared bole.

3.5 Statistical Analysis

The Profile Equation Data Calculator (Beard et al., In Press) was first used to convert optical dendrometer readings to diameters at their associated heights. The resulting diameter and height pairs for both optical dendrometer and felled tree measurements provided the inputs to TProfile© (Matney, 1996) for estimating the parameters of the segmented profile equation developed by Max and Burkhart (1976) and Clark, Souter, and Schlaegel's (1991) form class segmented profile equation. These two models were compared for absolute residuals along the entire length of the tree stem, root mean square error (RMSE), and index of fit.

Residuals were calculated along the bole as the average difference between observed and predicted relative diameter values. The square root of the average of the absolute value of the squared residuals was calculated to produce RMSE. Index of fit was calculated as one minus the quantity of the error sum of squares divided by the total sum of squares. A table of RMSE and index of fit values was constructed for each profile equation model and for destructive green ash and non-destructive walnut and green ash profile data. In addition, a graphical evaluation of model performance was made by plotting relative height and relative diameter for standing green ash and felled green ash to determine how well each model predicted standing tree profile data. This evaluation was used together with the tabular RMSE and index of fit values to determine the profile equation model that produced the best fit for black walnut and green ash. Further analysis utilized the best fit model exclusively.

3.5.1 Assessment of Profile Equation Performance

Graphical evaluation was used to assess the performance of the relative height to relative diameter curve for each profile equation. Relative height is defined as the variable height divided by total height, for a given point along the stem. Relative diameter is defined in a similar manner with the variable diameter divided by diameter at breast height. These dimensionless ratios were calculated for each sample tree and reduced variation correlated with size. Relative diameter may be expressed through diameter outside bark or diameter inside bark depending on the desired evaluation. The graph for each tree was inspected for non-uniformity to the overall trend presented by the fitted profile equation for each species and data collection method.

3.5.2 Presence of Sample Tree Anomalies

When an anomaly occurred for a particular tree, field data sheets were checked for entry errors. If there were no obvious entry errors, then RMSE and index of fit were calculated by species and data collection method for all profile data (including the anomaly tree) and for the profile data excluding the anomaly tree. If the removal of the tree produced a better fitted profile equation, the tree was removed from the data set. Only one such anomaly tree was found.

3.5.3 Fitted Green Ash Profile Equation Comparison

Absolute residuals at each relative height were graphed for the comparison between standing and felled green ash. This comparison related the fitted profiles for green ash for the validation of accuracy of the optical dendrometer and accuracy of the black walnut fitted profile equation.

CHAPTER IV

RESULTS

4.1 Profile Data Sets

There were a total of 62 black walnut trees and 40 green ash trees measured during data collection. Each green ash tree produced two datasets which represented the standing and felled methodologies. Single tree profile data for standing black walnut and standing and felled green ash were graphically examined using relative diameter and relative height to isolate measurement errors and outliers using SAS® Version 9.2 (SAS Institute Inc., 2010). Graphs revealed that one green ash tree deviated significantly from the other trees in the data set so the tree was excluded from the profile data set. On closer examination the tree was found to have excessive swell throughout the bole and did not represent a typical woods-grown green ash example. The data associated with this tree were removed from both standing tree and felled tree data sets. No other trees sampled by the study exhibited outlying tendencies. The final profile data set groups included a total of 62 black walnut trees and 39 green ash trees. Diameter and height class frequency tables for standing black walnut and standing and felled green ash study measurements are given in Tables 4.1 through 4.3. Tables 4.4 through 4.6 provide the descriptive statistics for the same respective data sets.

Table 4.1 Frequencies of measured total height and diameter at breast height of standing black walnut trees.

	Height class												
Diameter class	50	55	60	65	70	75	80	85	90	95	100	105	Total
10	2	3	3	1	1								10
12	1		1		4	5	2	1					14
14	1			4			3	1	1				10
16				1	1	1	1		1	3			8
18	1			1	2		2	4	1	1	1		13
20					1						1	1	3
22					1						2		3
26											1		1
Total	5	3	4	7	10	6	8	6	3	4	5	1	62

Table 4.2 Frequencies of measured total height and diameter at breast height of standing green ash trees.

	Height class								
Diameter class	70	75	80	85	90	95	100	105	Total
10	1	1	3	2	1		1	1	10
12		2	3	3	4	2		3	17
14	1	1	2		3			1	8
16						2	1	1	4
Total	2	4	8	5	8	4	2	6	39

Table 4.3 Frequencies of measured total height and diameter at breast height of felled green ash trees.

	Height class								
Diameter class	70	75	80	85	90	95	100	105	Total
10	1		1	5	1	1		1	10
12			3	3	4	3	1	3	17
14		1		2	2	1	1	1	8
16						2		2	4
Total	1	1	4	10	7	7	2	7	39

Table 4.4 Descriptive statistics for diameter at breast height (DBH) and total height (THT) classes for standing black walnut trees.

	Standing Black Walnut Profile Data Group (n=62 trees)			
	Mean	Standard Deviation	Min	Max
DBH	14.9	3.67	9.2	25.9
THT	76.5	14.34	48.0	103.5

Table 4.5 Descriptive statistics for diameter at breast height (DBH) and total height (THT) classes for standing green ash trees.

	Standing Green Ash Profile Data Group (n=39 trees)			
	Mean	Standard Deviation	Min	Max
DBH	12.4	1.72	10.0	16.5
THT	89.0	10.08	72.0	107.0

Table 4.6 Descriptive statistics for diameter at breast height (DBH) and total height (THT) classes for felled green ash trees.

	Felled Green Ash Profile Data Group (n=39 trees)			
	Mean	Standard Deviation	Min	Max
DBH	12.5	1.75	10.0	16.5
THT	92.0	9.18	72.0	107.0

4.2 Selected Profile Equation Model Form

Following initial data inspection, the three data groups of standing black walnut, standing green ash and felled green ash were input in TProfile$^{©}$ to obtain parameter estimates for the Max and Burkhart (1976) profile equation model and the Clark, Souter, and Schlaegel (1991) profile equation model. RMSE and index of fit for diameter outside bark and diameter inside bark models along with the graphical evaluation of absolute residuals indicated that study profile data were best fit (lower RMSE and higher index of fit) to the Clark, Souter, and Schlaegel (1991) profile equation model (Table 4.7 and Table 4.8). Tables 4.9 through 4.11 give the parameters estimated for the Clark, Souter, and Schlaegel (1991) model for both outside bark and inside bark diameters together with the total number of observations/measurements utilized in model fitting. Figures 4.1 through 4.6 illustrate the performance of each profile equation model for an indicated profile data group. The profile curve of the Clark, Souter, and Schlaegel (1991) model appears to be a better fit than the Max and Burkhart (1976) model.

Table 4.7 Root mean square error and index of fit for the estimated diameter outside bark (DOB) profiles of black walnut (BW) and green ash (GA).

		DOB Profiles		
Profile Equation Model		BW Standing	GA Standing	GA Felled
Max and Burkhart	RMSE	0.072645	0.055859	0.059402
	Index of Fit	0.946	0.968	0.963
Clark, Souter, and Schlaegel	RMSE	0.060222	0.047386	0.051535
	Index of Fit	0.963	0.977	0.972

Table 4.8 Root mean square error and index of fit for the estimated diameter inside bark (DIB) profiles of black walnut (BW) and green ash (GA).

		DIB Profiles		
Profile Equation Model		BW Standing	GA Standing	GA Felled
Max and Burkhart	RMSE	0.064448	0.052405	0.056232
	Index of Fit	0.945	0.967	0.963
Clark, Souter, and Schlaegel	RMSE	0.063468	0.049490	0.054218
	Index of Fit	0.960	0.975	0.971

Table 4.9 Estimated parameters and fit statistics for the Clark, Souter, and Schlaegel (1991) profile model for standing black walnut.

Parameter	Outside Bark Profile	Inside Bark Profile
a	48.618027	52.504031
b	0.570950	0.633880
c	369.444072	289.398386
d	5.521187	5.814973
e	1.107288	1.109531
alpha	0.199508	0.197643
No. Obs.	1004	1004
RMSE	0.060222	0.063468
Index of Fit	0.963	0.960

Table 4.10 Estimated parameters and fit statistics for the Clark, Souter, and Schlaegel (1991) profile model for standing green ash.

Parameter	Outside Bark Profile	Inside Bark Profile
a	53.379103	53.587903
b	1.270846	1.340018
c	144.079129	154.401680
d	13.902377	14.263543
e	2.180770	2.168713
alpha	0.695956	0.691592
No. Obs.	751	751
RMSE	0.047386	0.049490
Index of Fit	0.977	0.975

Table 4.11 Estimated parameters and fit statistics for the Clark, Souter, and Schlaegel (1991) profile model for felled green ash.

Parameter	Outside Bark Profile	Inside Bark Profile
a	60.012466	62.684722
b	1.317155	1.399983
c	256.613802	287.843810
d	13.408658	14.499798
e	2.253484	1.978287
alpha	0.695492	0.645063
No. Obs.	1002	1002
RMSE	0.051535	0.054218
Index of Fit	0.972	0.971

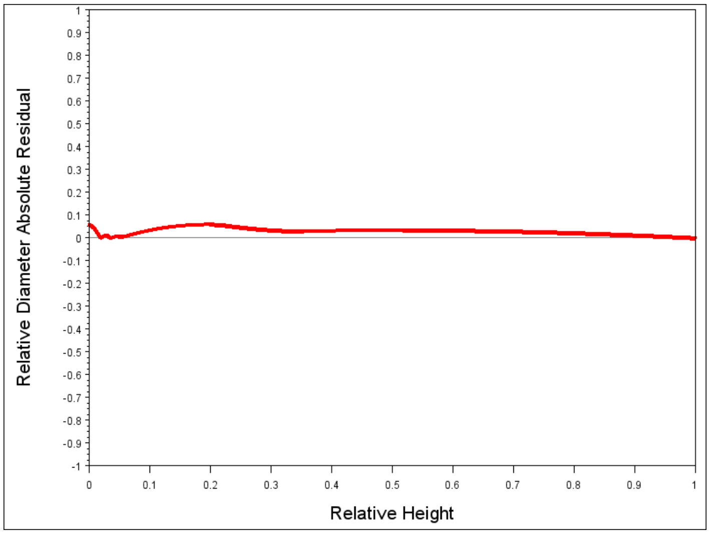

Figure 4.1 Absolute residuals between the Max and Burkhart (1976) and Clark, Souter, and Schlaegel (1991) profile equation models for standing black walnut profile data.

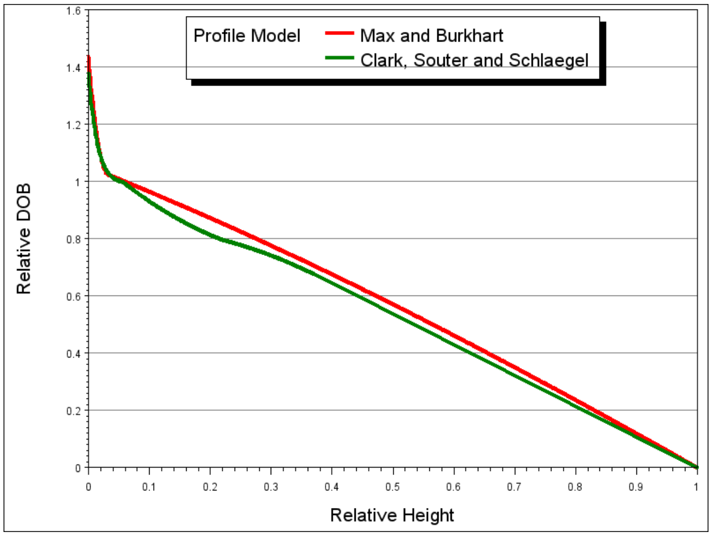

Figure 4.2 Performance of the Max and Burkhart (1976) and Clark, Souter, and Schlaegel (1991) profile equation models for standing black walnut profile data.

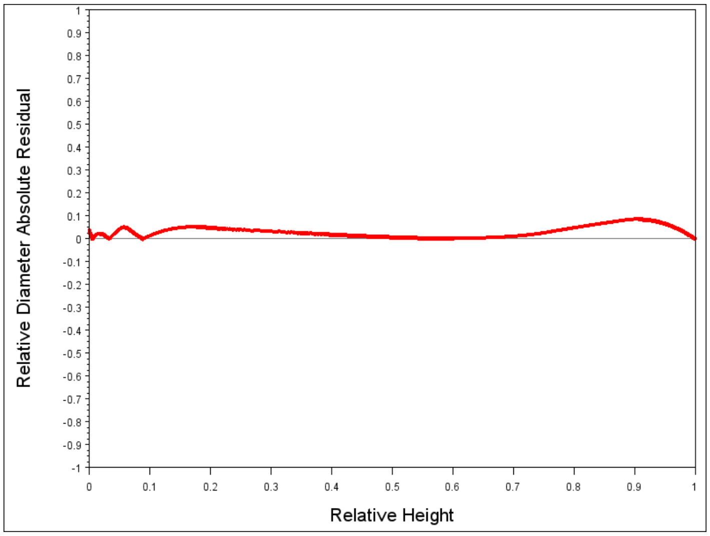

Figure 4.3 Absolute residuals between the Max and Burkhart (1976) and Clark, Souter, and Schlaegel (1991) profile equation models for standing green ash profile data.

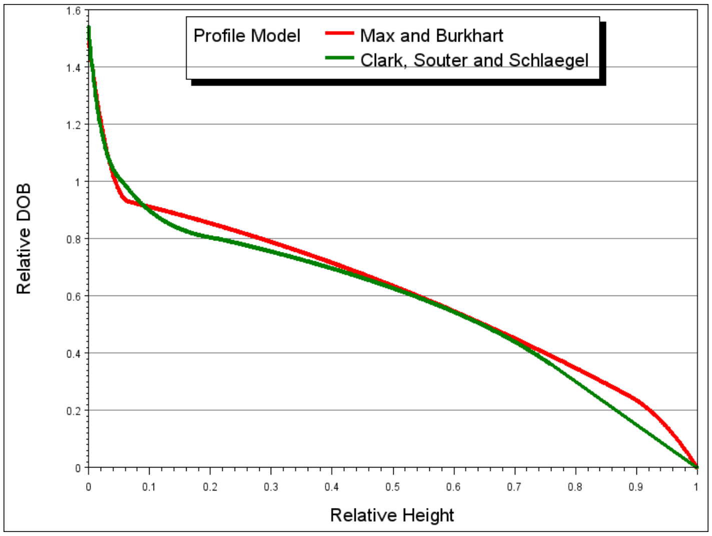

Figure 4.4 Performance of the Max and Burkhart (1976) and Clark, Souter, and Schlaegel (1991) profile equation models for standing green ash profile data.

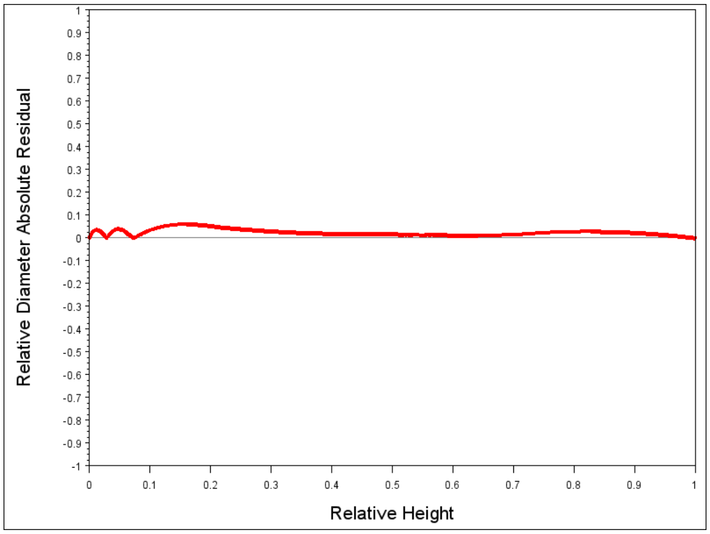

Figure 4.5 Absolute residuals between the Max and Burkhart (1976) and Clark, Souter, and Schlaegel (1991) profile equation models for felled green ash profile data.

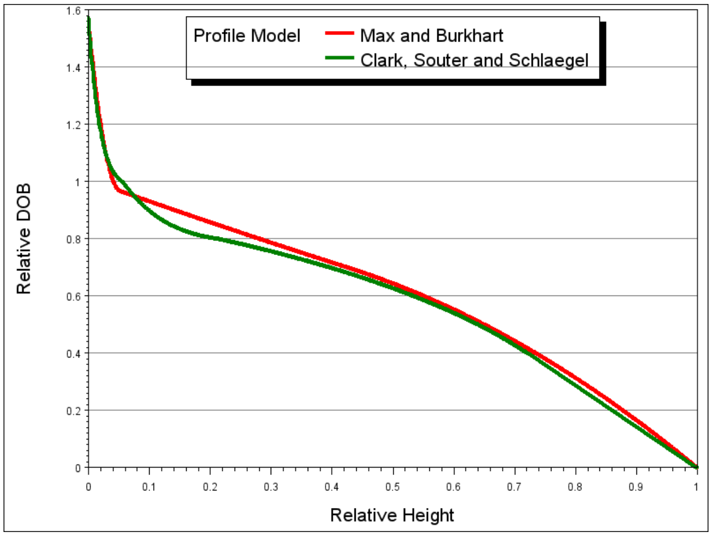

Figure 4.6 Performance of the Max and Burkhart (1976) and Clark, Souter, and Schlaegel (1991) profile equation models for felled green ash profile data.

4.3 Profile Equation Comparisons

Utilizing the Clark, Souter, and Schlaegel (1991) profile equation, comparisons were made between standing black walnut and green ash, and standing and felled green ash profile equations. Graphical comparisons were made to visualize the difference between the standing and felled models. Figure 4.7 illustrates the absolute residuals detected between the standing and felled green ash models for relative diameter versus relative height. The butt portion of the stem (<0.1 relative height) and the upper stem (>0.5 relative height) display the main areas of residual differences between the models. Figure 4.8 indicates that observed and predicted green ash profile curves are nearly identical. The tabular format of data expressing the relationship between relative height and relative diameter for the models is presented in Tables 4.12 through 4.14. Average residuals between the fitted profile equation and the observed field profile equation are given at each relative height interval.

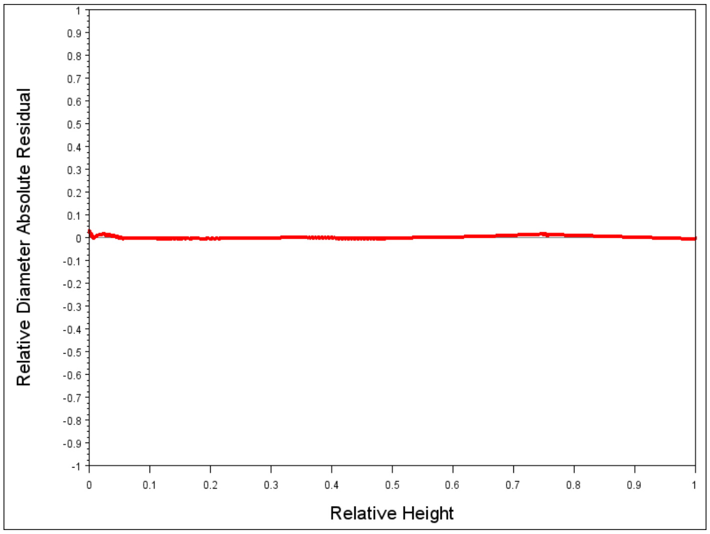

Figure 4.7 Absolute residuals detected between observed (felled) and predicted (standing) green ash profile equations in Mississippi.

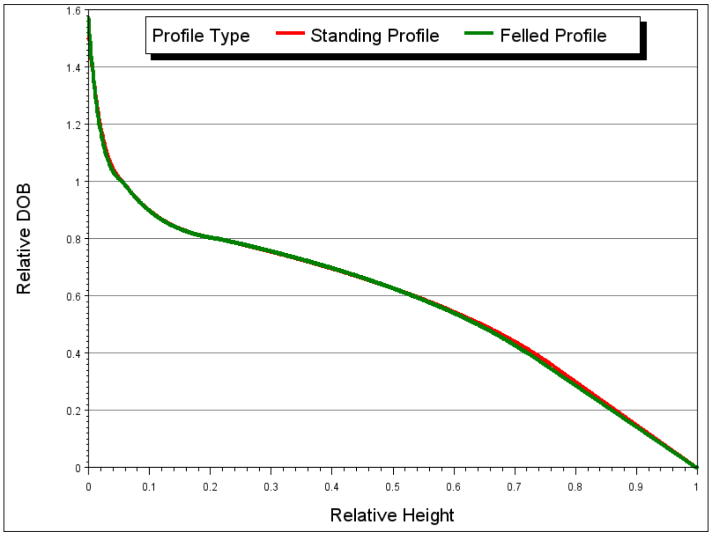

Figure 4.8 Comparison of the observed (felled) and predicted (standing) green ash Clark, Souter, and Schlaegel (1991) profile equations in Mississippi.

Table 4.12 Statistical measures of the Clark, Souter, and Schlaegel (1991) model for the standing black walnut profile equations sorted by relative height.

Relative Height	N	Observed Relative Diameter	Predicted Relative Diameter	Average Residual	RMSE
0.00(0.01)	114	1.18	1.18	0.001130	0.086900
0.05(0.04)	97	1.03	1.03	0.001700	0.031500
0.10(0.10)	58	0.95	0.95	0.001300	0.038400
0.15(0.15)	49	0.89	0.89	0.003270	0.035800
0.20(0.20)	51	0.85	0.86	0.001880	0.032100
0.25(0.25)	45	0.83	0.82	0.009580	0.042600
0.30(0.30)	54	0.80	0.79	0.002830	0.039500
0.35(0.35)	50	0.74	0.74	0.000617	0.067700
0.40(0.40)	46	0.70	0.70	0.001260	0.080900
0.45(0.45)	45	0.63	0.63	0.006630	0.080400
0.50(0.50)	42	0.58	0.59	0.004530	0.090200
0.55(0.55)	41	0.52	0.52	0.000698	0.086800
0.60(0.60)	46	0.44	0.46	0.026400	0.093000
0.65(0.65)	37	0.41	0.41	0.001690	0.088700
0.70(0.70)	27	0.35	0.35	0.000136	0.064100
0.75(0.74)	12	0.32	0.30	0.025500	0.069100
0.80(0.81)	4	0.33	0.24	0.087100	0.118000
0.85(0.00)	0	0.00	0.00	0.000000	0.000000
0.90(0.00)	0	0.00	0.00	0.000000	0.000000
0.95(0.00)	0	0.00	0.00	0.000000	0.000000
1.00(0.00)	0	0.00	0.00	0.000000	0.000000
Overall	818	0.80	0.80	0.000415	0.066600

Table 4.13 Statistical measures of the Clark, Souter, and Schlaegel (1991) model for the standing green ash profile equations sorted by relative height.

Relative Height	N	Observed Relative Diameter	Predicted Relative Diameter	Average Residual	RMSE
0.00(0.01)	78	1.31	1.31	0.000955	0.102000
0.05(0.05)	70	1.03	1.03	0.001470	0.032300
0.10(0.10)	34	0.91	0.92	0.004490	0.027200
0.15(0.15)	37	0.87	0.87	0.003040	0.017300
0.20(0.20)	38	0.84	0.84	0.000240	0.021300
0.25(0.25)	37	0.81	0.81	0.001550	0.023300
0.30(0.30)	40	0.79	0.79	0.001030	0.023300
0.35(0.35)	31	0.76	0.76	0.005070	0.030200
0.40(0.40)	35	0.73	0.73	0.002190	0.035000
0.45(0.45)	32	0.70	0.69	0.011200	0.037100
0.50(0.49)	33	0.67	0.65	0.016900	0.042400
0.55(0.55)	41	0.61	0.61	0.000623	0.056400
0.60(0.60)	33	0.55	0.56	0.011700	0.058900
0.65(0.65)	30	0.50	0.51	0.011900	0.048300
0.70(0.70)	32	0.44	0.45	0.013400	0.056700
0.75(0.75)	20	0.38	0.38	0.001740	0.055600
0.80(0.79)	11	0.36	0.33	0.031200	0.065500
0.85(0.84)	2	0.36	0.25	0.112000	0.160000
0.90(0.00)	0	0.00	0.00	0.000000	0.000000
0.95(0.00)	0	0.00	0.00	0.000000	0.000000
1.00(0.00)	0	0.00	0.00	0.000000	0.000000
Overall	634	0.80	0.80	0.000527	0.051400

Table 4.14 Statistical measures of the Clark, Souter, and Schlaegel (1991) model for the felled green ash profile equations sorted by relative height.

Relative Height	N	Observed Relative Diameter	Predicted Relative Diameter	Average Redisual	RMSE
0.00(0.01)	74	1.29	1.30	0.005800	0.116000
0.05(0.05)	79	1.01	1.01	0.003750	0.029300
0.10(0.09)	54	0.93	0.93	0.001540	0.017900
0.15(0.15)	44	0.89	0.88	0.007540	0.024900
0.20(0.20)	44	0.86	0.85	0.005710	0.014300
0.25(0.25)	46	0.84	0.84	0.002180	0.014000
0.30(0.30)	44	0.81	0.81	0.000824	0.017600
0.35(0.35)	45	0.78	0.77	0.005330	0.023500
0.40(0.40)	47	0.74	0.74	0.000275	0.039900
0.45(0.45)	43	0.70	0.71	0.004420	0.051500
0.50(0.50)	41	0.67	0.67	0.003460	0.058300
0.55(0.55)	48	0.63	0.63	0.002820	0.056900
0.60(0.60)	43	0.59	0.58	0.005710	0.059100
0.65(0.65)	44	0.53	0.53	0.002560	0.063700
0.70(0.70)	48	0.46	0.47	0.006580	0.062300
0.75(0.75)	47	0.37	0.39	0.020200	0.071100
0.80(0.80)	47	0.32	0.32	0.004440	0.060600
0.85(0.85)	36	0.27	0.24	0.023900	0.049100
0.90(0.89)	11	0.23	0.17	0.053700	0.062900
0.95(0.00)	0	0.00	0.00	0.000000	0.000000
1.00(0.00)	0	0.00	0.00	0.000000	0.000000
Overall	885	0.73	0.73	0.001470	0.054700

CHAPTER V

DISCUSSION

Avery and Burkhart (2002) cite several factors for the evaluation of a profile equation. These include applicable species, applicable region, number of sample trees used in development, the authoring group, entry measures required, volumes of user interest, original profile data bole measurements, method of statistical calibration, and evidence of equation validation. These factors were all considered in the development of black walnut and green ash profile equations reported here. Species and Mississippi region specific profile equations were constructed using the Max and Burkhart (1976) segmented model and the Clark, Souter, and Schlaegel (1991) segmented form class model which were originally developed for species including black walnut and green ash. The number of sample trees measured in this study (60 black walnut trees and 39 green ash trees) was considered to be an appropriate number for predicting diameter from user entry data for each species. Measurements required for the Clark, Souter, and Schlaegel (1991) profile equation model are variable height, total height, diameter at breast height and DOB at Girard form class height. This was a greater number of variables than required by the Max and Burkhart (1976) profile equation model, but given the predictive capability of the Clark, Souter, and Schlaegel (1991). model, the extra effort was justified. TProfile© (Matney, 1996) was used to fit the profile data sets to the Clark, Souter, and Schlaegel (1991) and Max and Burkhart (1976) models. Validation of both the instrument accuracy and predicted, standing tree profile equations was confirmed through the comparison of the standing green ash profile to the felled green ash profile.

The evaluation of each model's relative performance to each of the three profile data sets (standing black walnut, standing green ash, and felled green ash) showed that the Clark, Souter, and Schlaegel (1991) model performed best in all instances. The Max and Burkhart (1976) model did not exhibit high performance when constrained by a lack of upper stem diameter data for all standing tree data instances, whereas the Clark, Souter, and Schlaegel (1991) model provided a more robust equation able to perform under these constraints. A reason for reduced upper stem performance of the Max and Burkhart (1976) model may have been an insufficient number of observations in the upper crown area. For those who wish to employ the same methods in other studies, every effort should be made to obtain more measurements in the upper crown than was achieved in this study.

The predicted profile equations developed from the optical dendrometer profile data are indicative of an accurate tree profile for each species. The maximum absolute residuals was less than 0.05 between the observed (felled) and predicted (standing) green ash profile equations as shown in Figure 4.7. This indicates that profile equations developed from optical dendrometer profile data are reliable for practical purposes in volume estimation. A spline plot of the equations is shown in Figure 4.8.

CHAPTER VI

CONCLUSIONS

The Clark, Souter, and Schlaegel (1991) profile equation model form was fitted to black walnut and green ash profile data from Mississippi. A profile equation for southeastern black walnut is now available for general use. The Max and Burkhart (1976) profile equation model was not as robust as the Clark, Souter, and Schlaegel (1991) model for extrapolating upper stem diameters.

The Barr & Stroud FP15 optical dendrometer produced standing tree diameter and height measurements for green ash that were essentially equivalent to felled tree measurements at comparable points along the bole. Thus, use of the Barr & Stroud was regarded as suitable for profile equation development. The black walnut profile equation is applicable to individual trees within the diameter at breast height and total height ranges of 9 – 26 inches and 48 – 104 feet, respectively. The green ash profile equation is applicable to individual trees within the diameter at breast height and total height ranges of 10 – 17 inches and 72 – 107 feet, respectively. Given the extent of the height and diameter ranges and variety of plot locations, the black walnut profile equation is suitable for broad application within Mississippi. The purpose of the green ash profile equation was primarily to validate the accuracy of the Barr & Stroud dendrometer.

The black walnut and green ash profile equations can be implemented in TCruise$^{©}$ (Matney, 1996) or other similar inventory software to provide practical, improved estimates of stem volume. The methodology presented here allowed the development of standing tree profile equations, where felled, direct measurement was not possible, through surrogate species validation.

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APPENDIX A

FIELD IMAGES

Figure A.1 Forest stand where green ash trees were optically measured and then felled for direct sampling on the John W. Starr Memorial Forest, Mississippi State University, Winston County, Mississippi, in 2012.

Figure A.2 Barr & Stroud FP15 optical dendrometer.

Figure A.3 Sampled standing black walnut tree with twenty-five foot height pole placed in accordance with measurement protocol.

Figure A.4 Standing and felled green ash sample trees.

Standing trees were marked on the face where Barr & Stroud dendrometer measurements were recorded for sampling to ensure consistency with caliper measurements taken on the ground. Stumps were cut at one-half foot.

Figure A.5 Destructive sampling of green ash trees on the John W. Starr Memorial Forest, Mississippi State University, Winston County, Mississippi, in 2012.