Biomass Estimation Using the Component Ratio Method for White Oak.

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Abstract

With higher demands on biomass, the ability to accurately estimate the amount in a stand is more important now than ever before. Existing models currently in use by the Forest Inventory and Analysis (FIA) program of the United States Department of Agriculture (USDA) Forest Service include the Component Ratio Method (CRM). However, testing of the CRM models is needed to validate and calibrate them. The objective of this research was to test and develop a system of equations capable of producing consistent volume and biomass estimates for standing trees of commercially important hardwood species in the southeastern United States. Testing and comparing was done through use of new and legacy data to establish component ratios of trees and contrast these results to those from existing models. Specifically, analyses were completed for models of merchantable and whole stem volume, wood densities models and averages, and the component ratios for wood, bark, branches, and foliage. The existing models were then calibrated and adjusted. Results on accuracy and fitted results of updated models are reported, along with testing the effects of applying updated models over the state of Virginia.

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Introduction

Emphasis is increasingly placed on the assessment and utilization of whole trees, mainly due to changing societal demands for forests to contribute to bioenergy production, carbon sequestration, and a sustainable supply of a range of other goods and services (Aguilar and Garrett 2009, Lamlom and Savidge 2003, Sundstrom, et al. 2012). Traditionally, forest inventories focused on merchantable volumes that mainly reflected the extraction of logs for use in making solid wood and fiber products. Estimation of weight or biomass, the contents of small stems or branches, and tree components such as foliage or bark were given less attention. Increasingly, wood is bought and sold on the basis of its weight rather than volume. Further, technology allows for a greater portion of small stems and branches to be captured in harvesting operations (Haynes 2002). Information on all aboveground components is desired, whether for planning forest operations or for long-term monitoring and management.

Changing information needs pose a challenge in forest inventory and assessment. While many traditional inventories needs remain unchanged, (e.g., the need for estimates of standing wood contents in sawtimber and pulpwood trees), new uses and utilization standards require information on attributes that were not traditionally included in forest inventories. One example is the aboveground dry weight, or biomass, of standing trees. Since the biomass of standing trees cannot be measured directly, due to cost and the destructive manner of measuring, models are needed to estimate it from inventory-type measurements such as species, diameter at breast height (DBH), and tree height. Another example of a new need is the partitioning of biomass or volume contents into components such as stem wood to a specified merchantable top, wood above merchantable tops, wood and bark in branches, bark, and the foliage contents of standing trees. Models for these and other attributes that remain consistent with traditional inventory

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outputs, such as estimates of solid wood and pulpwood fiber contents, are needed (Clark, et al. 1985).

A large number of regression models have been developed for the purpose of predicting or estimating the biomass contents of standing trees (Jenkins, et al. 2004). Many of them were developed for trees of a particular geographic region (Gower, et al. 1997, Martin, et al. 1998, Whittaker, et al. 1974). Few biomass equations were designed or parameterized with the stated purpose of being applicable to a wide geographic range, e.g., the native range of a widely-occurring species (Clark, et al. 1985, Clark, et al. 1986a, Clark, et al. 1986b, Clark and Schroeder 1986). In cases where multiple models were developed for use in different portions of a species' range, a typical outcome is that their predictions are not consistent where they overlap. Applying one equation in one part of the species' range and another equation in an adjacent part of its range will likely lead to undesirable discontinuities at the boundary that separates them.

Some biomass equations provide estimates for branch and foliage components separate from stem wood and bark (Alemdag 1984, Gower, et al. 1991), but others do not (Ouellet 1983). Even in models capable of producing separate component biomass estimates, few are designed so the components can be added together to produce an additive estimate of the total aboveground biomass (Jenkins, et al. 2004). One efficient way to ensure additivity is with Seemingly Unrelated Regressions (SUR). SUR is both empirically and theoretically superior to simply adding independently developed model predictions together when trying to estimate additive biomass components simultaneously (Parresol 2001). Consequently, it has been recognized as an effective means of modeling additive components (Parresol 1999, Parresol 2001, Sabatia, et al. 2008).

Flexibility to determine the contents between two points on a tree stem has long been seen as a powerful feature of some volume and taper models (Brister, et al. 1980). Such flexibility allows for the estimation of one or more merchantable stem section in a standing tree based on its size (diameter at breast height (DBH) and total height) and specified merchantability limits. Modeling to account for flexible merchantability standards can be accomplished by taking a volume ratio approach, with the top diameters or merchantable heights specified as model input variables (Cao and Burkhart 1980). Other approaches involve using taper functions that can be integrated between any two points on the stem to estimate stem section volumes (Gregoire, et al. 2000).

While volume ratio and taper-based volume modeling approaches are common in estimating stem volumes, biomass models often are not designed with such capabilities in mind (Bullock and Burkhart 2003); however, if basic wood density – dry weight, green volume basis – is known, it can be multiplied by a stem section volume estimate to determine the merchantable biomass of the stem section (Brooks 2007). A possible challenge may arise when volume and density estimates are inconsistent with biomass estimates, such as when biomass and volume equations are fitted independently to data. This may be especially relevant in trees where wood density is known to vary systematically within or between stems. For example, loblolly pine (*Pinus taeda*) is known to have denser wood, on average, in some portions of its range, and can also vary in density from pith to bark and vertically up stems (Tasissa and Burkhart 1998).

Few equations are designed to incorporate volume, biomass, and component predictions into a single, unified system. One exception is the component ratio method (CRM) of Heath et al. (2009). A brief outline of the steps involved in implementing the CRM follows (Woodall, et al. 2011):

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a. Merchantable stem volume is estimated from regional volume equations, e.g., the cubic foot volume equations of Oswalt and Conner (2011) for states in the Southern U.S.

b. Merchantable stem volume is converted to biomass based on published wood density, bark density and bark fraction values of Miles and Smith (2009).

c. Biomass component ratios from Jenkins et al. (2003, 2004) are then used as scaling factors to estimate whole tree aboveground biomass based on merchantable stem biomass. (Heath, et al. 2009)

d. Whole tree biomass is apportioned into remaining components, such as branches, wood, bark, and foliage.

A known limitation of the CRM is its reliance on models that assign multiple species to a single group, thereby making predictions for all species in the group identical (Jenkins, et al. 2003). Another limitation is that the component ratios used in step C were developed from a small number of observations and from a limited number of species (Jenkins, et al. 2003). Biomass component ratios in the CRM are also limited to a single merchantability standard, namely a 1 foot stump height and a top diameter of 4 inches. The accuracy of estimates obtained from the CRM system may be high for some attributes, but low for others. In general, their accuracy has not been demonstrated for species in the southeastern United States.

Taper equations can be used to predict the volume of any section of a stem which can then be converted into biomass (Brooks 2007). One challenge to select an appropriate model for analytical needs is that there are so many taper models already in existence. From work such as that complied by Gregoire in his 2004 bibliography it is apparent that many taper equations and function forms exist that may be used in a range of taper modeling applications (Gregoire 2004).

Given the abundance of models or equation forms, it can be challenging to select an appropriate model from for a particular application. However, a great deal of work has already been done to evaluate different taper models to determine which models are most appropriate (Kozak 2004, Kozak and Smith 1993, Li and Weiskittel 2010) so this will not be a focus of this work. Another challenge is that many functional forms exist that can be used to model stem taper. However, by using a taper-based approach, the system will be able to accommodate flexible merchantability standards in predicting stem volume. The goal here is to choose a model that can work with a few important species to establish a modeling procedure and that is appropriate for the geographic region of the data. After the taper model has been chosen it will then be applied to the CRM.

White oak (*Quercus alba* L.) is among the top five most abundant tree species in the Virginia (Rose 2013). White oak occurs naturally throughout the eastern U.S. including southwestern Maine, central Michigan to southeastern Minnesota, south to western Iowa, eastern parts of Kansas, Oklahoma, Texas, and east from these states to northern Florida and Georgia (Burns and Honkala 1990). However, it is typically absent in the high elevations of the Appalachians, the Delta region of the lower Mississippi, and the coast of Texas and Louisiana. White oak was chosen for this study due to its large geographic range (Figure 1) and its commercial importance.
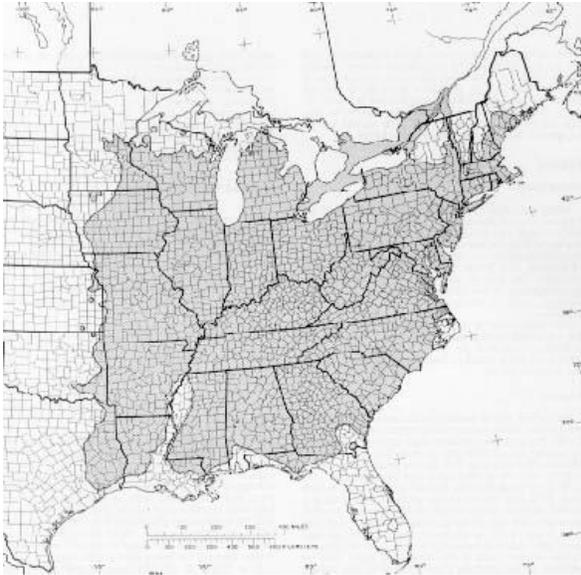
Figure 1. Geographic range of White Oak (Burns and Honkala 1990) .

This work was aimed at testing and adjusting the existing system of equations capable of producing consistent volume and biomass estimates for standing trees of white oak in the southeastern United States. This study involved testing elements of merchantable and whole stem volume and biomass, wood and bark density, and component ratios for wood, bark, branches and foliage. Existing models were calibrated and adjusted with several available datasets. The updated models were applied to Virginia, and the statewide effects were compared to current Forest Inventory and Analysis (FIA) data

Material & Methods

Two main sources of data were available for this research. One of the data sources was legacy data from Clark(1985, 1986a, 1986b, 1986), Martin(1998), and Wiant (1977) and the other being new field data collected for development and testing of white oak biomass models. The legacy data cover a wider geographic range and have a larger sample size. The new field

data represent a smaller part of the species' range, but include greater detail for eventual consideration of more detailed taper and biomass modeling that will follow the work presented here.

Legacy Data

Legacy data were compiled from white oak trees from Clark et al.(1985, 1986a, 1986b, 1986), Martin (1998) and Wiant et al. (1977) . Each dataset comes with different sample sizes and distribution of the data. Clark's data came from Alabama, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee at 18 different site locations and a sample size of 246. Clark included trees ranging from 1 inch DBH to 21.7 inches DBH with the average tree being 8.8 inches DBH. The stump height ranged from 0 feet to 1.5 feet with variable top diameters. Martin's data came from North Carolina with 1 site location and a sample size of 10 trees. These data ranged from 2.76 inches DBH to 24.80 inches DBH with an average DBH of 11.73 inches. The stump was measured at the ground and the top diameter not reported. The data from Wiant came from West Virginia from 1 site location and a sample size of 21. These data ranged from 3.2 inches DBH to 15.9 inches DBH with an average DBH of 9 inches. The stump height was measured at half a foot with a top diameter of 4 inches.

Table 1. Summary of legacy data.

Author	Sample Size	Min DBH (in)	Max DBH (in)	Average DBH (in)
Clark	246	1	21.7	8.8
Martin	10	2.76	24.80	11.73
Wiant	21	3.2	15.9	9

Table 2. Comparison of legacy data for Clark, Martin and Wiant

Publication	Region	Stump Height	Sample Size	Min DBH (in)	Max DBH (in)	Top Diameter (in)
Clark	GA	0-2.1'	69	2.2	20.9	Variable
Clark	NC	0-1.6'	73	1.1	21.7	Variable
Clark	SC	0.5'	1	6.4	6.4	Variable
Clark	AL	0.1'	15	1	3.6	Variable
Clark	MS	0.2-5.0'	20	1.3	12.6	Variable
Clark	TN	0.2-2.5'	25	3.6	10.6	Variable
Clark	KY	0.2-1.0'	43	5	20.5	Variable
Martin	NC	0'	10	2.76	24.80	not reported
Wiant	WV	0.5'	21	3.2	15.9	4

Field Data

New data were collected to supplement legacy data, in part to fill gaps in geographic location and tree sizes, and for the development and testing of biomass measurement protocols that could be used to facilitate data sharing and long-term archival of data sets for use in future biomass studies. White oak (n = 36) trees were selected for destructive sampling at five sites in Virginia, two in Montgomery County and one each in Buckingham, Patrick, and Scott counties. Three white oaks had poor form, three had hollow stems, two were dead, and three had broken or dead tops, but the majority of the trees selected were of good form and sound.

Timing of destructive sampling was controlled so that foliage collection would represent either full display of foliage during the growing season for leaf-on measurements, or no display corresponding to the leaf-off condition in hardwoods during the dormant season. Growing season specimens were collected after the leaves had expanded fully in the spring – at least 6 weeks after bud break – and before the onset of color changes that signaled fall senescence. Dormant season data were collected during the winter months when no foliage was displayed in hardwood specimens.

Felled trees were measured for total height by tape, stump height (usually at 0.5 feet), diameter at stump height, diameter at 2.5 feet above ground line, DBH, diameter at 8 feet above ground, and every 4 feet thereafter until the main stem diameter measured 4 inches or less. Detailed branch measurements were made for a related study, with the relevant measurements and procedures here including: removing foliage from all branches and moving it to a laboratory for desiccation and subsequent dry weight determination; weighing all wood and bark from green branches upon severing them from the main stem; collecting subsamples of wood and bark material from all branches; weighing subsamples green; and finally transporting subsamples to the laboratory for subsequent desiccation and dry-weight determination.

Stem volume was determined by dimensional measurements including: length of each section (nearest 0.01 foot) with tape placement made to account for cuts not perpendicular to the main stem; outside-bark diameter calipered at right angles and averaged on both ends of each cut section; dimensions and degree of cull (slight, medium, or high) in interior defects for subsequent determination of cull volume; and green weight of each section measured with a hanging scale in the field and recorded to a minimum of three significant digits.

After the sections were weighed, one or two disks were cut from each section and taken to the lab for detailed measurements. Green disk measurements were made as soon as possible after felling, generally within a few hours. If green measurements could not be made promptly, disks were stored in plastic bags in cold storage until measuring could take place, usually within one or two days. Green disk measurements included calipering across the widest disk diameter (± 1 mm) and perpendicular to the first caliper measurement. The thickness of the disk (± 0.1 mm) was taken at four equally spaced points around the perimeter of the disk and averaged. Green weight (g) was recorded to 3 or more significant digits. Interior defects were noted the

same way as on the sections weighed in the field. Bark was removed with a knife or a chisel and weighed green. Inside-bark disk diameter measurements were repeated following the debarking. Not all of the trees have inside-bark measurements; the decision to add bark measurements was made after some data had already been collected. Therefore inside-bark analysis was completed with a smaller sample size than outside-bark analysis. Disk wood and bark specimens were dried at 100° C and re-weighed following a monitored period of drying to obtain dry weights and determine moisture content.

Branch subsamples were weighed fresh and subsequently dried at 100°C to determine their moisture content. Subsample dry-weight to green-weight ratio (DWGW) was subsequently multiplied to the field-measured branch green weights to estimate each branch's dry weight (Clark, et al. 1985, Clark, et al. 1986a, Clark, et al. 1986b, Clark and Schroeder 1986). No volumetric measurements or bark fraction measurements were made for branches or branch subsamples. Foliage was dried at 65°C and weighed daily until equilibrium moisture content had been reached. Following desiccation and before weighing, leaves were separated by hand from small twigs and stems that were collected along with them. The dry weights of the small twigs and stems were subsequently added back to the corresponding branch specimens from which they had been pruned during field data collection.

Bark and Wood Fraction

Stem bark and wood fractions for field-measured trees were needed to compare component biomass with the CRM predictions. Individual disk measurements were used to find the bark and wood fractions. Bark (or wood) fraction is the dry weight of the bark (or wood) divided by the dry weight of the total disk. Since the disks are only composed of wood and bark the bark fraction and the wood fraction add up to 1. Once the wood and bark fractions of the

disks were computed (equation (1)) they were used to estimate bark and wood component dry weights for stem sections to obtain total stem bark and wood fraction estimates of the tree.

$$Bark\ Fraction = \frac{Bark\ Dry\ Weight}{Disk\ Dry\ Weight} = \frac{Bark\ Dry\ Weight}{Bark\ Dry\ Weight + Wood\ Dry\ Weight} \quad (1)$$

The bark fraction values used by Miles and Smith (2009) are calculated differently. To get the bark fraction bark volume was used. The bark fraction is the bark volume as a percentage of wood volume, so Miles and Smith's bark fraction does not add up to 1. They calculate bark fraction using the following equation:

$$Bark\ Fraction = \frac{Bark\ Volume\ Fraction * Bark\ Density}{Bark\ Volume\ Fraction * Bark\ Density + Wood\ Density} \quad (2)$$

To determine the best way to compare the bark and wood fraction of the disks to the corresponding whole tree two methods were used. One method was taking an average of the bark fraction and the wood fraction of the tree. The other method took a weighted average of the sections to account for different sections having different bark fractions. Neither method used the disks if they did not have both bark and wood fractions.

Moisture Content and Dry-Weight Green-Weight

Moisture Content (MC) was calculated from disk oven dry-weight and green weight measures as

$$Moisture\ Content = \frac{Green\ Weight - Oven\ Dry\ Weight}{Oven\ Dry\ Weight} * 100\% \quad (3)$$

Closely related to moisture content is the dry-weight to green-weight (DWGW) (Picard, et al. 2012).

$$DWGW = \frac{DW}{GW} \tag{4}$$

Where DW is the dry-weight in either pounds or grams and GW is the green weight in either

pounds or grams, with both measurements having matching units. The relationship to moisture

content can be seen is

$$MC = \frac{1}{DWGW} - 1 \tag{5}$$

An advantage of DWGW is that this ratio can be multiplied by the green weight of a stem, disk

or section to get the dry weight. DWGW was used throughout the analysis instead of MC, except

when noted. Examinations of DWGW data in relation to stem diameter, height and relative

diameters or heights were carried out by graphical inspection. The relative height was the height

of the disk divided by the total height of the tree and relative diameter is the diameter of the disk

divided by DBH.

Density

Basic wood density, related to basic specific gravity, is oven dry mass in pounds divided

by the weight of an equal volume of water (Williamson and Wiemann 2010). Basic density

however does not include the weight of the water, making basic density have units.

$$Basic\ Density = \frac{Oven\ dry\ mass}{green\ volume} \tag{6}$$

Basic density was determined for the disks. Since both diameter and height of the disk were

included, volume was calculated. To calculate the volume of the whole disk (wood and bark) the

outside diameter was used. To calculate the wood volume, inside bark diameter was used and

bark volume was the subtraction of the two volumes. Dry weight of the wood and bark were then

used to calculated basic density values and evaluated based on relative diameter to DBH and

relative height to total height. Trees with interior defects might have an influence on the density

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since the weight of the defected area may be zero even though the volume is still accounted for.

Disks with defects were highlighted to identify which densities included defects.

The Miles and Smith (2009) density is one of the key parts of the CRM because the density is used to convert the volume of a stem into the biomass. To test the estimate of density used by Miles and Smith, new data from Virginia Tech and legacy data from Clark (1985, 1986a, 1986b, 1986) were used. The Virginia Tech data consisted of basic density from 553 observations and Clark's density measures consisted of 246 published values. Miles and Smith report only one published observation each for bark and wood for white oaks. The average and standard error for Miles and Smith, Virginia Tech and the Clark legacy data were calculated and compared.

Field Data Volume Calculation

Inside bark stem section volumes for the field data were obtained for each section from taped lengths and calipered section end diameters using Smalian's formula:

$$V = \frac{A_1 + A_2}{2} \times L \tag{7}$$

where V is the volume (ft^3), A_1 is the area of the small end of the section, A_2 is the area of large end of the section, and L is the length of the section (Avery and Burkhart 2002). For the trees greater than 5 inches DBH only the section data was needed to compute the amount of volume for a one foot stump and a four inch top using equation (7) for all sections of the tree.

The bottom and top sections including the stump and the four inch top were handled slightly differently. For the stump section the diameter of the stump was calculated. This was done by fitting a simple linear function (equation (8)). The diameter at the top and bottom and the height of the top and bottom of the section were used to predict the diameter of the stump at 1

foot, equation (8), with diameter measurements in inches and height measurements in feet (Figure 2).

$$\text{stump diameter} = \text{base diameter} + \left(\frac{\text{top diameter} - \text{base diameter}}{\text{top height} - \text{base height}}\right)$$

$$* (\text{stump height} - \text{base height}) \tag{8}$$

From equation (8) the diameter of the stump was found which could then be put into Smalian's formula to find the volume of the lowest stem section, adjusted for a 1 foot stump for pole or saplings or a 0 foot stump for seedlings. The same process was applied to find the height at a 4 inch top with the equation arranged as in equation (9). Equation (9) was used with the diameter at the bottom and top and the height at the top and bottom of the section being put into the equation (Figure 2). Once the height for the 4 inch top was calculated the volume of the merchantable part of the section was then calculated using Smalian's formula.

$$4" \text{ top height} = \text{base height} + (4 - \text{base diameter})\left(\frac{\text{top height} - \text{base height}}{\text{top diameter} - \text{base diameter}}\right) \tag{9}$$
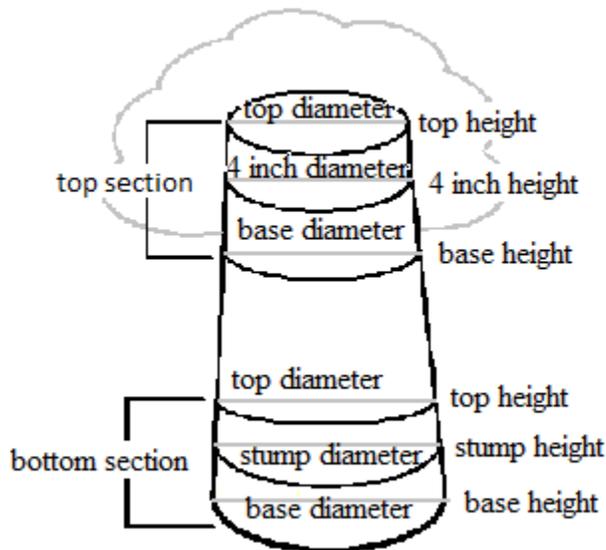

Figure 2. Top and bottom sections of a tree showing the variable for equations (8) and (9).

Stem section volumes, whether unmodified or adjusted for stump height or top diameter, were multiplied by the dry-weight-green volume density to determine section dry weights. Following adjustment of stem sections for stump height and merchantable top diameter section, volumes were summed to obtain merchantable volume for each tree. The dry weight above the 4 inch top was added into the branch dry weight measurements. For saplings, field measured stem volumes had to be adjusted to reflect the Oswalt & Conner (2011) sapling merchantable limits of a zero foot stump, and height to the tip and the volumes were adjusted the same as poles and sawtimber. The dry weight was adjusted by moving the dry weight of the top section to the stem weight and subtracting it from the branches.

For trees that did not have section inside bark measurements, because they were not recorded, the inside bark diameter had to be estimated. For the trees that had both inside and outside bark diameters for the disk corresponding to a section, the inside bark diameter was interpolated using the diameter fraction, which is diameter inside bark divided by diameter outside bark, and then multiplied by the section outside bark. For the sections that did not have disks with corresponding inside bark diameter data, a simple linear regression was estimated using the disk data that had inside bark measurements and applied to the section outside bark.

Merchantable Stem Volume

The first step of the CRM is to calculate the merchantable stem volume (ft^3)for trees greater than 5 inches DBH from a 1 foot stump to a 4 inch top and ground to tip for trees less than 5 inches DBH. White oak merchantable stem volume estimated from the equations of Oswalt and Conner (2011) was compared to tree volumes based on detailed stem measurements of the same trees. The merchantable volumes for trees greater than 5 inches DBH, from a one foot stump to a 4 inch top, were computed using equations (10) and (11). Equation (10) predicts

the volume for pole size trees, 5 inches DBH to 11 inches DBH, and equation (11) predicts

volume for sawtimber trees, greater than or equal to 11 inches DBH. The whole volume for

saplings, less than 5 inches DBH, ft^3, from the ground to the tip of the tree is computed in

equation (12) (Oswalt and Conner 2011).

$$CV4_{Pole} = C1 * C2 * (DBH^2 * HT) \tag{10}$$

$$CV4_{Sawtimber} = D1 * D2 * (DBH^2 * HT) \tag{11}$$

$$CV_{Sapling} = A1 * A2 * (DBH^2 * HT) \tag{12}$$

Where C1=-0.37698, C2= 0.001948, D1 =0.148434, D2= 0.00188, A1=0.044339,

A2=0.002539, and HT is the total height. These volumes were then compared to the volume

measurements predicted from Smalian's equation for the new field data.

Legacy Volume

Since the legacy data sets were not collected using exactly the same methods as the

newly observed field data their calculated weights, densities and component ratios were obtained

using slightly modified methods. The first step was to calculate the volume of the merchantable

section of the stem, for trees greater than 5 inches DBH, from a 1 foot stump to a 4 inch top. This

was done using the Clark et al. (1991) taper model, which required information on tree species,

DBH, total height, stump height and top diameter, because there were not enough measurements

along their stems to be able to use Smalian's equation. Clark et al.'s (1991) volume equation was

considered most appropriate for this application since it was developed using 636 white oak

trees, 246 of which were obtained for use as legacy data here (Equation (13)).

$$VOLCLARK = \tag{13}$$

$$0.005454 \left(I_1 DBH^2 \left((1-GW)(U_1 - L_1) + \frac{W\left(\left(1-\frac{L_1}{H}\right)^r (H-L_1) - \left(1-\frac{U_1}{H}\right)^r (H-U_1)\right)}{(r+1)} \right) + \right.$$

$$I_2 I_3 \left(T(U_2 - L_2) + Z \frac{\left(\left(1-\frac{L_2}{H}\right)^p (H-L_2) - \left(1-\frac{U_2}{H}\right)^p (H-U_2)\right)}{(p+1)} \right) + I_4 F^2 \left(b(U_3 - L_3) - \right.$$

$$b\left(\frac{(U_3 - 17.3)^2 - (L_3 - 17.3)^2}{(H-17.3)}\right) + \frac{b}{3}\left(\frac{(U_3 - 17.3)^3 - (L_3 - 17.3)^3}{(H-17.3)^2}\right) + I_5 \frac{1}{3}\left(\frac{1-b}{a^2}\right)\frac{\left(a(H-17.3) - (L_3 - 17.3)\right)^3}{(H-17.3)^2} -$$

$$\left. \left. I_6 \frac{1}{3}\left(\frac{1-b}{a^2}\right)\frac{\left(a(H-17.3) - (U_3 - 17.3)\right)^3}{(H-17.3)^2} \right) \right)$$

Where VOLCLARK is the volume (ft^3) of the merchantable stem,

DBH is in inches,

F is the diameter (inches) at 17.3 feet above ground,

H is the total tree height (feet).

a=0.31541,

b= 1.3263,

c=0.84829,

e=232.96,

p= 12.28295,

r= 26.85889

L is the lower height of interest (feet)

U is the upper height of interest (feet)

L_1 is the maximum of L and 0,

U_1 is the minimum of U and 4.5,

L_2 is the maximum of L and 4.5,

U_2 is the minimum of U and 17.3,

L_3 is the maxim of L and 17.3,

U_3 is the minimum of U and H.

I_1 is 1 when L < 4.5 otherwise 0,

I_2 is 1 if L > 17.3 otherwise 0,

I_3 is 1 if U > 4.5 otherwise 0,

I_4 is 1 if U > 17.3 otherwise 0,

I_5 is 1 if $(L_3-17.3) < a(H-17.3)$ otherwise 0,

I_6 is 1 if $(U_3-17.3) < a(H-17.3)$ otherwise 0,

$G = (1-4.5/H)^r$, $W=(c+e/D^3)/(1-G)$,

$X=(1-4.5/H)^p$,

$Y=(1-17.3/H)^p$,

$Z=(D^2-F^2)/(X-Y)$,

$T=D^2-ZX$.

Merchantable stem biomass for the CRM approach and the taper-based estimates from Clark et al. (2002) were obtained by multiplying species-specific basic density values for both wood and bark and percent bark from Miles and Smith (2009) by VOLCLARK and CV4, respectively.

Component Ratios

Component ratios that partition aboveground biomass into stem wood and bark, foliage and branches are key parts of the CRM biomass estimates. Component ratios for field measured trees were calculated for comparison to those predicted by the equations reported by Jenkins et al. (2004) (Table 3). Since the published equations require metric units, the field measurements

of DBH (in) were converted to centimeters before being entered into the ratio equation. To

compute the component ratios of field observations, the observed component dry weights (bark,

wood, foliage and branches) were divided by the tree's aboveground dry weight. Since

aboveground weight was calculated as the sum of dry weights for stem wood and bark, plus

branches and foliage, the sum of observed component ratios was ensured to equal one for any

tree. In the equations of Jenkins et al. (2004) the ratios were designed to sum to 1.0; the branch

component ratios were determined by subtraction.

Table 3. Table of parameters and biomass ratio equations from Jenkins, et al. 2004

Biomass component	Parameter		Data points[b]	R2
	α_0	α_1		
Hardwoods				
Foliage	-4.0813	5.8816	632	0.256
Coarse roots	-1.6911	0.816	121	0.029
Stem bark	-2.0129	-1.6805	63	0.017
Stem wood	-0.3065	-5.424	264	0.247
Softwood				
Foliage	-2.9584	4.4766	777	0.133
Coarse roots	-1.5619	0.6614	137	0.018
Stem bark	-2.098	-1.1432	799	0.006
Stem wood	-0.3737	-1.8055	781	0.155

Biomass ratio equation:

$$ratio = Exp(\alpha_0 + \frac{\alpha_1}{dbh})$$

where

ratio = ratio of component to total aboveground biomass
for trees 2.5 cm and larger in DBH

dbh = diameter at breast height (cm)
Exp = exponential function
ln = log base e(2.718282)

[b]Number of data points generated from published
equations (generally at intervals of 5 cm DBH) for
parameter estimation.

Legacy Data Calculations

Calculations of merchantable volumes to various specified stump heights and top diameters were needed to adjust legacy field measurements to the one foot stump height and four inch top diameter standard used in the CRM estimates. Briefly, the Clark volume (VOLCLARK) for each legacy tree was estimated using equation (13) with the field-observed stump height and top diameter specified as inputs. The merchantable volume (VOLMERCH) for the same trees was estimated using equation (13) specifying a stump height of one foot and a top diameter of 4 inches. Field-observed stem weights were then adjusted by multiplying them by VOLMERCH/VOLCLARK. Care was taken to subtract any weight adjustments for stump height from the aboveground total and to add any weight adjustment for the merchantable top to the weight of the branches.

The legacy data for most stems included both bark and wood dry weight values. The weights were adjusted for merchantability limits, assuming no difference in the relative proportions. Once the observed dry weights of the merchantable stem, wood, bark, foliage and branches were all calculated they were then summed to obtain aboveground dry weight. Component ratios were subsequently calculated for all legacy trees for comparison to predictions from Jenkins et al. (2004).

The Clark (1991) model does not predict well for saplings so the VOLMERCH/VOLCLARK method was not used for trees less than 5 inches. The CRM gives volumes for trees less than 5 inches that are from the ground to the tip. The legacy data for small trees was close to whole stem volume so the values for stem wood, stem bark, foliage and branches were kept the same to compute the ratios.

The Jenkins equations include ratio equations for merchantable stem bark, merchantable stem wood and the foliage. Branch ratio is obtained by subtraction from 1, ensuring that all components sum to match the total aboveground biomass. Since the Jenkins ratios are for total aboveground biomass, this means that the stump, from the ground to one foot, is included in the branches, unless the stump volume and biomass are also calculated (Jenkins, et al. 2004). To calculate the biomass of the stump FIA used the Raile (1982) stump equations to find the volume of stump wood and bark. To compute the bark volume FIA finds the volume of both outside and inside bark and then subtracted the inside bark volume estimate from the outside bark estimate. Once FIA have both of these volume estimates, they are then multiplied by the bark and wood densities as published in Miles and Smith (2009) and summed together to get the total stump biomass estimate.

Since the Raile (1982) model is used in the CRM it was further investigated. This model works by predicting the diameter of the base of the stump and the diameter at the top of the stump and then integrating over the whole height of the stump to give the volume as shown in equation (14).

$$V = \frac{4 * (DBH)^2}{4 * (144)} * [(A - B)^2 h + 11B(A - B)\ln(h + 1) - \frac{30.25}{h + 1}B^2]_a^b \qquad (14)$$

The coefficients A and B are different for species and whether volume outside bark or volume inside bark was computed. For white oak inside bark volume A=0.92267 and B= 0.12506 and for outside bark A=1 and B=0.12798. This research did not measure volume of the stumps or diameter at the base of the stump but it did measure the diameter at a measured height of stump. The diameter at the measured stump height, usually 0.5 feet, was predicted using the Raile

(1982) stump diameter equation, which has the same coefficients as the inside bark and outside

bark volume equations as in equation (14).

$$diameter = A(DBH) + B(DBH)\frac{4.5 - h}{h + 1} \qquad (15)$$

The predicted diameter was then compared to the observed diameter to examine prediction error.

Effects of No Foliage

In both the legacy and new field data there are trees that were measured in the dormant

season that do not include foliage measurements. Since foliage is one of the components of the

CRM, it is necessary to determine how the ratios change when the foliage is not included in a

tree measurement. To determine the effect of foliage quantity, ratios were determined for each

tree as if they did not have foliage. The amount of foliage was subtracted from the total

aboveground biomass to give a no foliage biomass value. The stem wood, stem bark and branch

measurements were then divided by the no foliage aboveground biomass to give no foliage

ratios. To compare these ratios to the original ratios with foliage they were plotted together on

the same graph with the original ratios plotted with a circle and the no foliage ratios plotted with

an x to be able to differentiate the two ratios.

Re-estimation of the Jenkins Ratio Coefficients

Once the observed ratios were calculated to match the Jenkins component ratios the

model parameters were refitted. To match the form of the Jenkins component ratio regression

model (Table 3), the predictor and response variables were defined as (1/DBH) and ln(ratio),

respectively. The published Jenkins model is for DBH in centimeters but since this work is being

compared to the current Forest Service models the parameters were fitted with DBH in inches. A

simple linear model was produced from the data in the form of $ln(ratio) = \beta_0 + \beta_1(\frac{1}{DBH})$. From

this model the residuals of all the ratios were examined in addition to the R^2 values. The model

was refitted with the field and legacy data (observed data) and was applied to the observed

values to determine if it is predicting better than the published Jenkins ratios. The foliage was

fitted with n=249 data observations while the bark and wood were both fitted with n=238 data

observations. This ratio value is referred to as the refitted Jenkins ratio.

Examining Merchantability Limits

The current CRM in use has limits due to the fact that it is based on the merchantable

portion of a tree. Merchantability is practical but not biological, which may cause some issues in

the prediction capabilities of the model. The CRM has higher prediction error for smaller trees

which can cause biased results (Nelson, et al. 2014). One way to try and account for this bias is

by adjusting the limits of the main stem from the merchantable portion to the total stem volume.

The Oswalt and Conner (2011) volume equation has served for merchantable volume

prediction in the Southern Research Station FIA estimates since 2010 (Woodall, et al. 2011).

Merchantability limits can be adjusted using appropriate factors. An adjustment factor was

developed using the Clark (1985, 1986a, 1986b, 1986) volume equation, defined as

VOLCLARK in equation (13). VOLCLARK is computed twice, once for the current

merchantable limits of the 1 foot stump and the 4 inch top (VOLMERCH), and once for a total

stem approach from the ground to the tip of the tree (VOLTOT). This model was chosen because

its flexibility, the large data base used in its estimation and how well it preforms. Once the two

volumes were calculated they were then converted into an adjustment factor by dividing

VOLTOT by VOLMERCH. This VOLTOT/VOLMERCH was multiplied by the Oswalt and

Conner volume to give merchantable volume estimates applied to a whole stem.

To calculate the biomass of the adjusted components VOLTOT/VOLMERCH was multiplied by the stem wood and stem bark biomass, which were added together to calculate the whole stem biomass. The branch biomass was calculated by subtracting the whole stem and foliage biomass from the aboveground biomass. The adjusted ratios were calculated by dividing the adjusted component biomass by the aboveground biomass.

Refitting the Whole Stem Ratios

The whole stem ratios were fitted two different ways. One made use of the form of the Jenkins model but with the stem adjusted from the ground to the tip, known as the whole stem ratio. Once the model was refitted the residuals were examined, along with the R^2 to determine how well this model fits the data. The new coefficients from refitting were then applied to the data. The foliage was fitted with n=253 data observations while the bark and wood were both fitted with n=240 data observations.

The second approach, called the adjusted stem and ratio, consisted of transforming both the ratio and the DBH to logarithmic form. This model form was used because of the data, the simplicity of the model form and the ease of using this model. The model was refitted and the residuals and R^2 were evaluated to see how well the models were predicting. Since it is a log-log transformation a correction factor is needed, a correction factor (Baskerville 1972) was applied, namely $\hat{Y} = e^{(\hat{\mu}+\frac{\hat{\sigma}^2}{2})}$ where σ^2= RMSE. Once the model was adjusted with the correction factor it was then reapplied to the data.

FIA Comparisons

The effects of applying the updated models over the State of Virginia were tested by using results from the adjusted stem and ratio approach and applying those results to the FIA data. All the data was downloaded for the state of Virginia and the appropriate tables were used

(Table 1). To determine how to replicate the FIA data and calculate the state level estimates "The

forest inventory and analysis database: database description and user's manual version 5.1.6 for

Phase 2" (O'Connell, et al. 2013) was used. The parts used were specifically Appendix J (for

replications) and Chapter 4 starting on page 313 (for state-level estimates). The instructions laid

out in the database were followed to replicate the current CRM model in use with FIA (

Table 5).

Relevant FIA estimates were calculated and compared to published values to verify the

accuracy of estimates. From there the statewide biomass estimates for white oak were calculated

for both the current model and the revised model, and differences on a state level were

determined. Tree level estimates for both of the models were also compared to each other to

determine if there was a systematic change in the model.

To calculate the stump and top for the adjusted model to compare to the current FIA

CRM model an adjustment factor was needed. For the stump this was done using the

VOLCLARK equation (13) with the limits of 0 foot stump to a 1 foot height (VOLSTUMP). The

adjustment was then VOLSTUMP/VOLTOT multiplied by the adjusted stem biomass. To

compute top biomass VOLCLARK was used from a 4 inch top height to a 0 inch top

(VOLTOP). Then to get the adjusted top it was VOLTOP/VOLTOT multiplied by the adjusted

stem biomass plus the adjusted branches. These values have the same limits of the current FIA

CRM model so they can be compared to each other. To calculate the adjusted stem and ratio

sapling estimates the Oswalt and Conner sapling volume (whole stem) was multiplied by the

Miles and Smith density and then divided by the adjusted stem and ratio stem ratio to give

aboveground biomass. No adjustment was necessary because Oswalt and Conner sapling volume

is predicting whole stem volume.

Table 4. FIA tables need to replicate FIA estimates.

Table name	Alias
VA_PLOT	p
VA_COND	c
VA_TREE	t
VA_POP_PLOT_STRATUM_ASSGN	ppsa
VA_POP_STRATUM	psm
VA_POP_ESTN_UNIT	peu
VA_POP_EVAL_TYP	pet
VA_POP_EVAL_GRP	peg
VA_POP_EVAL	peg
REF_SPECIES	ref
REF_POP_ATTRIBUTE	rpa

Table 5. Steps to necessary to estimate State level biomass estimates for Virginia.

Action	Records
Load all tables into R	
Subset ppsa to include only unique PLT_CN and EVALID==511201	4592
Subset t so t$STATUSCD = 1	775670
Subset c so c$COND_STATUS = 1	25340
Subset t so t$PLT_CN and t$CONDID match c$PLT_CN and c$CONDID	775380
Subset ppsa to include only "PLT_CN","STRATUM_CN"	4592
Merge t and ppsa so t$PLT_CN=ppsa$PLT_CN, naming merge t	93160
Subset psm to include only "ADJ_FACTOR_MICR","ADJ_FACTOR_SUBP","CN","EXPNS"	2369
Merge t and psm so t$STRATUM_CN=psm$CN, naming merge t	93160
Subset peu to include only "CN","EVAL_CN"	1142
Merge t and peu so t$ESTN_UNIT_CN=peu$CN, naming merge t	93160
Subset pev to include only "CN","EVAL_CN"	41
Merge t and pev so t$EVAL_CN=pev$CN, naming merge t	93160
Subset pet to include only "EVAL_CN","EVAL_GRP_CN","EVAL_TYP"	84
Merge t and pet so t$EVAL_CN=pet$EVAL_CN, naming merge t	186320
Subset t so t$EVAL_TYP= "EXPVOL"	93160
Subset peg to include only "CN", "EVAL_GRP"	14
Merge t and peg so t$EVAL_GRP_CN=peg$CN, naming merge t	93160
Subset t so t$EVAL_GRP=512012	93160
Subset t so t$SPCD = 802 (FIA code for white oak)	4889
Subset ref to only include colums 1:4,35:47,49,57,59:61	2362
Subset ref so ref$SPCD = 802	1
Subset rpa to only include "ATTRIBUTE_NBR", "ATTRIBUTE DESCR", "EXPRESSION","WHERE_CLAUSE"	
Select rpa for the ATTRIBUTE_NBR of intrest	

Results

Bark and Wood Fraction

Comparison of the averaged and weighted averaged volumes showed they were similar, but the weighted procedure produced somewhat better results (Figure 3).

(A)   (B)
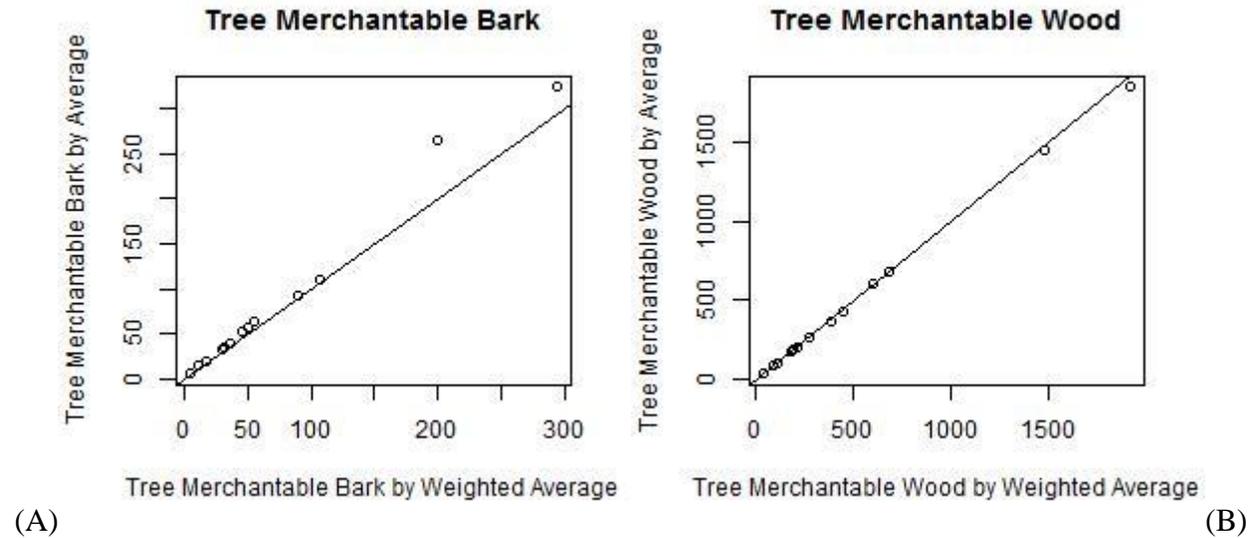
Figure 3. Merchantable stem bark (A) and wood (B) weights using non weighted bark-fraction averages compared to those from section-weighted bark fraction averages.

Generally the bark fraction increases with increasing height in the stem (Figure 4). Since wood fraction and bark fraction add up to 1, the plots of the wood fraction show opposite trends of the bark. When the bark is decreasing based on diameter (Figure 5) the wood is increasing (Figure 6). As the disk diameter increases the bark fraction decreases on both a relative and absolute scale (Figure 5). With increasing height, both relative and absolute, the bark fraction increases (Figure 4) and the wood fraction decreases (Figure 7). The weighted average bark and wood fraction for a tree based on the DBH does not have a significant trend (Figure 8). Absolute diameter is the diameter of the disk, absolute height is the height of the disk from ground level and relative diameter and relative height are as defined earlier.
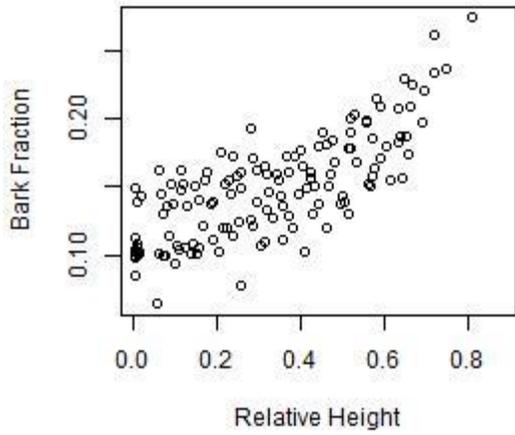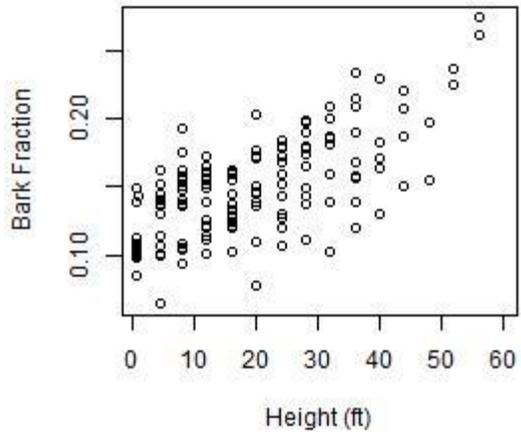
(A)   (B)

Figure 4. Weighted bark fraction at relative height (A) and absolute height (B).
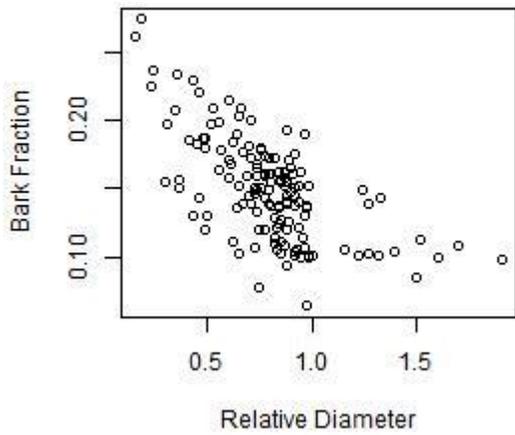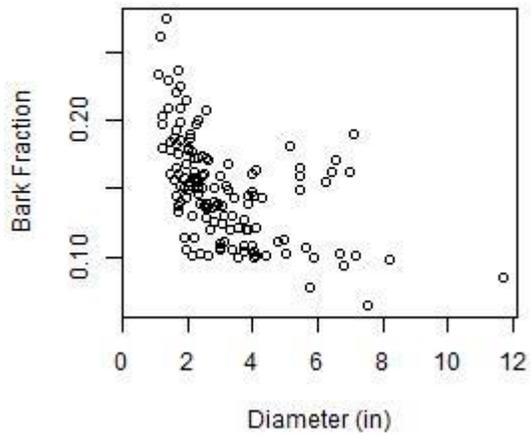
(A)   (B)

Figure 5. Bark fraction variation with relative stem diameter (A) and absolute stem diameter (B).
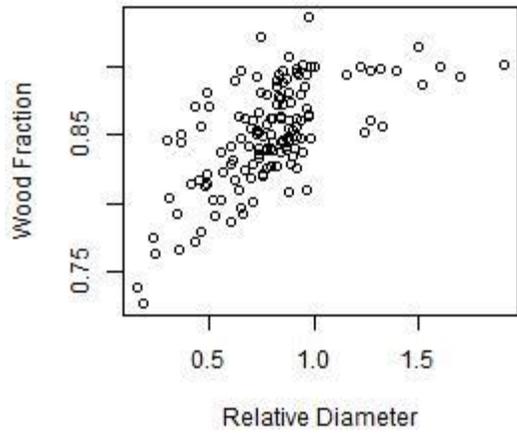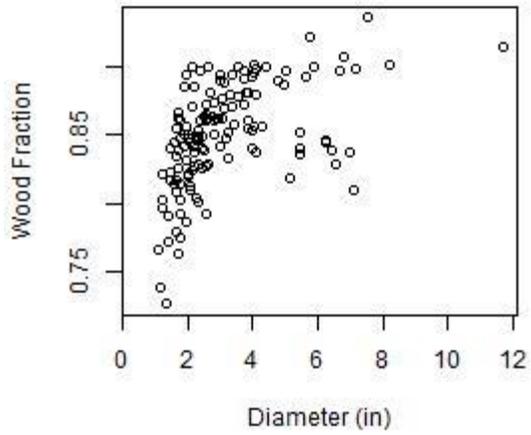
(A)   (B)

Figure 6. Wood fraction variation with relative stem diameter (A) and absolute stem diameter (B).
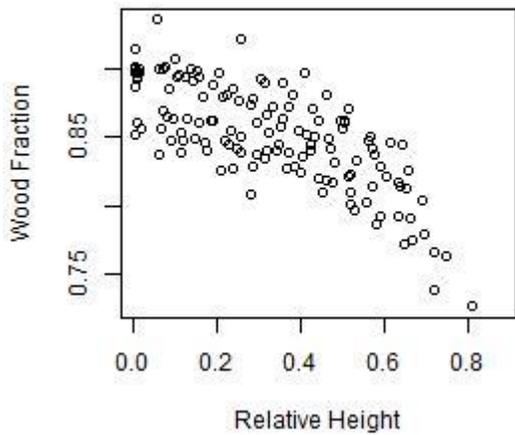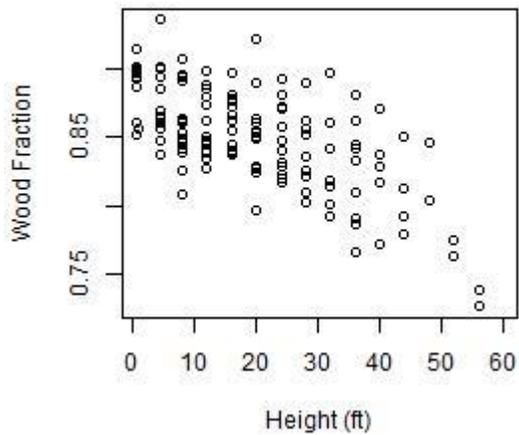
(A)   (B)

Figure 7. Wood fraction at relative height (A) and absolute height (B).
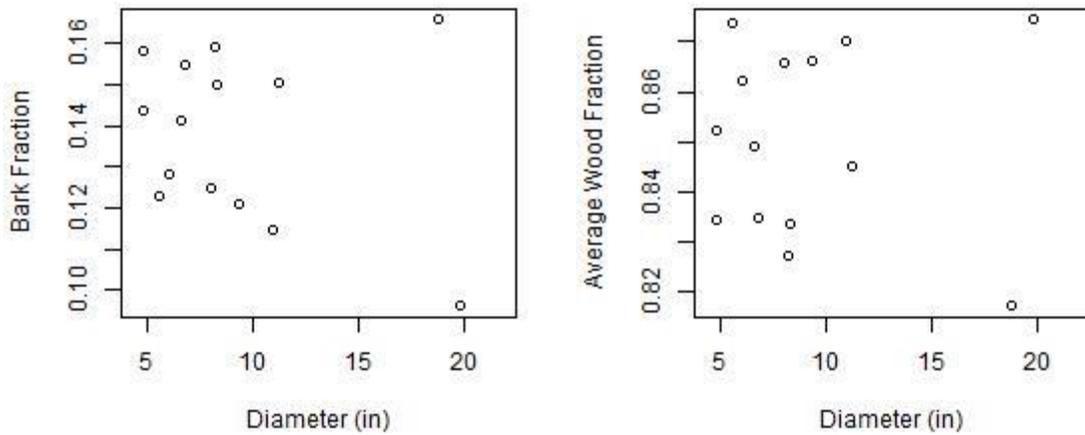
(A)   (B)

Figure 8. Tree level bark (A) and wood (B) fraction computed by a weighted average based on dbh.

Dry-Weight Green-Weight

The dry weight to green weight ratio (DWGW) of the disks appears to be slightly increasing up the stem and as the diameter of the disk gets closer to the DBH, but the trend is clearer with heights where the DWGW is decreasing slightly as the height of the disk approaches total height (Figure 9). The slight decrease starts when the disk height is at about 60 percent of the total height. The bark DWGW, however, does not appear to have a trend (Figure 10). The DWGW appears to decreases as the DBH increases until it gets to about 15 inches and then it slowly starts to increase (Figure 11). There are 32 total trees being examined but some trees are occluded and cannot be distinguished from others. When looking at the weighted average of the DWGW of the whole tree based on DBH there is a random scatter and no apparent trend (Figure 12). The mean DWGW for bark is higher than for wood, with the mean bark DWGW being 0.68 and the mean wood DWGW being 0.63. Relative height is based on total height.
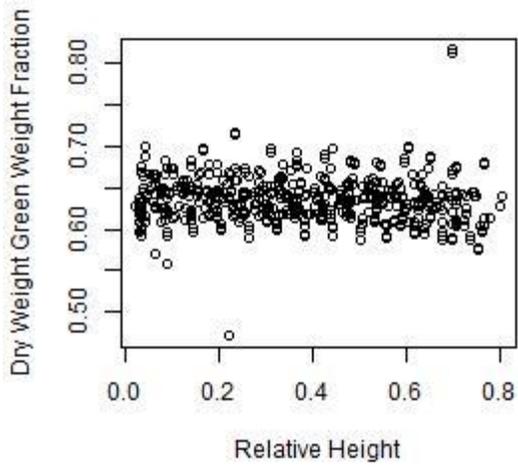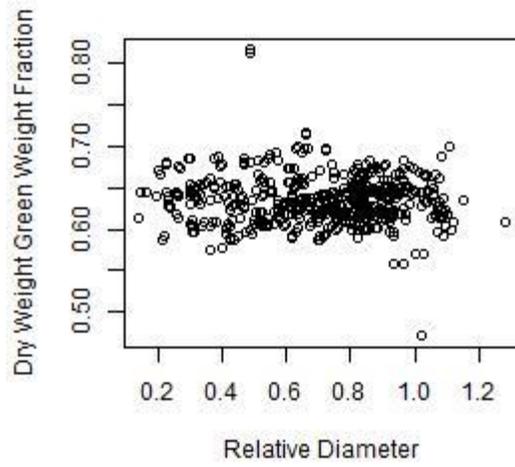
Figure 9. Dry-weight to green-weight fractions of sample disks collected across a range of relative heights (A) and relative diameters (B).
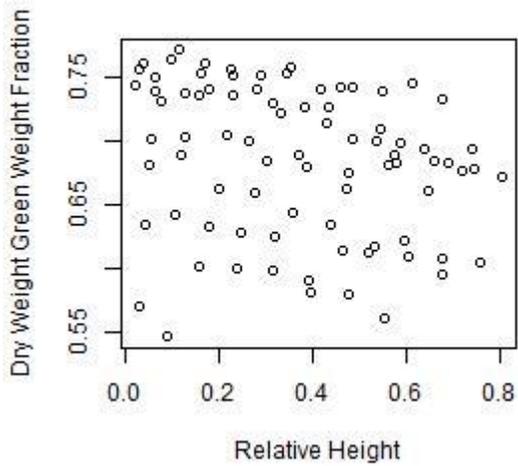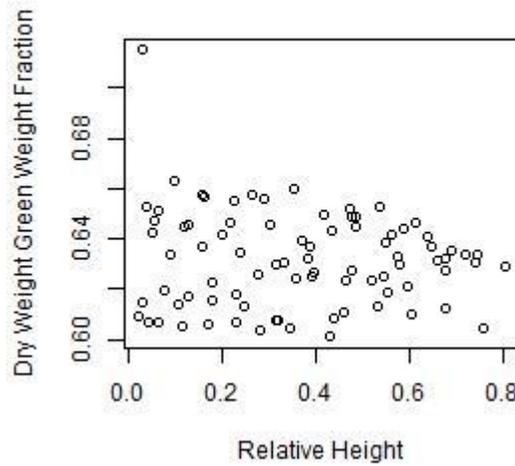
Figure 10. Bark (A) and wood (B) dry-weight to green-weight ratios of sample disks collected across a range of relative heights.
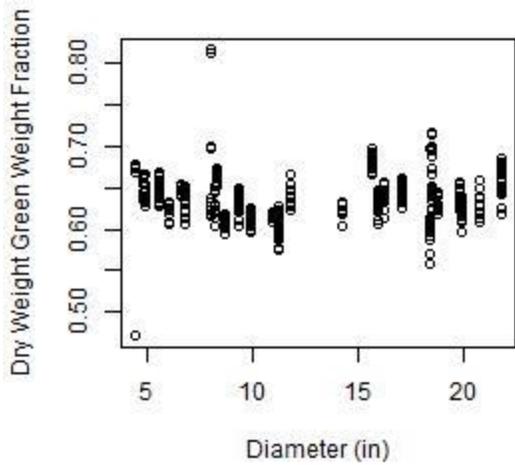
Figure 11. Dry-weight green-weight fraction variation of disk specimens within trees, grouped by tree dbh, n= 32 trees.
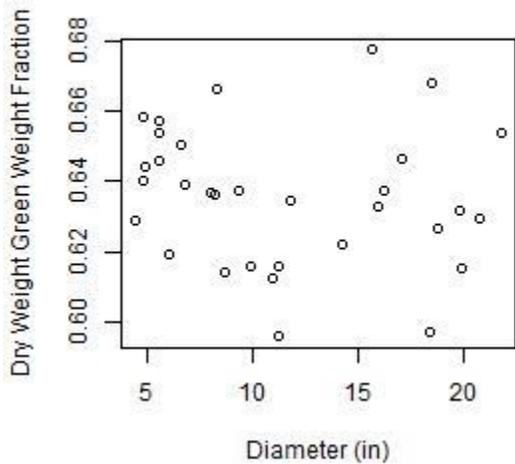

Figure 12. Average tree dry weight green weight fraction based on dbh

Density

Basic density does appear to vary systematically with relative disk diameter and relative height (Figure 13). There is only a slight trend that seems to show that density decreases slightly around 20 percent increases again at around 35 percent of the total tree height. There are parts of

32

the data that seem to be outside of the typical data points. To account for these data the interior

defects or cull codes of the disks were highlighted and classified into the 3 codes slight (code 1),

medium (code 2), or high (code 3). The average percent volume of bark based on wood volume

(bark volume/wood volume) is 21.9% for a sample of 233 disks.
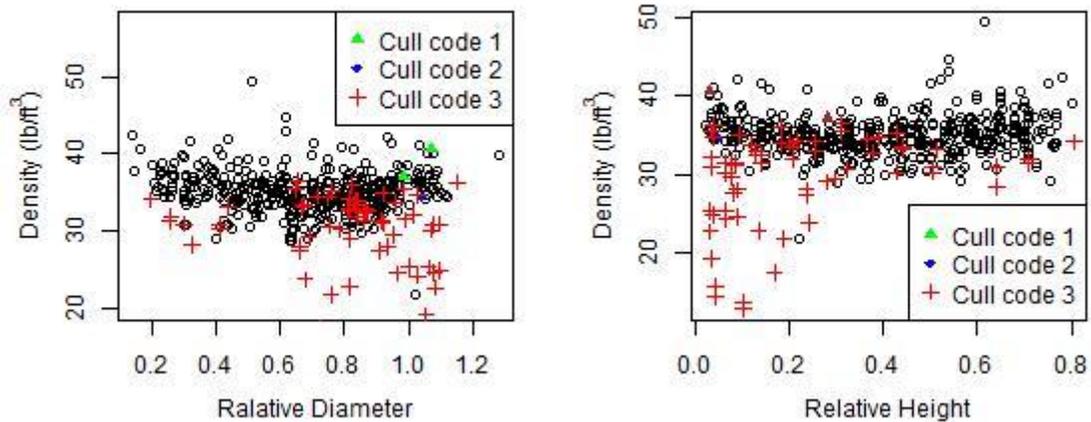
(A)   (B)

Figure 13. Disk density, green volume basis across the range of relative disk diameters(A) and
relative heights (B).

The densities from whole trees do not overlap the Miles and Smith published values. For

the wood and wood and bark densities the Miles and Smith estimate is between the Clark and

Virginia Tech estimates with the Virginia Tech estimates seeming lower than expected (Figure

14 (A) and Figure 15). However the Miles and Smith bark estimate is higher than the Clark and

Virginia Tech estimates (Figure 14 (B)). The error bars are larger on the Virginia Tech data. The

data for Virginia Tech is for 553 disk level estimates while the available Clark data is for 246

tree level estimates for a merchantable stem.
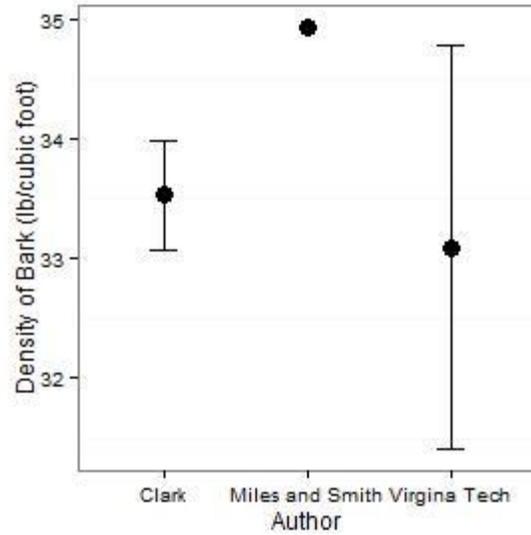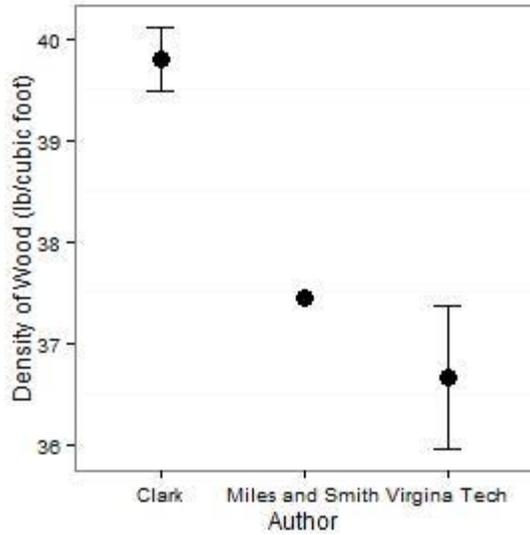
(A)   (B)

Figure 14. Density of wood (A) and bark (B) for three different datasets.
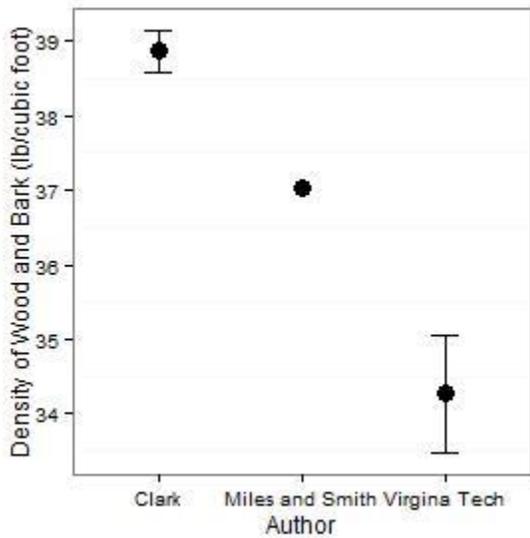
Figure 15. Density of wood and bark for three different datasets.

Volume

Since one of the main parts of the component ratio system is volume estimation, the field

data volume calculation using Smalian's volume equation was compared to the Oswalt and

Conner volume estimates. Only the field data were compared to Oswalt and Conner predicted

volumes because there were not enough measurements in the legacy data to apply Smalian's

formula, and comparing two models was not of interest. The Oswalt and Conner volume is

predicting the observed volume accurately (Figure 16). The data are centered on a 1:1 line,

meaning that it is predicting with high accuracy and an overall mean square error (MSE) of

29.38. The pole-sized and sapling-sized trees are tighter to the line with an MSE of 0.736. The

larger trees add more error but overall the model is predicting well. To predict inside bark

volume a simple linear model was fit to the disk data with inside and outside bark measurements

where diameter inside bark = -0.4296703+0.9351186*(diameter outside bark).
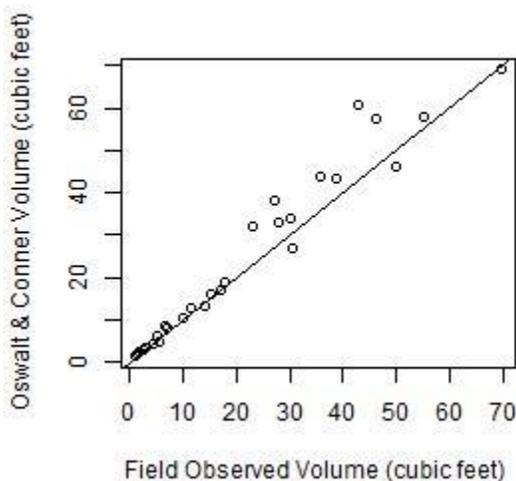
Figure 16. Field observed volume (cubic feet) plotted against the Oswalt & Conner (cubic feet) volume estimates.

Field Observed Component Ratios

Some inconsistencies were noted between field-observed branch biomass ratios and

estimates from the model of Jenkins et al. (Figure 17 (A)). As the diameter increases the ratio of

branches should decrease; however, the actual observation is that as the diameter increases,

branch ratio increases. As the observed wood ratio is decreasing, the Jenkins ratio shows that it is

increasing (Figure 17 (C)). The Jenkins ratio shows the bark ratio increasing while the observed

data shows it decreasing (Figure 17 (D)). The Jenkins foliage ratio appears to be overestimating

the ratio but following the same trend as the observed data (Figure 17 (B)). Since all of the trees

did not have both individual wood and bark measurements the wood and bark can be added

together as one ratio (wood and bark ratio). The Jenkins model is predicting the ratio to increase

as the diameter increases, while the observed ratio is decreasing (Figure 18). The Jenkins model

tends to underestimate the branch biomass by 59% but overestimated foliage by 217%, wood by

121%, bark by 229%, and wood and bark by 206%. The results from this analysis helped

determine the next step in improving the model.
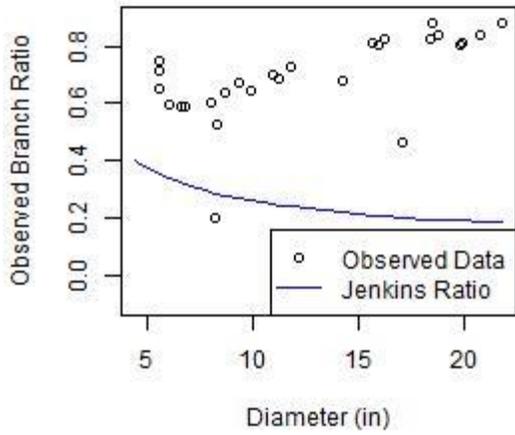
(A)
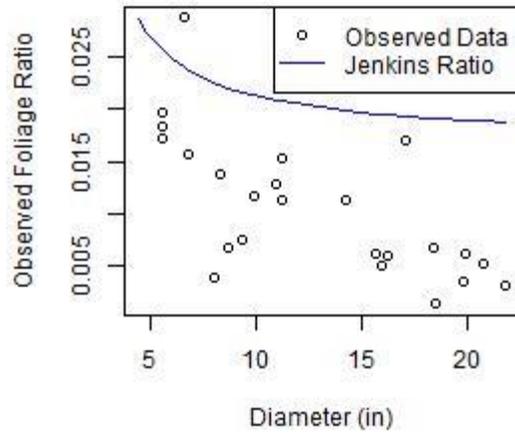
(B)
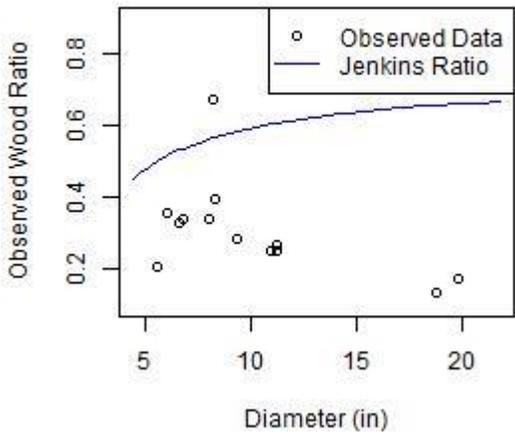
(C)
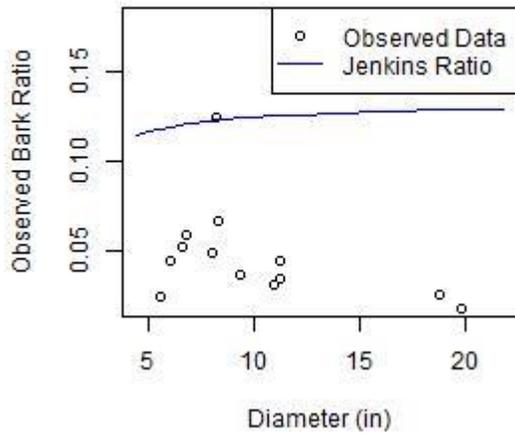
(D)

Figure 17. Observed branch for n=32 (A), foliage for n=28 (B), wood n=15 (C) and bark n=15 (D) biomass component ratios of white oak collected in Virginia.
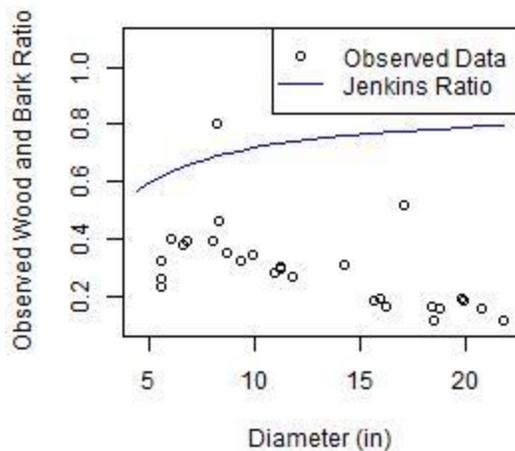
Figure 18. Observed stem (wood and bark) biomass component ratios of white oak collected in Virginia, n=32.


Legacy Data Comparisons

With the larger sample size of the legacy data, the Jenkins ratios seem to be predicting better for some of the components but still have inconstancies. As pole sized tree DBH approaches 5 inches, the observed branch fractions seem to increase rapidly to values greater than 60% of the aboveground biomass (Figure 19 (A)). There is a noticeable discontinuity between the small pole-sized and the sapling-sized (<5"DBH) trees. The saplings which are only slightly smaller in DBH have branch biomass ratios of only about 1/3rd of the slightly larger small pole-sized trees. The same trend can be seen in wood and bark. As the observed pole-sized wood fractions approach 5 inches DBH the ratio seem to rapidly decrease to values less than 30% of the aboveground biomass (Figure 19 (C)), and bark fractions rapidly decrease to values less than 5% of the aboveground biomass (Figure 19 (D)), with the saplings ratios about a 1/3rd larger than the small pole-sized trees.

This disconnect makes the overall predictions seem close to the observed value for both foliage and wood. The Jenkins model appears to consistently overestimate the foliage biomass by

38

5 % and wood by 1%,. The branches and bark, however, are significantly over predicted with branches over predicted by 93% and bark by 57%. Predictions of foliage with the Jenkins model is the only component with the same trend as the observed data (Figure 19 (B)), and with the over prediction of only 5%; the foliage is not effected by the disconnect as are the other 3 ratios. The Jenkins branch ratio predicts closely to the observed data around 10 inches, but for all other measurements the model and observed data disagree and are in opposite directions (Figure 19 (A)). The observed wood ratio is decreasing where the model predicts it to be increasing (Figure 19 (C)). The Jenkins bark model is predicting a much higher ratio value than the observed bark data is showing (Figure 19 (D)). The saplings (less than 5 inches DBH) are all separate from the rest of the data.
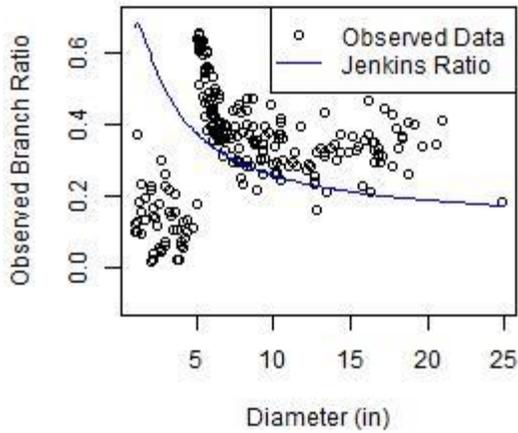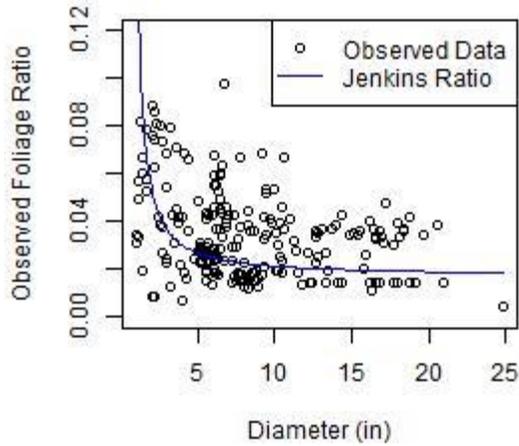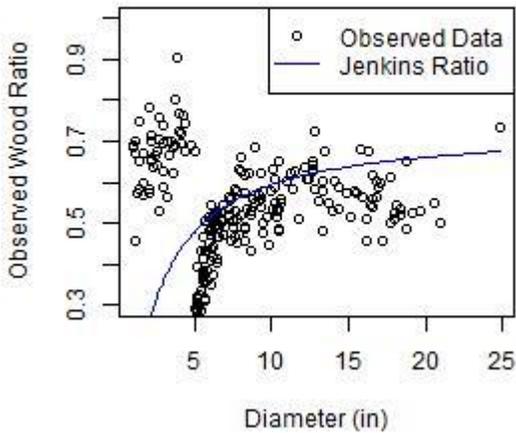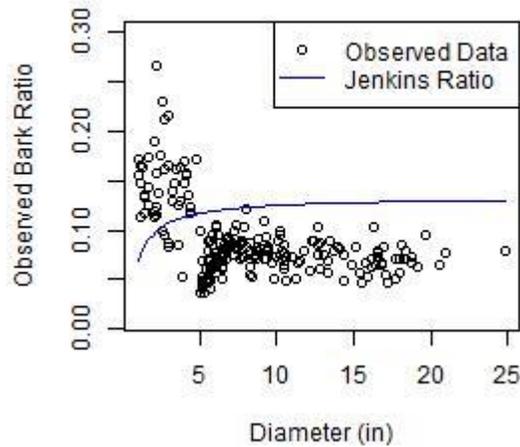
Figure 19. Legacy observed and Jenkins ratio for branches (A), foliage (B), wood (C) and bark(D).

When the predicted inside and outside bark diameter measurements were compared to the

observed values it seems that the Raile (1982) diameter equation is over predicting the inside

diameter by about 16% (Figure 20 (A)). The outside bark equation appears to be predicting

closely to the observed values because the outside bark observations are randomly distributed

around the 1:1 line; the equation is under predicting by only 0.10% (Figure 20 (B)).
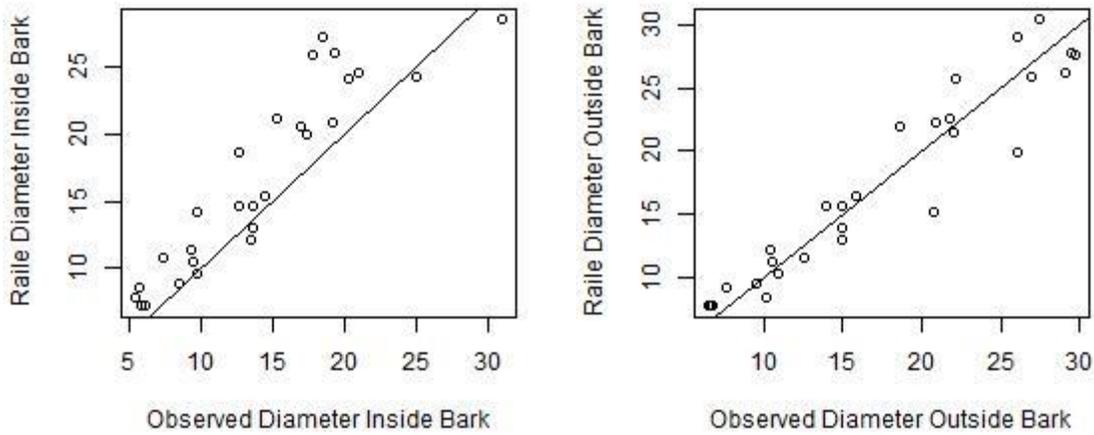
(A)   (B)

Figure 20. Observed stump inside bark (A) and outside bark (B) diameter of white oak collected in Virginia at the lowest height measured, n=32.

Effects of No Foliage

The plots that contain the ratio both with foliage and without foliage give an insight to how much the presence of foliage affects the ratios. The foliage ratios were most effected, going from a ratio greater than 0 to a ratio equal to 0. The branch, wood, bark, and wood and bark ratios have a mean prediction difference of 3.4%, meaning that not including the foliage decreases the branch, wood and bark ratios by 3.4%. On the bigger diameter trees the branch, bark and wood ratios are hardly effected. However, the smaller the tree, the more there seems to be a difference in the ratio (Figure 21), with it still not being a significant difference if the foliage is included in the aboveground biomass ratios.
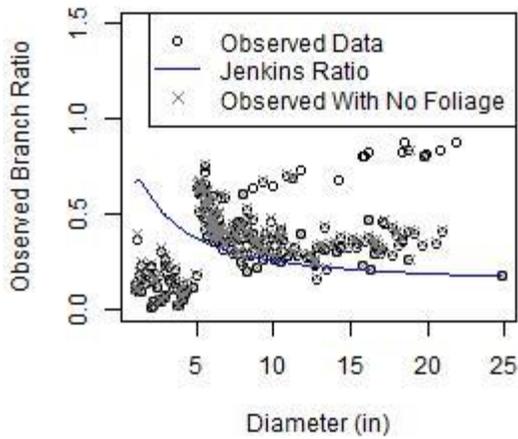
(A)
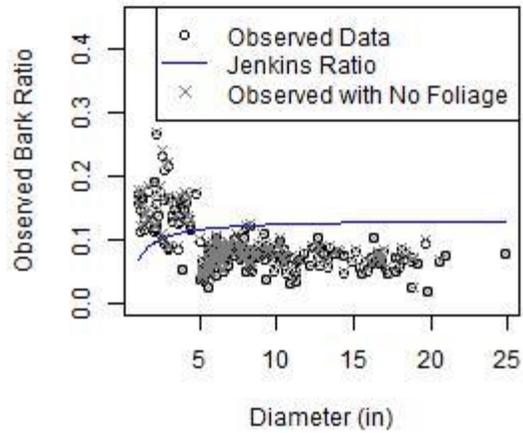
(B)
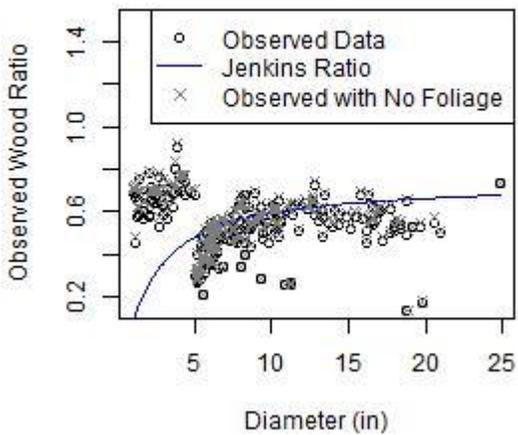
(C)
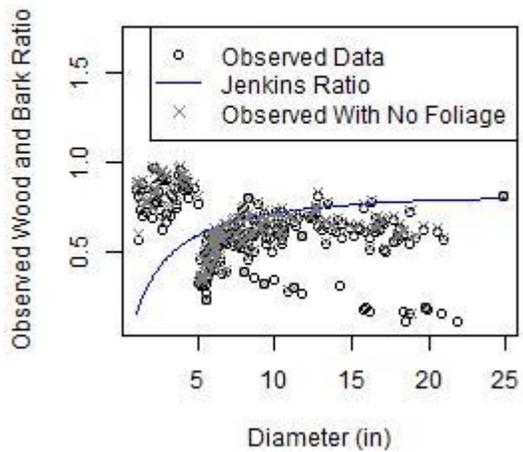
(D)

Figure 21. Branch (A), bark (B), wood (C) and wood and bark (D) ratios with and without foliage in aboveground biomass ratios.

Re-estimation of the Jenkins Ratio Coefficients

The residuals for the refitting of the Jenkins models (Equation (16)) were examined carefully and showed that the model does not fit the data well. The residuals appear to have a non-linear pattern instead of the satisfactory random scatter (Figure 22). This pattern in the residuals is an indicator that the data do not appear to be well-represented by the model in its

ln(ratio) versus 1/DBH form. Even though the residuals show that the model does not fit the data well, the refitted model was applied to the data to observe how well it is predicting. The model that appears to have the least change from the current model is the foligae ratio (Figure 23 (B)). When looking at this plot the new model does not seem to have changed much and still seems to be fitting through the data fairly well. In the other ratio plots the refitted model fits the observed data better, however with the disconnect at 5 inches between the saplings and small pole-sized trees the model could still be improved (Figure 23 (A), (C), (D)). When the refitted model is compared to the Jenkins ratios only the bark R^2 increases while the foliage and wood R^2 values decrease (Table 7).

$$Refitted\ Jenkins\ model = e^{(\beta_0 + \frac{\beta_1}{DBH})}$$

(16)
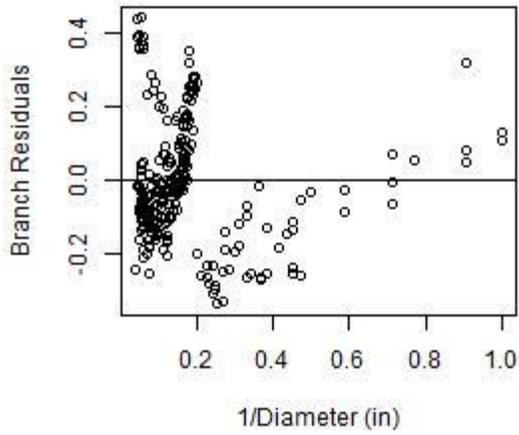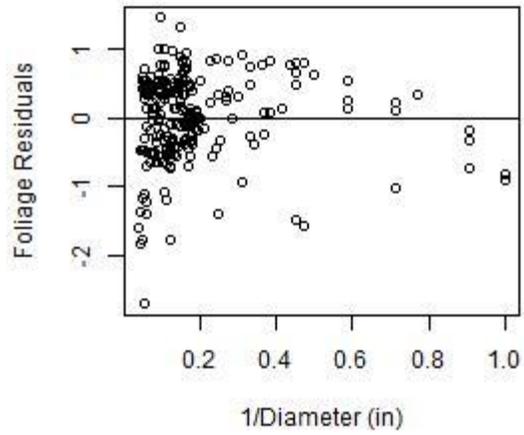
(A)   (B)
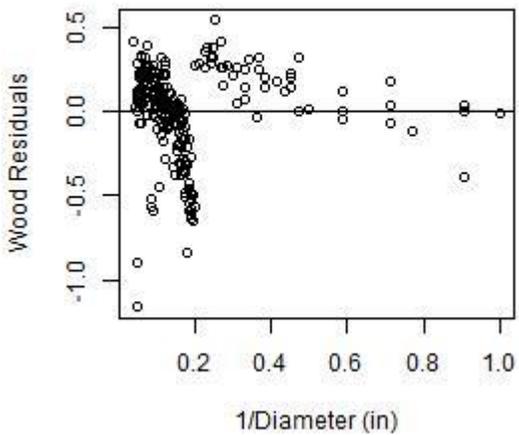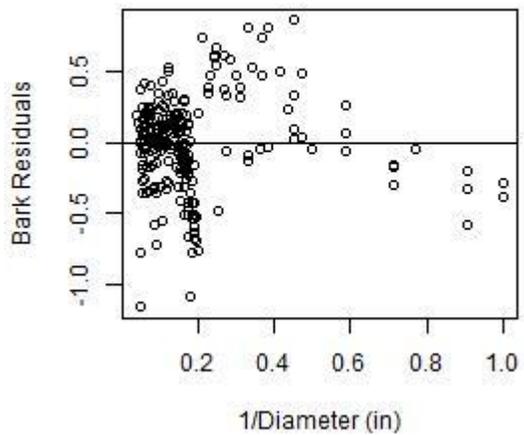
(C)   (D)

Figure 22. Branch (A), foliage (B), wood (C) and bark (D) residuals for the refitted of the Jenkins unadjusted model.
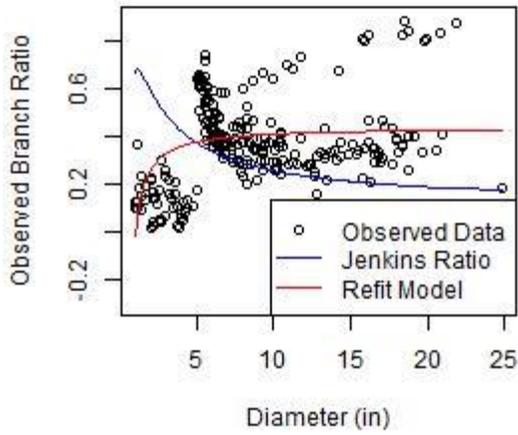
(A)
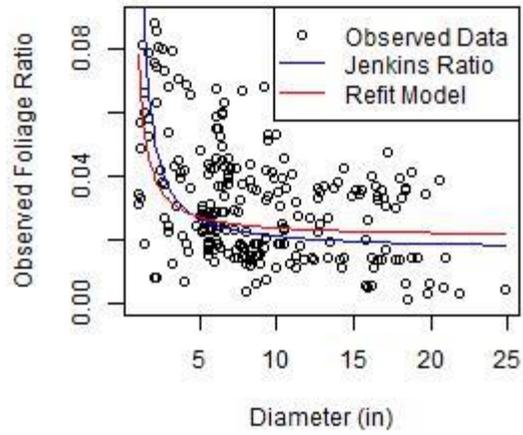
(B)
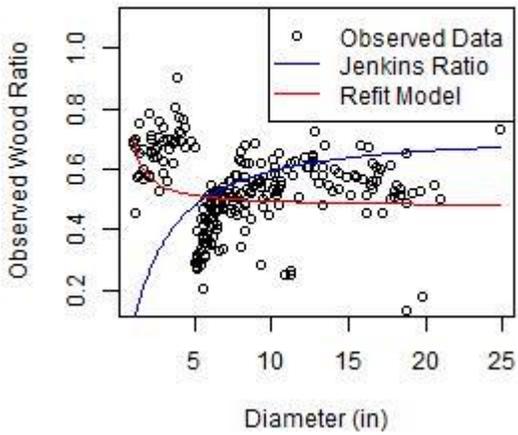
(C)
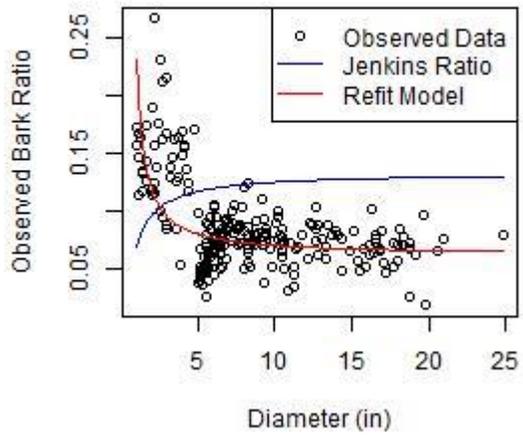
(D)

Figure 23. Branch (A), foliage (B), wood (C), and bark (D) refitted unadjusted ratio model, revised ratio model and observed ratios.

Table 6. Refitted Jenkins Ratio and Jenkins Ratio coefficients.

Regression	Coefficient	β_0	β_1	R^2	Data Points
Refitted Jenkins Ratio	Bark	-2.78894	1.322966	0.3016	238
	Wood	-0.74388	0.392994	0.05252	238
	Foliage	-3.86616	1.322007	0.106	249
Jenkins Ratio	Bark	-2.0129	-1.6805	0.017	63
	Wood	-0.3065	-5.4240	0.247	264
	Foliage	-4.0813	5.8816	0.256	632

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Examining Merchantability Limits

The adjusted ratios account for the stem measured from the ground to the tip. The adjusted biomass component ratios for wood, bark, and branches exhibit relatively continuous trends across the range of observed DBH. The disconnect around 5 inches is no longer an issue in these plots (Figure 24). With the disconnect in the data gone, the ratios have a clearer trend. To determine how strong the new trends are, spearman rank correlation coefficients (SRCC) were calculated and examined. The SRCC were weak for all components but branches with SRCCs of 0.02 for foliage, 0.05 for wood, and 0.16 for bark. The branch SRCC was moderate at 0.57. This explains that trends exist but they are not strong trends.
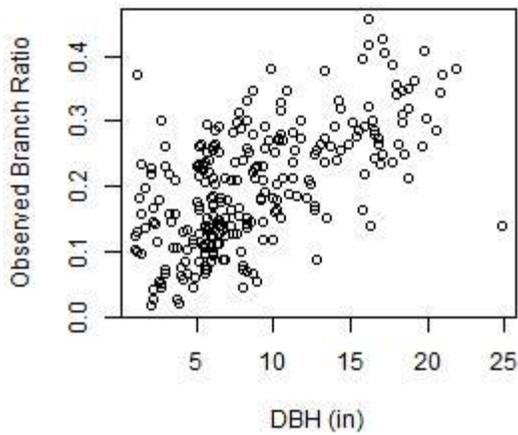
(A)
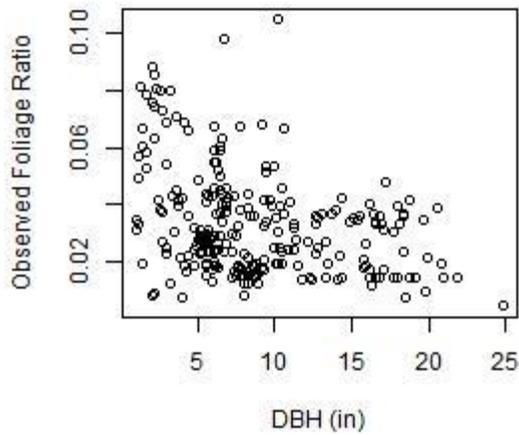
(B)
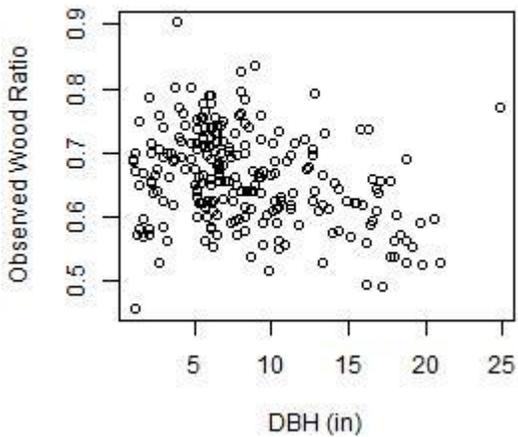
(C)
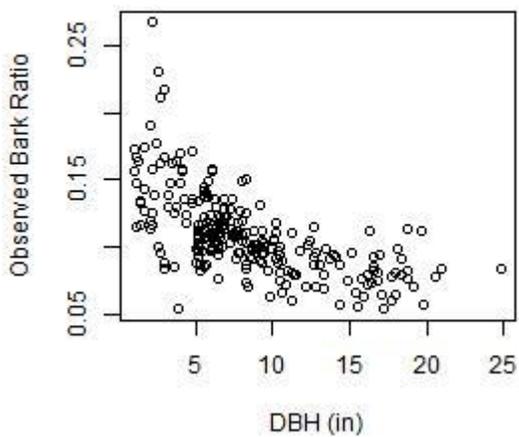
(D)

Figure 24. Observed branch (A), foliage (B), wood (C), and bark (D) ratios after being adjusted for ground to tip stem.

Refitting with Whole Stem Ratios

The second refitting of the model, the Jenkins adjusted stem ratios (Equation ((17)) have better residuals than the refitted Jenkins ratio models. The Jenkins adjusted stem ratios residuals also have a non-linear trend (Figure 25). There is more of a scatter in the residuals than the previous model but there is still a systematic pattern with the residuals at x=0.2. The non-linear

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trend and the pattern at x=0.2 are evidence that a transformation is needed to make a better

mode.

$$whole\ stem\ ratio = e^{(\beta_0 + \frac{\beta_1}{DBH})} \tag{17}$$

When the model was applied to the observed data it appears to follow the trend of the

data for foliage and bark (Figure 26 (B) and (D)). Wood and branches seem to have a leverage

point that is bringing the model prediction lower than observed data for the branches and higher

than the observed data for wood (Figure 26 (A) and (C)). When the leverage point (DBH is 24.8

inches) is removed from the data it does not affect the whole stem ratio model meaning this point

will be kept in the data for analysis. When the refitted model is compared to the Jenkins ratios

and refit Jenkins Ratios all of the R^2 values decrease (Table 7) showing that even though the

whole stem ratio model improves the residuals this model needs improvement and is not the

most approproite model.
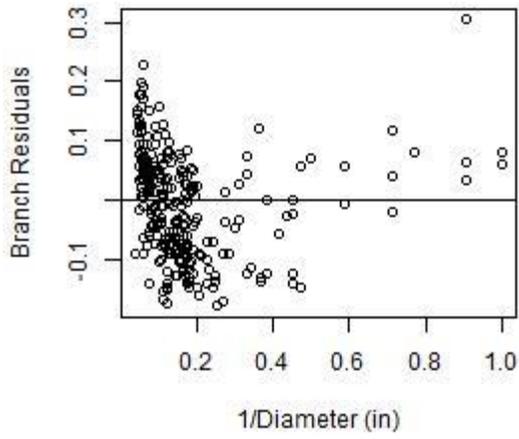
(A)
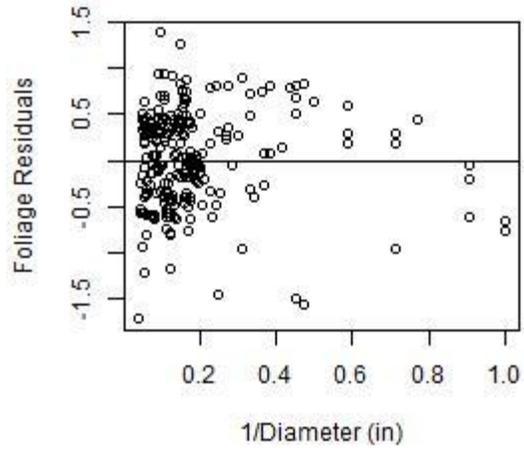
(B)
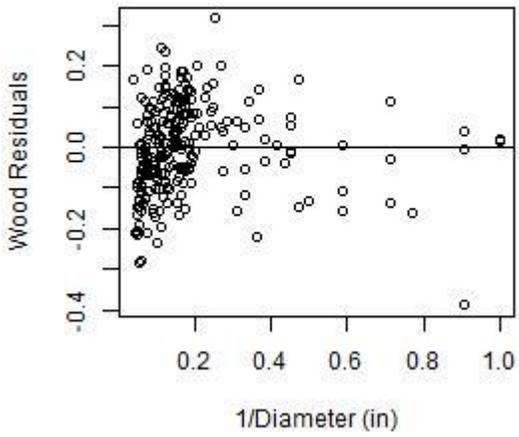
(C)
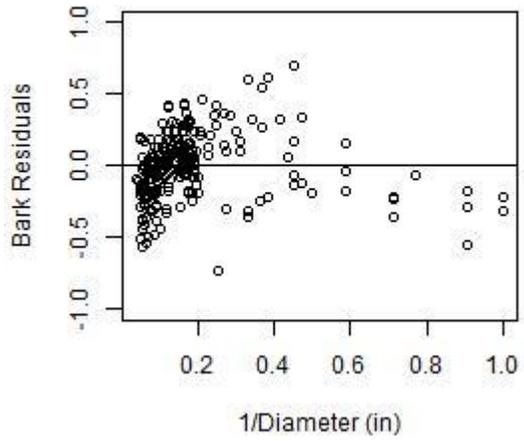
(D)

Figure 25. Branch (A), foliage (B), wood (C), and bark (D) residuals for the refit of the Jenkins adjusted stem model.
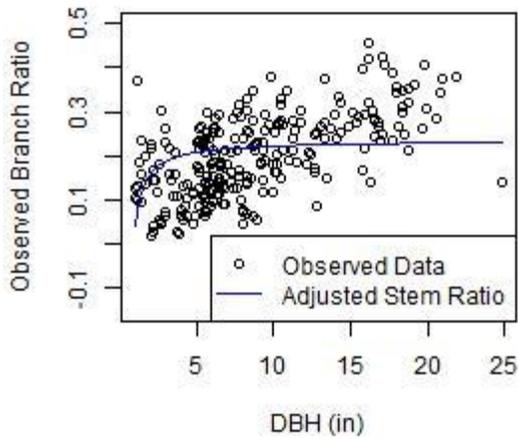
(A)
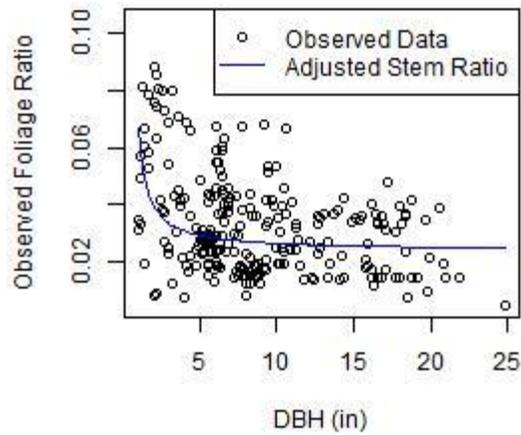
(B)
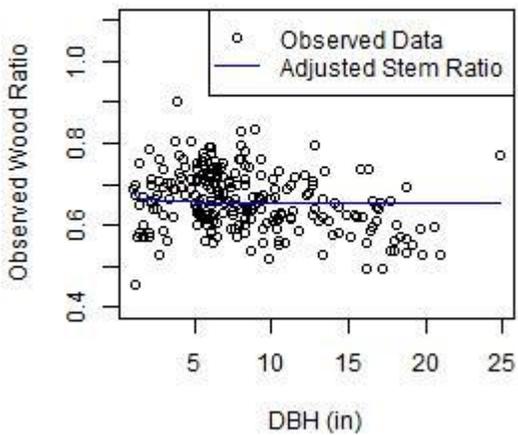
(C)
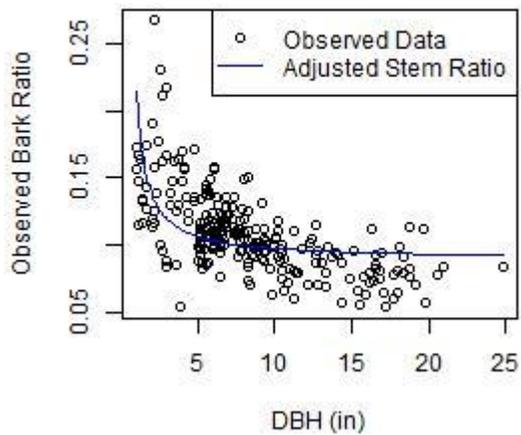
(D)

Figure 26. Branch (A), foliage (B), wood (C), and bark (D) refitted whole stem ratio model.

The third way the model was refitted, the fitted whole stem ratio, (Equation ((18)) resulted in more satisfactory residual plots. There is a random scatter for the residuals and no pattern to the residuals for both bark and foliage(Figure 27 (B) and (D)). There appears to still be a slight trend in the branch and wood residuals (Figure 27 (A) and (C)). The slight non-linear trend is less apparent then with other models but is still there. The transformation of the data

appears to have improved the model based on the residuals even though the model is not completely satisfactory.

$$Adjusted\ stem\ and\ adjusted\ ratio = e^{(\beta_0 + \beta_1 * \ln(DBH))}$$

(18)

When the models were applied to the observed data and corrected with the correction factor, predictions were better than for the previous two models (Figure 28). The foliage and the bark adjusted stem and ratio models appear to be following the same trend as the observed data (Figure 28 (B) and (D)). The branch and wood model is still being pulled toward a high leverage point even though it is not as much as the previous model (Figure 28 (A) and (C)). The R^2 values were the highest for both the bark (0.4528) and foliage (0.1239) for the fitted whole stem ratio models (Table 7). The R^2 values was second highest for the wood in this model with the highest being 0.05252 for the refitted Jenkins ratios model. The R^2 values are not significant but they are similar to the Jenkins published R^2 values in Table 3. The RMSE values are also included so they can be used in the Baskerville correction factor.
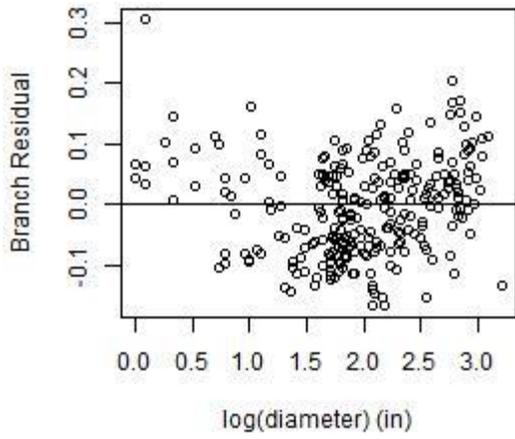
(A)
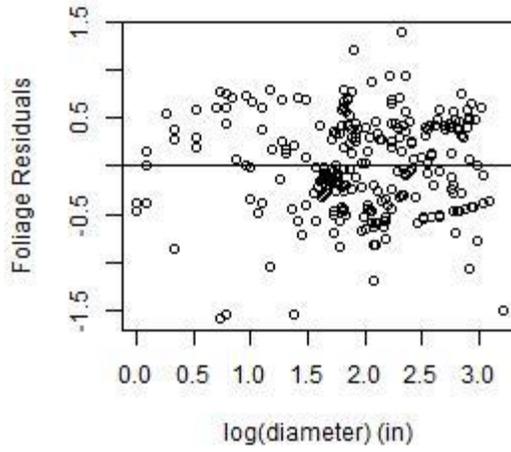
(B)
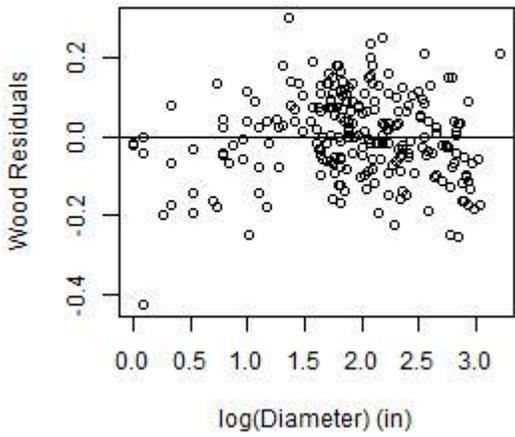
(C)
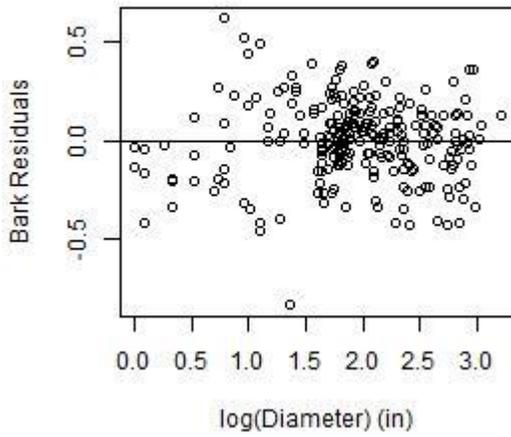
(D)

Figure 27. Branch (A), foliage (B), wood (C), and bark (D) residual for the fitted whole stem ratio model.
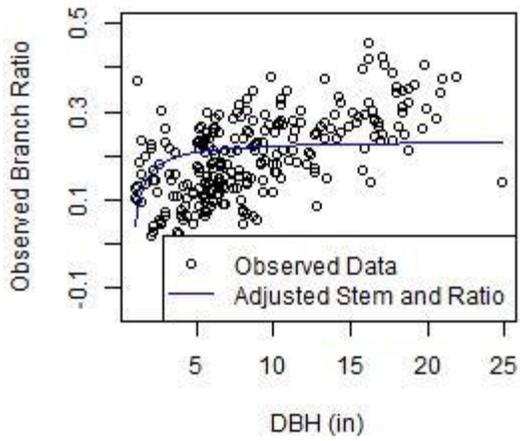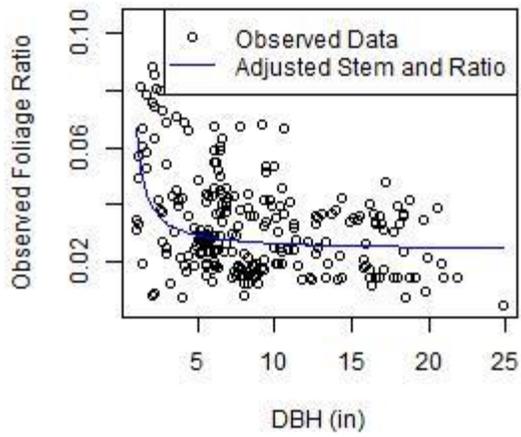
(A)   (B)
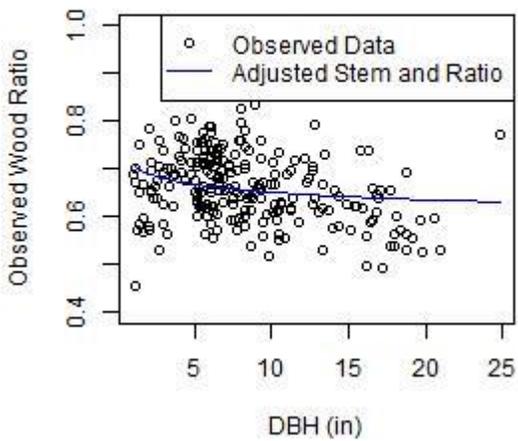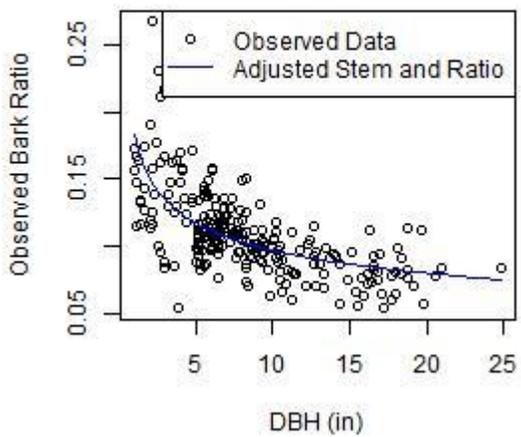
(C)   (D)

Figure 28. Branch (A), foliage (B), wood (C), and bark (D) refitted ratios for the fitted whole stem ratio model.

Table 7. Regression coefficients for the three refitted models.

Regression	Biomass Component	β_0	β_1	RMSE	R^2
Refitted Jenkins ratio	Bark	-2.78894	1.322966	0.3397	0.3016
	Wood	-0.74388	0.392994	0.2728	0.05252
	Foliage	-3.86616	1.322007	0.6326	0.106
Whole stem ratio	Bark	-2.41988	0.880421	0.2287	0.2949
	Wood	-0.42789	0.036509	0.1103	-0.0016
	Foliage	-3.73507	1.027059	0.5079	0.09838
Fitted whole stem ratio	Bark	-1.72016	-0.27675	0.2015	0.4528
	Wood	-0.35149	-0.03594	0.1079	0.04283
	Foliage	-2.98977	-0.28423	0.1274	0.1239

FIA

When comparing the current FIA aboveground predictions it is expected that both models are not going to have the same results. The adjusted aboveground biomass model predictions tend to be larger than the current CRM model that FIA uses (Figure 29). State level biomass estimates (Table 8) show how much the current model tends to predict smaller values than what the adjusted model is predicting. The adjusted model is predicting about 16 million more tons of total aboveground biomass for the state of Virginia or a difference of about 30%.
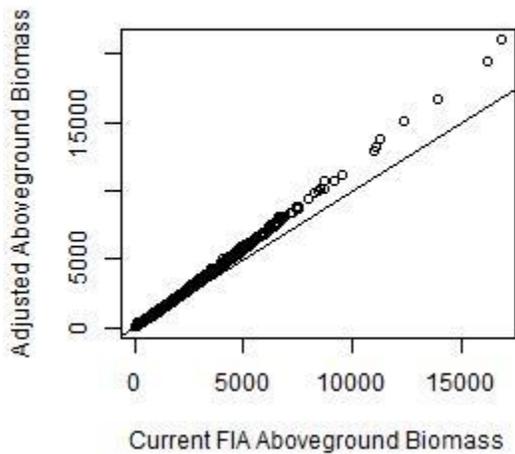
Figure 29. Current FIA aboveground biomass and new adjusted aboveground biomass with a 1:1 ratio line.

Table 8. Virginia state level biomass estimates for the current and adjusted model with
Merchantable limits.

Component	Current Method (short tons)	New Adjusted Method (short tons)
Bole Biomass	67,900,976	66,946,845
Top Biomass	15,993,895	25,327,394
Stump Biomass	3,699,694	5,300,714
Sapling Biomass	2,860,269	3,756,596
Total Aboveground Biomass	90,454,834	103,833,618

To further investigate where the differences in the state level estimates occur the figures
were broken down into 2 inch diameter classes (Table 9). The biggest difference ((adjusted
biomass-current biomass)/adjusted biomass) was in the top with a mean difference of 51%. The
difference in the top biomass increased as the DBH increased. The stump had a mean difference
of 31%, and the difference decreased as DBH increased. The stem biomass difference was only
2% between the current and adjusted methods.

Another way to examine how the adjusted model compares to the current model is to run
one tree with a set DBH and set total height through both the current CRM model and the
adjusted model. The two models will give different values as did the statewide estimates but it
more readily shows where the differences in the models occur. This was done with a white oak
tree with a DBH of 7.8 inches and a total height of 50.6 feet (Table 10).

Table 9. Virginia state level biomass estimates for the current and adjusted model with merchantable limits broken into two-inch diameter classes in million short tons.

Diameter Class	Current Biomass	Adjusted Biomass	Current Top Biomass	Adjusted Top Biomass	Current Stem Biomass	Adjusted Stem Biomass	Current Stump Biomass	Adjusted Stump Biomass
2	0.65	0.91	0.00	0.00	0.00	0.00	0.00	0.00
4	1.69	2.14	0.00	0.00	0.00	0.00	0.00	0.00
6	2.99	4.30	0.72	1.50	1.59	1.61	0.16	0.48
8	5.59	6.42	1.40	1.94	3.89	3.91	0.31	0.57
10	7.89	8.71	1.74	2.37	5.75	5.75	0.40	0.59
12	9.48	10.47	1.89	2.76	7.15	7.10	0.44	0.60
14	11.81	13.12	2.19	3.46	9.11	9.00	0.51	0.66
16	11.80	13.26	2.06	3.52	9.26	9.12	0.48	0.61
18	13.04	14.80	2.16	3.98	10.37	10.18	0.51	0.64
20	7.80	8.95	1.24	2.44	6.27	6.14	0.29	0.37
22	6.70	7.74	1.03	2.14	5.43	5.30	0.24	0.30
24	4.64	5.42	0.69	1.52	3.79	3.69	0.16	0.21
26	2.27	2.67	0.33	0.76	1.87	1.81	0.07	0.10
28	1.12	1.32	0.16	0.38	0.93	0.90	0.04	0.04
30	0.99	1.18	0.14	0.34	0.82	0.80	0.03	0.04
32	0.13	0.16	0.02	0.05	0.11	0.10	0.00	0.01
34	0.47	0.57	0.06	0.17	0.40	0.38	0.01	0.02
36	0.56	0.67	0.07	0.20	0.47	0.45	0.02	0.02
38	0.49	0.60	0.06	0.18	0.41	0.40	0.01	0.02
46	0.33	0.42	0.04	0.13	0.28	0.27	0.01	0.02
Total	90.45	103.83	15.99	27.83	67.90	66.95	3.70	5.30

Table 10. Step by step calculations for both the current FIA CRM model and the proposed adjusted method.

	DBH	7.8	Numbers in Italics refer to line numbers	
	HT	50.6		
	CULL	0		
	Current FIA Method Step	**Value**	**New Adjusted Method Step**	**Value**
1	Oswalt and Conner Voume -0.37698+0.001948*DBH^2*HT	5.620	Oswalt and Conner Volume -0.37698+0.001948*DBH^2*HT	5.620
2	Biomass of stem wood (*1* * 37.4)	210.186	Biomass of stem wood (*1* * 37.4)	210.186
3	Biomass of stem bark(*1* * 34.9*0.16)	31.382	Total Clark Volume (using Clark volume eq 0'stump to 0"top)	5.439
4	Biomass of stem wood + stem bark	241.568	Merch Clark Volume (using Clark volume eq 1'stump to 4"top)	4.224
5	Drybio_bole = step *4*	241.568	Top Clark Volume (using Clark volume eq 4"top to 0"top)	0.667
6	Total Aboveground Biomass (exp(-2.0127+2.4342* log(DBH*2.54))*2.2046)	422.871	Stump Clark Volume (using Clark volume eq 0'stump to 1"stump)	0.547
7	Stem ratio (exp(-0.3065+-5.424/(DBH*2.54)))	0.5600	Clark adjustment factor (*3/4*)	1.287
8	Bark ratio (exp(-2.0129+-1.6805/(DBH*2.54)))	0.123	Top Adjustment Factor (*5/3*)	0.101
9	Foliage ratio (exp(-4.0813+5.8816/(DBH*2.54)))	0.023	Stump Adjustment Factor (*6/3*)	0.123
10	Stem biomass Jenkins (Jenkins biomass (*6*) times ratio (*7*))	236.700	Merch Adjustment Factor (*4/3*)	0.777
11	Bark biomass Jenkins (Jenkins biomass (*6*) times ratio (*8*))	51.9014	Adjusted stem biomass (*2*7*)	270.592
12	Bole biomass Jenkins (*10 + 11*)	288.602	Whole stem ratio (exp((-0.3514935+-0.03593996*(log(DBH)))+(0.1079^2/2)))	0.657
13	Foliage biomass Jenkins (Jenkins biomass (*6*) times ratio (*9*))	9.608	Adjusted bark ratio (exp((-1.7201618-0.27675475*(log(DBH)))+(0.2015^2/2)))	0.103
14	Stump wood volume ((pi*(DBH)^2/(4*144)*((.92267-.12506)^2*1+11*.1*(.92267-.12506)*log(1+1)-30.25/(1+1)*(.12506^2)))-(pi*(DBH)^2/(4*144)*((.91130-.14907)^2*0+11*.14907*(.92267-.12506)*log(0+1)-30.25/(0+1)*(.12506^2))))	0.491	Adjusted foliage ratio (exp((-2.9897711-0.28423489*(log(DBH)))+(0.1274^2/2)))	0.0283

#		Value		Value
15	Stump bark volume ((pi*(DBH)^2/(4*144)*((1-.12798)^2*1+11*.12798*(1-.12798)*log(1+1)-30.25/(1+1)*(.12798^2)))-(pi*(DBH)^2/(4*144)*((1-.12798)^2*0+11*.12978*(1-.12978)*log(0+1)-30.25/(0+1)*(.12978^2)))- (line *14*))	0.130	Adjusted branch ratio (1- *12 - 13 - 14*)	0.211
16	Stump wood biomass (*14* * 37.4)	18.378	Adjusted aboveground biomass (*11/12*)	411.624
17	Stump bark biomass (*15* * 34.9)	4.542	Adjusted branch biomass (*16*15**(1-(cull/100)))	86.794
18	Stump biomass (*16+17*)	22.920	Adjusted foliage biomass (*16*14**(1-(cull/100)))	11.642
19	Top Biomass Jenkins (*6-10-11-13-18*)	101.741	Adjusted bark biomass (*16*13**(1-(cull/100)))	42.596
20	Adjustment factor (*5/12*)	0.8370	Adjusted stem biomass (*11**(1-(cull/100)))	270.592
21	Drybio_top (*19*20**(1-(cull/100)))	85.160	Adjusted aboveground biomass (*16**(1-(cull/100)))	411.624
22	Drybio_bole (*5*20**(1-(cull/100))	241.568	Adjusted bole biomass (*19 + 20*)	313.188
23	Drybio_stump (*18*20**(1-(cull/100))	19.185	Drybio_top (*19 *8 + 17*)	118.288
24	Total tree biomass (*21+22+23*)	345.912	Drybio_bole (*19 *10*)	243.273
25			Drybio_stump (*19 *8*)	38.421
26			Total tree biomass (*23 + 24 + 25*)	399.982

Discussion

Rose (2014) reported the merchantable white oak wood volume as 3155.9 million cubic feet for 2012 in Virginia, which matches the result obtained from the EVALIDator web application of Miles (2014). The white oak merchantable wood volume converts roughly to 67.9 million short tons [1]of white oak merchantable stem biomass based on wood and bark density factors published by Miles and Smith (2009). This figure is the same as the predicted FIA

[1] 1 short ton = 2000 lb

biomass estimate of 67.9 million short tons (Table 8). The process of applying both a new model and adjusted model for comparison has been done by Nelson, et al. (2014). The estimates for both the current FIA model and the adjusted model (Table 8) are computed using the same trees and plots. The difference between the current FIA model and the adjusted model is about 16 million short tons of biomass, or 12%. The current FIA model predictions are lower than the adjusted model's with the larger trees having more of an impact than the smaller trees (Table 9). The whole stem ratios (Equation (18)) equation fit is improved so the adjusted model (Equation (18)) may be more accurate.

The CRM has several parts (volume, density, and components) and it is likely that some of these components are predicted more accurately than others. The Oswalt & Conner (2011) volume equations predict closely when compared to the field observed volume (Figure 16). This result was expected because a large database of volume and taper measurements from the southeastern US was used to develop those volume equations (Woodall, et al. 2011). Pole-sized and sapling-sized tree volume predictions are consistent with the observed data (Figure 16). Volume prediction errors for sawtimber-sized trees are larger, with an apparent over prediction bias that may merit further investigation (Figure 16). Since the equations of Oswalt and Conner (2011) were not substantially out of agreement with values observed here, its use in estimating white oak biomass in Virginia is largely supported by the results of this study.

Different density values were noted for wood, bark, and wood and bark together, depending on the source of information. One source of information, that of new field data collected here, came entirely from southwestern Virginia. The second source, legacy data from Clark (1985, 1986a, 1986b, 1986), came from a broader region spanning the southeastern US. The third source, that of Miles and Smith (2009), pertains to the entire species range; however,

no detailed description of the source data is provided (Miles and Smith 2009). Differences in the spatial extent and geographic scope of these information sources may explain the differences noted here. Given no reason to exclude the Miles and Smith (2009) density values, it seems reasonable to continue using them in biomass estimation for white oaks in Virginia. Further research may seek to incorporate spatial information in published wood density values like those given by Miles and Smith (2009), as that information may be useful in future applications.

Predictions from the Jenkins et al. (2004) ratio models were inconsistent with some of the data observed and compiled here (Figure 17, Figure 18, and Figure 19). There is a disconnect in the observed data at 5 inches DBH where there is a shift in merchantable limits. The predicted Jenkins bark ratios increase as the observed data values decrease (Figure 19). The Jenkins (2003) ratio models were fit with a relatively small number of observations and categorized only as hardwoods versus softwoods. Rather than actual observed data, the ratio models were fit with pseudo data with only DBH as a predictor (Jenkins, et al. 2003).

The residuals for the refitted Jenkins model (Equation (16)) shows the discontinuity (Figure 22) in part because of the merchantable limits of the data. Oswalt and Conner (2011) defined stem volume for trees < 5 inches DBH from the ground to tip, while their definition in larger trees applies to only the merchantable stem volume between a one foot stump and a 4 inch top. By adopting a single, consistent definition that considers the stems of all trees from ground to tip, the inconsistency between sapling and pole or sawtimber sized trees was largely eliminated here. Since tree measurements are often made in relation to merchantability limits, it was necessary to formulate procedures for translating merchantable stem measurements -- such as the diameter at a 1-foot stump and height at a 4-inch top diameter -- to their counterparts at ground line and the tip of the main stem.

The whole stem ratio model (Equation (17)) exhibits satisfactory residuals, which indicates that the problem with the discontinuity has been resolved: however, the curved pattern in the residuals indicates an obvious nonlinearity in the data that is as of yet unaccounted for (Figure 25). Regardless, the model form was still not the most significant model form for the data based on R^2 values and residual plots. The residuals for the whole stem ratio model still have a nonlinear pattern to them (Figure 25); to improve the model another transformation such as a log-log transformation may be needed (Sit and Poulin-Costello 1994). The predicted wood component values did not match the observed values, which caused the branch predictions to be worse than bark and foliage.

The Jenkins model calculates branch ratios by subtraction from one, if any one of the three ratio equations (wood, bark, or foliage) predicts poorly then branch ratio predictions will likely also be inaccurate. Other techniques, such as seemingly unrelated regression (SUR), has been applied to ensure additivity of the components (Kozak 1970, Parresol 2001). SUR is both empirically and theoretically superior to adding independently developed model predictions together (Parresol 2001). SUR fits models for all components of interest while ensuring all the components add up to the total tree biomass (Parresol 1999, 2001, Sabatia, et al. 2008). The subtraction method of Jenkins et al. (2003) causes the branches estimate to be fully dependent on the other 3 estimates. In SUR all of the estimates are dependent on each other which eliminates one of the 3 dependent estimates from skewing the dependent subtracted estimate.

The whole stem data fitted to the fitted whole stem model form from Equation (18) improves the fit of the data. This model had the best residuals and the highest bark and foliage R^2 values of 0.4528 for bark and 0.1239 for foliage. The wood R^2 value of 0.04283 was only slightly lower than refitted Jenkins ration (Equation (16)) of 0.05252. This model worked as well

as it did because the log-log transformation improved the residuals for these ratios. Based on the R^2 values and the residual plots the best model is the fitted whole stem ratio model (Equation (18)). The wood and foliage R^2 values are not the largest for this model with the Jenkins model having a larger R^2 for the foliage and the refitted Jenkins model having a larger R^2 for the wood. For the data analyzed here the modified model form, Equation (18), did provide a better fit to data than the model form, Equation (16), used by Jenkins et al. (2003). However, neither model form fit the data particularly well which seems to warrant more research to find a more suitable model form for predicting tree component ratios from DBH.

To determine the amount of biomass in the stump of a tree, the stump volume equation of Raile (1982) was used with the Miles and Smith (2009) densities in this work and in the FIA stump biomass estimates. In Raile's approach, diameter both inside and outside bark are predicted for a tree stump, then used to compute a predicted stump volume (Raile 1982). Stump inside bark diameters over predictions were observed for the data used in this work (Figure 20 (A)). The over prediction may be due to regional differences in the data since Ralie used 2,975 trees form Michigan, Minnesota and Wisconsin (Raile 1982) to develop his models. There are many equations for estimating the volume of trees based on stump diameter measurement; these equations are often needed in appraising values in cases of timber theft (Martinez-Lopez and Acosta-Ramos 2014, Weigel and Johnson 1997). The legacy data available for this research did not include stem diameter below DBH so the legacy data were not usable in the comparison of how well the model is predicting. There is a need for regionally accurate stump models, warranting additional research.

The observed data shows that the density decreases to around 20 percent of the total height and then increases again at around 35 percent of the total height (Figure 13). Due to

density decreasing and slightly increasing as the measurements go up the tree it has been proposed in other work, e.g. (Brooks, et al. 2007), that a trend be included in a biomass model. It has also been determined that the higher up a tree a disk is taken the smaller the wood fraction (Alemdag 1984, Chan, et al. 2012). The observed data shows that as the height of a tree increases the wood fraction decreases (Figure 10). The trend was strong in both absolute and relative heights and diameters.

One of the biggest issues with the current CRM is the difference in how volume and biomass are calculated at 5 inches DBH. The merchantability limits of the current CRM pose many challenges, and adjusting to a whole-stem basis seems like the most feasible option. By adding legacy data to supplement the field data, the sample size was sufficiently large for estimating new parameters for the ratio equations. The Oswalt and Conner (2011) volume calculations and the Miles and Smith (2009) densities appear to be predicting well and are not an issue in the current CRM. There are still improvements that could be done to the CRM but this work lays out a framework to handle the issue of merchantable limits putting unnecessary bounds on the model.

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