BIOMASS QUANTIFICATION OF LIVE TREES IN A MIXED EVERGREEN FOREST USING DIAMETER-BASED ALLOMETRIC EQUATIONS

by

William Ryan Coltrin

A Thesis

Presented to

The Faculty of Humboldt State University

In Partial Fulfillment

Of the Requirements for the Degree

Masters of Science

Natural Resources: Forestry

March, 2010
ABSTRACT

BIOMASS QUANTIFICATION OF LIVE TREES IN A MIXED EVERGREEN FOREST USING DIAMETER-BASED ALLOMETRIC EQUATIONS

William Ryan Coltrin

Biomass quantification methods have become of increased interest recently due to the threat of climate change. Organizations such as the California Climate Action Registry (CCAR) have suggested the use of generalized biomass equations to quantify forest carbon stocks. However, studies have shown that biomass equation generalization can lead to inaccurate estimates of biomass of live trees. In this study, a mixed evergreen forest type in northwestern California was inventoried and total aboveground biomass was quantified using different types of biomass equations. A new model was developed to predict biomass of bay-laurel trees, which were found to be abundant at the study site. A total of 14 trees ranging from 7.6 – 61 cm dbh were destructively sampled. Biomass and dbh were log-linearized and fitted with ordinary least squares linear regression. The bay-laurel equation was used in conjunction with other biomass equations developed in similar geographic regions to quantify stand-level biomass at the study site, which was 292.3 Mg ha\(^{-1}\). This estimate was then compared to the estimate using the biomass quantification methods outlined by CCAR, which was 265.9 Mg ha\(^{-1}\). It was assumed that site and regional biomass equations are the standard method to predict biomass. When compared with the standard method, it was found that CCAR’s equations differed significantly than the standard method and therefore did not accurately predict biomass at the study site.
ACKNOWLEDGEMENTS

This project was funded through grants by McIntire-Stennis (#147) and the L.W. Schatz Demonstration Tree Farm. I wish to thank my major professor, Christopher B. Edgar, who provided me with this research opportunity. Dr. Han-Sup Han provided me with great insight on outlining this thesis. Dr. Andrew Stubblefield gave me calming support which helped me envision the light at the end of the tunnel. Thanks to Larry Fox for listening to my frustrations with graduate school, your patience and advice was invaluable. A very special thanks goes out to Bill Bigg for his quick responses and endless answers to so many of my statistics questions. Your teaching and advice was invaluable to me, I’ve learned skills from you that will be with me forever. Dr. David Hankin also supported me as I struggled through statistics when ill and injured. Martin Ritchie of the Pacific Southwest Research Station also provided me with an enlightening voice of reason. Thanks also go out to George Pease and Gayleen Smith for providing equipment and administrative support.

I’d also like to thank the L.W. Schatz Tree Farm manager and summer crews, Gordon Schatz, Jonathan Dockweiler and Steve Alton for their assistance with data collection. Emily Miller also provided me with endless hours of comic relief and support which helped me endure the process. Other people who voluntarily contributed to data collection were Aaron McDowell, Nate Burns, and Glen Gerbatz. However, a very special thanks goes to Steve Alton for his endless and tireless help over the past two summers stomping through poison oak, pulling leaves, lifting logs and handling many of the project’s logistics.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF APPENDICIES</td>
<td>viii</td>
</tr>
<tr>
<td>CHAPTER ONE: Predicting total above ground biomass of bay-laurel trees</td>
<td>1</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>METHODS</td>
<td>4</td>
</tr>
<tr>
<td>Study Site</td>
<td>4</td>
</tr>
<tr>
<td>Tree Selection</td>
<td>6</td>
</tr>
<tr>
<td>Tree Sampling</td>
<td>6</td>
</tr>
<tr>
<td>Laboratory Measurements</td>
<td>7</td>
</tr>
<tr>
<td>Calculations</td>
<td>8</td>
</tr>
<tr>
<td>Fitting Bay-laurel Biomass Data to Equations</td>
<td>9</td>
</tr>
<tr>
<td>RESULTS</td>
<td>12</td>
</tr>
<tr>
<td>Bay-laurel Biomass Equation</td>
<td>12</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>16</td>
</tr>
<tr>
<td>LITERATURE CITED</td>
<td>18</td>
</tr>
</tbody>
</table>
### TABLE OF CONTENTS (CONTINUED)

**CHAPTER TWO:** An examination of the California Climate Action Registry’s aboveground biomass quantification methods of live trees ........................................24

**INTRODUCTION** ..................................................................................................................24

**METHODS** .........................................................................................................................28

- Study Site ...............................................................................................................................28
- Generalized Biomass Equations ..........................................................................................30
- Site-specific and Regional Biomass Equations ..................................................................30
- Tree and Stand-level Biomass Estimations .........................................................................33
- Test for Difference of Biomass Estimations ......................................................................34
- Biomass Distribution Comparison ......................................................................................35
- CCAR’s Sampling Error Protocols ....................................................................................35

**RESULTS** ............................................................................................................................36

- Tree and Stand-level Biomass Estimations ........................................................................36
- Test for Difference of Biomass Estimations ......................................................................36
- Biomass Distribution Comparison ......................................................................................41
- CCAR’s Sampling Error Protocols ....................................................................................41

**DISCUSSION** ....................................................................................................................44

**LITERATURE CITED** ..........................................................................................................50
LIST OF TABLES

CHAPTER 1

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression equation, root mean square error (RMSE) and coefficient of determination ($R^2$) for prediction total aboveground biomass of bay-laurel.............14</td>
</tr>
</tbody>
</table>

CHAPTER 2

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The species assignment of generalized biomass equations recommended by the California Climate Action Registry (CCAR) ..............................................................31</td>
</tr>
<tr>
<td>2</td>
<td>Author, geographic location, equation type and maximum diameter limit of alternate biomass equations to predict total aboveground biomass of species found at the study site.............................................................................32</td>
</tr>
<tr>
<td>3</td>
<td>Biomass predictions for each species located at the study site..............................37</td>
</tr>
<tr>
<td>4</td>
<td>Biomass per hectare, standard errors, and 90% confidence intervals for both 1) the site-specific and regional equations and 2) the generalized equations .........................40</td>
</tr>
<tr>
<td>5</td>
<td>Total aboveground biomass estimates and basal area of the study site and similar forest types.................................................................42</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

## CHAPTER 1

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Map of the distribution of bay-laurel throughout southern Oregon and California (Little 1976)</td>
</tr>
<tr>
<td>2</td>
<td>Map of the study site relative to Eureka, CA in Humboldt County. The map to the left outlines the property boundaries of the Tree Farm</td>
</tr>
<tr>
<td>3</td>
<td>The 95% confidence intervals and the 95% prediction intervals of the bay-laurel data are represented by the dotted lines and the dashed lines, respectively. The prediction values of the bay-laurel equation are represented by the solid line. The dots are bay-laurel biomass data points (n = 14)</td>
</tr>
</tbody>
</table>

## CHAPTER 2

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Map of the study site relative to Eureka, CA in Humboldt County. The map to the left outlines the property boundaries of the Tree Farm</td>
</tr>
<tr>
<td>2</td>
<td>Biomass predictions from two equations for Douglas-fir</td>
</tr>
<tr>
<td>3</td>
<td>Biomass predictions from the site-specific bay-laurel equation, the regional tanoak equation, and the generalized mixed hardwood equation</td>
</tr>
<tr>
<td>4</td>
<td>The sampling error percent at the 90% confidence intervals around the mean estimate is presented. The dotted line represents the site-specific and regional equations, the dashed line represents the generalized equations</td>
</tr>
</tbody>
</table>
LIST OF APPENDICIES

CHAPTER 1

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>21</td>
</tr>
<tr>
<td>B</td>
<td>23</td>
</tr>
</tbody>
</table>

A  Graphical representations of residual diagnostics for each equation form explored to fit the bay-laurel biomass data

B  Field and laboratory data collected to construct the bay-laurel biomass equation
CHAPTER ONE: Predicting total aboveground biomass of bay-laurel trees.

INTRODUCTION

Recently there has been increased interest in aboveground biomass quantification data and methods. Global climate change has sparked a change of forest management policies to include carbon sequestration. For example, the California Climate Action Registry was created to oversee carbon sequestration projects in forestlands. Through their protocols, diameter-based biomass equations are used to quantify the aboveground portion of biomass and carbon in live trees (California Climate Action Registry 2007). Other forest management interests in aboveground biomass accounting include fuel monitoring for fire effects. Diameter-based biomass equations can be used to quantify crown fuel weights, which can in turn help predict and manage fire behavior (Brown 1978). Further, the use of bio-energy from wood biomass has become of increased interest. Such equations can help quantify wood biomass weights for energy production (Nicholls et al. 2008).

The U.S. Forest Service recently compiled a list of all known published diameter-based biomass equations (Jenkins et al. 2004). However, for some species such as bay-laurel [Umbellularia californica (Hook. and Arn.) Nutt.] there is a lack of biomass data available. The Forest Service’s list of diameter-based biomass equations, and a search into research theses held in California universities libraries, reveals no biomass equations for bay-laurel.
Bay-laurel is abundant in southern Oregon and California (Figure 1). Forest Inventory and Analysis (FIA) reports that there are nearly 810 thousand hectares of a tanoak [Lithocarpus densiflorus (Hook. and Arn.) Rehder]/bay-laurel forest type in California (USDA Forest Service 2009). Therefore, forest managers and researchers interested in biomass would like to obtain data for the species. The objective of this study is to develop the most accurate diameter-based biomass equation specific to bay-laurel. The use of equations that lack precision and/or bias could lead to potentially inaccurate estimates of biomass. Therefore an equation with a high level of accuracy can be used to help better understand forest carbon sequestration, fire behavior, and potential bio-energy from wood biomass.
Figure 1. Map of the distribution of bay-laurel throughout southern Oregon and California (Little 1976).
METHODS

Study Site

The study site for this project is the L.W. Schatz Demonstration Tree Farm near Maple Creek, CA. The Tree Farm is 148 hectares in size and extends from 40°46’49” N to 40°45’56” N latitude and 123°52’21” W to 123°51’32” W longitude (T 5N, R 3E, Section 32) (Figure 2). The elevation of the property ranges from 140 to 430 meters.

The geology is characterized by an underlain Franciscan Formation, consisting of accreted fragments of oceanic crust and forearc sediments (Aalto and Harper 1989). The climate is characterized by hot dry summers averaging 29°C, and cool wet winters averaging 8°C. Annual precipitation, which occurs mainly as rainfall, averages roughly 120 cm, most of which occurs from December through April (Western Regional Climate Center 2009).

Historically, the Tree Farm consisted of old-growth Douglas-fir [Psuedotsuga menziesii (Mirb.) Franco] existing throughout the property, with old-growth tanoak and bay-laurel in the southeast portions. Since the early 1950’s, logging has drastically altered the forest structure and species composition (Schatz 2007, personal communication). Today, old-growth Douglas-fir stumps can be found underneath stands of fast growing tanoak and bay-laurel, which now co-dominate sections of the area with Douglas-fir. As a result, the property now consists of areas of pure Douglas-fir, pure hardwoods, and mixed stands of Douglas-fir and hardwoods. Some areas, particularly in the southeast portion of the property, still contain old-growth tanoak, bay-laurel and Douglas-fir.
Figure 2. Map of the study site relative to Eureka, CA in Humboldt County. The map to the left outlines the property boundaries of the Tree Farm.
Tree Selection

The tree selection method for destructive sampling was similar to that of Monserud and Marshall (1999). Trees that were not dying, diseased, defoliated, or seriously deformed were candidates for sampling. A total of 14 bay-laurel trees were sampled that covered a diameter range of 7.6 to 60.0 cm diameter at breast height (dbh). This diameter range encompasses 97% of the number of bay-laurel trees at the study site.

Tree Sampling

Before each tree was felled, measurements of dbh, total height, live crown ratio, and height to live crown were recorded. Destructive sampling techniques were similar to those of Snell and Little (1983), with the exception of branch sampling. Due to the highly variable branching habits of bay-laurel, branch sampling was not feasible for this study. After a tree was felled, the crown was divided into three sections, and each crown section was sampled separately in order to characterize crown properties as accurately as possible (Brown 1978). For each crown section all branches and limbs were removed from the main stem of the tree. Due to the natural forking patterns of bay-laurel trees, which can vary greatly, the main stem was defined as the portion of the fork of the stem that maintained the largest diameter on the tree. Once the branch material was removed, components for each crown section were separated. All leaves were removed and all branch material from 0 - 0.6 cm, 0.61 - 2.5 cm, 2.6 - 7.6 cm, and greater than 7.6 cm were separated and weighed fresh in the field. This was done for dead branch material as well. Sub-samples of each tree component for each crown section were taken and weighed fresh in the field to the nearest 0.1 gram.
The total weight of the main stem was determined from density and volumetric measurements. From a 2.54 cm top diameter to the base of the tree, the volume of 1.2 meter segments were calculated along the main stem. At each end of the segment, diameter outside bark and bark thickness were measured. Smalian’s formula (Avery and Burkhart 2002) was used to calculate the volume of this portion:

\[
\text{Smalian’s cubic volume (m}^3) = \frac{B + b}{2} L
\]

where \( B = \) cross-sectional area at large end of log (m\(^2\))

\( b = \) cross-sectional area at small end of log (m\(^2\))

\( L = \) log length (m)

The length of the remaining stem of 2.54 cm and less was recorded along with the diameter of the tip of the stem. A conoid formula (Avery and Burkhart 2002) was used to calculate volume of this portion:

\[
\text{Conoid: Cubic volume (m}^3) = \frac{B}{3} * L
\]

where \( B = \) cross-sectional area at base of tip (m\(^2\))

\( L = \) length of tip (m)

Three disks about three to five cm thick were cut from the lower, middle, and upper portions of the stem. Tree number 1 (dbh= 7.6 cm) was the only sample where no volumetric measurements were taken (Appendix B). For this tree the stem was weighed directly. All trees were sampled in the summer months of 2008.

**Laboratory Measurements**

The bark was removed from sample disks and the wood portion of each disk was immersed in water in order to obtain an accurate measurement of volume. The sample
disks and sub-samples of the tree components were then dried in ovens for 24 hours at 102° C (Snell and Little 1983). The oven-dry weights for each tree component were measured to the nearest 0.1 gram in order to obtain a dry weight to fresh weight ratio. The dry weight of bark and wood from the three sample disks were also recorded to the nearest 0.1 gram.

Calculations

The total dry crown weight was then calculated. Each dry weight to fresh weight ratio was multiplied by the total fresh weights of each component of each crown section and summed in order to obtain total crown dry weight.

The total main bole weight, was calculated as follows: 1) the dry weight of each sample disk of wood was divided by its corresponding volume, and then divided by the density of water (1000 kg m⁻³), providing a value for specific gravity (Simpson 1993). 2) The average specific gravity was calculated from the three disks and applied to the calculated volume of the bole in order to obtain the total dry weight. 3) The dry weight of the bark from each sample disk was measured to obtain an average dry bark weight to dry wood weight ratio. 4) The dry bark weight to dry wood weight ratio was multiplied by the total calculated dry wood weight value in order to obtain the total dry bark weight. 5) The total dry wood and dry bark weights were summed to obtain total dry bole weight. The total dry bole weight and total dry crown weight were added in order to obtain the total aboveground biomass of the tree.
Fitting Bay-laurel Biomass Data to Equations

Six models that are common to other published biomass equations were evaluated for their accuracy in predicting biomass:

\[ 1a \quad \ln bm = a + b \ln (dbh); \]

where

- \( bm \) = total aboveground biomass (kg)
- \( dbh \) = diameter at breast height (cm)
- \( \ln \) = natural log base “e” (2.718282)
- \( a, b \) = regression coefficients

With the equation form of \([1a]\), a logarithmic transformation was applied to the data so that the relationship between biomass and \( dbh \) was linear. This is a common technique that is used effectively in many other biomass studies (Brown 1978, Koerper and Richardson 1979, Snell and Little 1983, Espinosa-Bancalari and Perry 1987, Feller 1990). Once the data is linear, ordinary least squares regression equations can be fit to the data.

\[ 1b \quad \ln bm = a + b \ln (dbh) + c \ln (ht); \]

where

- \( bm \) = total aboveground biomass (kg)
- \( dbh \) = diameter at breast height (cm)
- \( ht \) = total height of tree (m)
- \( \ln \) = natural log base “e” (2.718282)
- \( a, b, c \) = regression coefficients
The equation form of [1b] uses an additional variable of total height (ht) along with dbh to estimate total aboveground biomass. This form uses multiple regression to determine if the added variable of total height significantly improves the accuracy of predicting biomass weight (kg).

Baskerville (1972) found that there may be an inherent downward bias in the biomass predictions when back-transforming the predicted values of equation forms [1a] and [1b]. In order to correct this problem, a correction factor is added to the equation. Many studies have used such a correction factor with the biomass equation forms of [1a] and [1b] (Brown 1978, Clark et al. 1986, Espinosa-Bancalari and Perry 1987). The equation forms with correction factors suggested by Baskerville (1972) for log-linear equations are:

\[
\begin{align*}
[2a] & \quad \ln \text{bm} = a + b \ln (\text{dbh}) + \text{mse}/2; \\
[2b] & \quad \ln \text{bm} = a + b \ln (\text{dbh}) + c \ln (\text{ht}) + \text{mse}/2;
\end{align*}
\]

where

\text{bm} = \text{total aboveground biomass (kg)} \\
\text{dbh} = \text{diameter at breast height (cm)} \\
\text{ht} = \text{total height of tree (m)} \\
\ln = \text{natural log base “e” (2.718282)} \\
a, b, c = \text{regression coefficients} \\
\text{mse} = \text{mean square error of a line fit by least squares regression}
Equation forms [3a] and [3b] use non-linear regression to estimate biomass that has been used in many other studies (Schmitt and Grigal 1981, Pastor et al. 1983, Barclay et al. 1985). A benefit of the use of these equation forms is that the data does not need to be transformed, thereby eliminating the need for a possible correction factor when back-transforming the data.

\[
[3a] \quad \text{bm}= a^*(\text{dbh})^b \\
[3b] \quad \text{bm}=a^*(\text{dbh})^b*(\text{ht})^c
\]

where

- \( \text{bm} \) = total aboveground biomass (kg)
- \( \text{dbh} \) = diameter at breast height (cm)
- \( \text{ht} \) = total height (m)
- \( a, b, c \) = regression coefficients

Each model was evaluated to comply with the underlying assumptions of regression by examining residuals and normal probability plots (Cook and Weisberg 1999). Models that met underlying assumptions were compared through the use of residual standard errors and coefficients of determination.
RESULTS

Bay-laurel Biomass Equation

Each model predicted reasonably similar biomass values across the entire diameter range studied. With equation [1a], standardized residuals show normality and constant variance across the diameter range, and no outliers were detected. With equation [1b], standardized residuals show normality, a constant variance when plotted against dbh and a non-constant variance when plotted against height. There were also potential height outliers. Standardized residuals of the non-linear equation [3a] show a non-constant variance and a non-normal distribution across the sample range. Standardized residuals of equation [3b] show constant variance and a non-normal distribution across the sample range. Equations [1a] and [1b] showed coefficients of determination 0.9751 and 0.9885, respectively. Equations [3a] and [3b] showed coefficients of determination of 0.9528 and 0.9927, respectively. The use of height in equation [1b] and [3b] significantly added to the accuracy of the prediction of biomass. However, the underlying assumptions of regression were not met with equation [1b] and [3b].

The use of correction factors with equation forms [2a] and [2b] only slightly increased the prediction of biomass. Other studies have revealed conflicting thoughts regarding the use of correction factors for such equations. For data sets with small sample sizes or replicated samples, there may be additional bias when applying correction factors (Koerper and Richardson 1979, Jenkins et al. 2003). Because of this
phenomenon and due to the relatively small sample size of the dataset, neither equation forms [2a] nor [2b] were chosen as the best model.

Equation form [1a] was chosen to best predict biomass for bay-laurel (Table 1). Prediction values, 95% confidence intervals about the mean and 95% prediction intervals were constructed and plotted from the bay-laurel data using equation [1a] (Figure 3). Graphical illustrations of the residual diagnostics for each equation form explored are presented in Appendix A.
Table 1. Regression equation, root mean square error (RMSE), and coefficient of determination ($R^2$) for predicting total aboveground biomass for bay-laurel.

<table>
<thead>
<tr>
<th>Equation (biomass in kg, dbh in cm)</th>
<th>dbh range</th>
<th>n</th>
<th>RMSE ln units</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>biomass = exp (-2.1001+2.3996* ln (dbh))</td>
<td>8-61 cm</td>
<td>14</td>
<td>0.2497</td>
<td>0.975</td>
</tr>
</tbody>
</table>
Figure 3. The 95% confidence intervals and the 95% prediction intervals of the bay-laurel data are represented by the dotted lines and the dashed lines, respectively. The prediction values of the bay-laurel equation are represented by the solid line. The dots are bay-laurel biomass data points (n = 14).
DISCUSSION

Although the underlying assumptions of regression were not completely met, the use of height as a secondary independent variable in equation [1b] and [3b] significantly added to the accuracy of the prediction of biomass. However, nearly 98% of the variation of biomass can be explained by dbh alone, as in equation [1a], which is why it was selected as the best model. Bunce (1968) came to similar conclusions. He found that adding height to a multiple regression routine only marginally improved the accuracy of the biomass predictions. Further, the measurement of height in the field can be difficult, time consuming and prone to error. Bay-laurel trees can exude a wide variety of branching habits, which can lead to widely different heights for similar diameter trees. Also, bay-laurel trees tend to curve downward in closed canopy stands, making an accurate height measurement extremely difficult to obtain.

Other studies involving the construction of diameter-based biomass equations used a slightly different methodology than used in this study. The destructive sampling techniques used to create this equation required a 100% sampling of the crown. Snell and Little (1983) performed similar measurements. However the total biomass of the crown was estimated by modeling branch weight on branch basal diameter. The only methodology of the current study that differed from Snell and Little (1983) was that every component of the crown was weighed. Although the methodology of the current study was time consuming to execute in the field, it may have provided a more accurate estimate of biomass for bay-laurel.
The data from this study may be used in conjunction with other studies to help better understand aboveground carbon accounting in live trees. Jenkins et al. (2003) recently published a study that produced national generalized biomass equations that could be applied to all tree species in the United States. Equations from groups of species with similar phylogenetic and taxonomical characteristics were compiled to form psuedodata that was used to create generalized equations. From these generalized equations total aboveground carbon content for all forest stands in the United States can be accounted for. Jenkins et al. (2003) suggested that the raw data from other biomass studies be published in order to help better develop generalized equations. The data from the current study may be used by other researchers to improve current generalized equations or create new ones. Therefore, data are presented in Appendix B.

The data from the current study may be used by others who are interested in increasing the diameter range and(or) the geographic range of the bay-laurel equation. Approximately 97% of the bay-laurel trees found at the study site are within the diameter range of the trees that were sampled at the site. However, the application of the equation to larger trees may introduce biased predictions. Further, there may be prediction errors associated with applying this equation to areas outside of the study site (Case and Hall 2008). A generalized regional equation could be produced for bay-laurel by using the data from this study in conjunction with data gathered elsewhere.

The data from this study is available to be used alone, or in conjunction with data from other studies for determining carbon distribution in trees, crown fire behavior, and potential bio-energy from wood chips. In addition, this data may be useful to other forest scientists for constructing generalized regional biomass equations.


Schatz, G. 2007. Personal Communication. 14345 Maple Creek Route, Korbel, CA 95550.


Appendix A. Graphical representations of residual diagnostics for each equation form explored to fit the bay-laurel biomass data.

Equation form [1a]

Equation form [1b]
Appendix A. Graphical representations of residual diagnostics for each equation form explored to fit the bay-laurel biomass data (continued).

Equation form [3a]

Equation form [3b]
Appendix B. Field and laboratory data collected to construct the bay-laurel biomass equation.

<table>
<thead>
<tr>
<th>Tree #</th>
<th>DBH (cm)</th>
<th>Leaf</th>
<th>0-0.6 cm</th>
<th>0.6-2.5 cm</th>
<th>2.5-7.6 cm</th>
<th>&gt; 7.6 cm</th>
<th>0-0.6 cm</th>
<th>0.6-2.5 cm</th>
<th>2.5-7.6 cm</th>
<th>&gt; 7.6 cm</th>
<th>Vol. (m$^3$)</th>
<th>Specific Gravity</th>
<th>Bark/Wood Wt. Ratio</th>
<th>Tree Dry Wt. (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.6</td>
<td>0.5</td>
<td>0.4</td>
<td>0.7</td>
<td>10.2</td>
<td>1.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>13.2</td>
</tr>
<tr>
<td>2</td>
<td>11.7</td>
<td>5.5</td>
<td>1.1</td>
<td>4.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0481</td>
<td>0.52</td>
<td>0.0979</td>
<td>38.5</td>
</tr>
<tr>
<td>3</td>
<td>13.2</td>
<td>1.2</td>
<td>1.3</td>
<td>1.6</td>
<td>9.2</td>
<td>24.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0623</td>
<td>0.55</td>
<td>0.0711</td>
<td>74.5</td>
</tr>
<tr>
<td>4</td>
<td>16.3</td>
<td>3.7</td>
<td>2.0</td>
<td>4.1</td>
<td>14.9</td>
<td>0.0</td>
<td>0.3</td>
<td>0.8</td>
<td>3.0</td>
<td>0.0</td>
<td>0.0850</td>
<td>0.45</td>
<td>0.0954</td>
<td>70.5</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>5.9</td>
<td>3.2</td>
<td>13.6</td>
<td>13.9</td>
<td>0.0</td>
<td>0.8</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2407</td>
<td>0.55</td>
<td>0.0594</td>
<td>178.3</td>
</tr>
<tr>
<td>6</td>
<td>23.9</td>
<td>13.2</td>
<td>10.5</td>
<td>22.2</td>
<td>30.3</td>
<td>58.0</td>
<td>0.2</td>
<td>1.9</td>
<td>4.7</td>
<td>0.0</td>
<td>0.2209</td>
<td>0.54</td>
<td>0.0818</td>
<td>269.7</td>
</tr>
<tr>
<td>7</td>
<td>26.4</td>
<td>12.7</td>
<td>6.1</td>
<td>23.5</td>
<td>39.6</td>
<td>31.7</td>
<td>0.1</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.4502</td>
<td>0.57</td>
<td>0.083</td>
<td>390</td>
</tr>
<tr>
<td>8</td>
<td>28.4</td>
<td>7.7</td>
<td>6.3</td>
<td>11.2</td>
<td>31.4</td>
<td>49.8</td>
<td>0.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.5890</td>
<td>0.6</td>
<td>0.0621</td>
<td>485.1</td>
</tr>
<tr>
<td>9</td>
<td>32</td>
<td>13.1</td>
<td>12.2</td>
<td>51.6</td>
<td>22.1</td>
<td>46.8</td>
<td>0.0</td>
<td>0.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.7646</td>
<td>0.57</td>
<td>0.0699</td>
<td>608.9</td>
</tr>
<tr>
<td>10</td>
<td>36.6</td>
<td>9.8</td>
<td>6.7</td>
<td>17.5</td>
<td>29.0</td>
<td>0.0</td>
<td>0.4</td>
<td>0.9</td>
<td>1.8</td>
<td>0.0</td>
<td>0.6456</td>
<td>0.57</td>
<td>0.0728</td>
<td>459.6</td>
</tr>
<tr>
<td>11</td>
<td>43.2</td>
<td>19.1</td>
<td>10.2</td>
<td>35.6</td>
<td>54.7</td>
<td>138.2</td>
<td>0.2</td>
<td>3.2</td>
<td>13.1</td>
<td>4.3</td>
<td>1.2006</td>
<td>0.61</td>
<td>0.0735</td>
<td>1067.9</td>
</tr>
<tr>
<td>12</td>
<td>50.3</td>
<td>43.2</td>
<td>30.7</td>
<td>50.2</td>
<td>111.4</td>
<td>371.4</td>
<td>2.0</td>
<td>2.4</td>
<td>1.8</td>
<td>0.0</td>
<td>1.2261</td>
<td>0.6</td>
<td>0.0783</td>
<td>1399.4</td>
</tr>
<tr>
<td>13</td>
<td>54.1</td>
<td>35.5</td>
<td>30.1</td>
<td>74.9</td>
<td>124.1</td>
<td>390.1</td>
<td>1.8</td>
<td>3.8</td>
<td>3.5</td>
<td>0.0</td>
<td>0.9628</td>
<td>0.62</td>
<td>0.0988</td>
<td>1323.6</td>
</tr>
<tr>
<td>14</td>
<td>61</td>
<td>79.7</td>
<td>54.1</td>
<td>141.6</td>
<td>234.6</td>
<td>200.2</td>
<td>1.6</td>
<td>1.6</td>
<td>21.0</td>
<td>0.0</td>
<td>2.9676</td>
<td>0.58</td>
<td>0.0728</td>
<td>2565</td>
</tr>
</tbody>
</table>
CHAPTER TWO: An examination of the California Climate Action Registry’s aboveground biomass accounting methods of live trees.

INTRODUCTION

In 2001 California passed legislation to help curb the increasing threat of climate change. In efforts to reduce anthropogenic greenhouse gas emissions, the California Climate Action Registry (CCAR) was created. The purpose of CCAR is to assist landowners with identifying their current greenhouse gas emissions, while at the same time helping with their greenhouse gas sequestration potential. With this in mind, CCAR created forestry protocols that outline methods to quantify carbon stocks and monitor carbon sequestration levels within forests. In September 2007, CCAR developed the Forest Project Reporting Protocol that outlines forest measurements required to obtain tree inventory data. The recommended method to quantify the carbon in live standing trees is to apply diameter-based biomass equations to tree inventory data. Such equations are used to predict the total aboveground oven-dry weight of trees. CCAR then requires biomass estimates be multiplied by 0.5 to obtain total carbon estimates.

There have been numerous studies that have developed diameter-based biomass equations. These equations have been used for many other applications such as predicting total gross primary production, crown fire behavior, logging slash residue, nutrient distribution, and quantitative ecological studies. There are three different types of biomass equations: local site-specific, regional, and generalized.

Local site-specific equations are developed for an individual species on a specific site. For example, Barclay et al. (1985) developed local site-specific equations for
Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] growing on a plantation in British Columbia. Likewise, Martin et al. (1998) developed local site-specific equations for ten deciduous southern Appalachian tree species at a site in western North Carolina. Equations such as theirs are often used at other sites of similar ecological and structural characteristics when there is a lack of site-specific equations. These equations are presumed to be the most accurate for the site on which they were built (Case and Hall 2008). However, the accuracy of the equation when applied to other sites is unknown (Case and Hall 2008).

Regional equations are commonly constructed for a species that cover numerous sites in a specified geographical region. For example, Snell and Little (1983) constructed equations for five western hardwoods on numerous sites throughout western Washington, Oregon, and northern California. These equations are constructed from data that have been pooled across numerous sites with varying characteristics. In the absence of site-specific equations, regional equations are presumed to be next best in terms of accuracy (Case and Hall 2008). However, the application of regional equations to areas outside the geographic region from which the equation was built poses potential problems.

Generalized equations are built that encompass entire growing ranges of individual species or groups of species with similar morphology and phylogenetic relationships. For example, Lambert et al. (2005) developed generalized equations for groups of species across all of Canada. Jenkins et al. (2003) developed similar equations for the United States. For example, the equation titled “mixed hardwood” was developed from 20 hardwood species throughout the eastern U.S. Generalized equations are presumed to be less accurate than regional equations (Case and Hall 2008).
With a variety of biomass equations of presumably unknown accuracies, it is desired by forest managers and researchers to know the best equation to use for a particular site, in order to obtain the best biomass estimate possible. Interesting relationships have been discovered regarding the allometric relationship of dbh and total aboveground biomass for species that grow on various sites. Studies have shown that site conditions such as stand structure, geographic location, and site productivity can alter the allometric relationship of dbh and total aboveground biomass, thus changing the biomass equation. Barclay et al. (1985) found biomass to differ between thinned and unthinned 34-year-old Douglas-fir stands in British Columbia. Feller (1990) reported that biomass for Douglas-fir was different between sites with low and high tree growth productivity, and across geographic areas. Koerper and Richardson (1979) also found that biomass of largetooth aspen \textit{(Populus grandidentata} Michx.) remained the same between sites of somewhat similar growth productivity, but then differed from sites with extremely low productivity. Gower et al. (1993) found that the influence of fertilization on ponderosa pine \textit{(Pinus ponderosa} Dougl. ex Laws) and red pine \textit{(Pinus resinosa} Ait.) stands changed the allometric relationship of dbh and foliage mass two years following treatment.

Other studies however have found that, for some species, generalized equations work well in predicting biomass. Schmitt and Grigal (1981) found that for white birch \textit{(Betula papyrifera} Marsh.), changes in the allometric relationship of dbh and total aboveground biomass are insignificant across sites in Minnesota, Wisconsin, New Hampshire, Maine and New Brunswick. Pastor et al. (1983) came to similar conclusions
for five tree species growing in northeastern United States. Singh (1986) also came to similar conclusions for eight boreal forest species.

It is interesting to note that because of these potential changes in biomass equations, estimations of carbon stocks may be affected. Upon their approval, CCAR allows use of any scientifically sound biomass equation to be applied to California tree species (California Climate Action Registry 2007). However, the 2007 Forest Project Reporting Protocol recommend that the generalized equations provided by Jenkins et al. (2003) be used for all tree species found in the forest stand of interest. The primary objective of this paper is to obtain and compare total biomass estimates of a mixed evergreen forest stand on the North Coast of California using 1) site-specific or regional biomass equations and 2) generalized biomass equations. Total carbon estimates may be affected because of potential differences of biomass predictions between site-specific, regional and generalized biomass equations.
METHODS

Study Site

The study site for this project is the L.W. Schatz Demonstration Tree Farm near Maple Creek, CA. The Tree Farm is 148 hectares in size and extends from 40°46’49” N to 40°45’56” N latitude and 123°52’21” W to 123°51’32” W longitude (Sec. 32, T 5N, R 3E, Humboldt P.M.) (Figure 1). The elevation of the property ranges from 140 to 430 meters. The geology is characterized by an underlain Franciscan Formation, consisting of accreted fragments of oceanic crust and forearc sediments (Aalto and Harper 1989). The climate is characterized by hot dry summers averaging 29°C, and cool wet winters averaging 8°C. Annual precipitation, which occurs mainly as rainfall, averages roughly 120 cm, most of which occurs from December through April (Western Regional Climate Center 2009).

Historically, the Tree Farm consisted of old-growth Douglas-fir existing throughout the property, with old-growth tanoak [Lithocarpus densiflorus (Hook. and Arn.) Rehder] and bay-laurel [Umbellularia californica (Hook. and Arn.) Nutt.] in the southeast portions. Since the early 1950’s, logging has drastically altered the landscape (Schatz 2007, personal communication). Today, old-growth Douglas-fir stumps can be found underneath stands of fast growing tanoak and bay-laurel, which now co-dominate sections of the area with Douglas-fir. As a result, the property now consists of areas of pure Douglas-fir, pure hardwoods, and mixed stands of Douglas-fir and hardwoods. Some areas, particularly in the southeast portion of the property, still contain old-growth tanoak, bay-laurel and Douglas-fir.
Figure 1. Map of the study site relative to Eureka, CA in Humboldt County. The map to the left outlines the property boundaries of the Tree Farm.
A systematic inventory, consisting of 65 0.04 hectare fixed radius plots, was conducted at the Tree Farm in 2006-2007. As in accordance with CCAR’s forestry protocols, species, height, and diameter at breast height (dbh) of all live trees at least 7.6 cm dbh were recorded.

**Generalized Biomass Equations**

The generalized biomass equations recommended by CCAR for species occurring at the study site, are presented in Table 1. Species of similar genera and growth forms are grouped together. Three equations are used multiple times for species found at the study site.

**Site-specific and Regional Biomass Equations**

The comprehensive list of all published diameter-based biomass equations provided by Jenkins et al. (2004) was the primary resource for selecting site-specific and regional biomass equations for each species found at the study site. The selection was based primarily on species, geographical proximity to the study site, and the maximum diameter limit on which the equation was built (Table 2). No site-specific or regional equations could be found for three species found in the inventory. Therefore the generalized equations were used for these species.
<table>
<thead>
<tr>
<th>Species</th>
<th>Generalized equation</th>
<th>Maximum diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Abies grandis</em> [(Douglas ex D. Don) Lindl]</td>
<td>True fir/hemlock</td>
<td>230</td>
</tr>
<tr>
<td><em>Acer macrophyllum</em> [Pursh]</td>
<td>Soft maple/birch</td>
<td>66</td>
</tr>
<tr>
<td><em>Alnus rubra</em> [Bong.]</td>
<td>Aspen/alder/cottonwood/willow</td>
<td>70</td>
</tr>
<tr>
<td><em>Arbutus menziesii</em> [Pursh]</td>
<td>Mixed hardwood</td>
<td>56</td>
</tr>
<tr>
<td><em>Lithocarpus densiflorus</em></td>
<td>Mixed hardwood</td>
<td>56</td>
</tr>
<tr>
<td><em>Psuedotsuga menziesii</em></td>
<td>Douglas-fir</td>
<td>210</td>
</tr>
<tr>
<td><em>Sequoia sempervirens</em> [((Lamb. ex D. Don) Endl.)]</td>
<td>Cedar/larch</td>
<td>250</td>
</tr>
<tr>
<td><em>Salix spp.</em> [L.]</td>
<td>Aspen/alder/cottonwood/willow</td>
<td>70</td>
</tr>
<tr>
<td><em>Tsuga heterophylla</em> [(Raf.) Sarg.]</td>
<td>True fir/hemlock</td>
<td>230</td>
</tr>
<tr>
<td><em>Umbellularia californica</em></td>
<td>Mixed hardwood</td>
<td>56</td>
</tr>
<tr>
<td>Other hardwoods</td>
<td>Mixed hardwood</td>
<td>56</td>
</tr>
</tbody>
</table>
Table 2. Author, geographic location, equation type and maximum diameter limit of alternate diameter-based biomass equations to predict total aboveground biomass of species found at the study site.

<table>
<thead>
<tr>
<th>Species</th>
<th>Author</th>
<th>Geographic Location</th>
<th>Equation Type</th>
<th>Maximum Diameter Limit (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Abies grandis</em></td>
<td>Gholz et al. 1979</td>
<td>Blue River, Oregon</td>
<td>site-specific</td>
<td>35.3</td>
</tr>
<tr>
<td><em>Acer macrophyllum</em></td>
<td>Snell and Little 1983</td>
<td>Western Washington</td>
<td>regional</td>
<td>45.7</td>
</tr>
<tr>
<td><em>Alnus rubra</em></td>
<td>Snell and Little 1983</td>
<td>Western Oregon and Washington</td>
<td>regional</td>
<td>63.5</td>
</tr>
<tr>
<td><em>Arbutus menziesii</em></td>
<td>Snell and Little 1983</td>
<td>S.W. Oregon and N.W. California</td>
<td>regional</td>
<td>63.5</td>
</tr>
<tr>
<td><em>Lithocarpus densiflorus</em></td>
<td>Snell and Little 1983</td>
<td>S.W. Oregon and N.W. California</td>
<td>regional</td>
<td>66</td>
</tr>
<tr>
<td><em>Psuedotsuga menziessii</em></td>
<td>Gholz et al. 1979</td>
<td>Pacific Northwest</td>
<td>regional</td>
<td>162</td>
</tr>
<tr>
<td><em>Sequoia sempervirens</em></td>
<td>Jenkins et al. 2003</td>
<td>Nationwide</td>
<td>generalized</td>
<td>250</td>
</tr>
<tr>
<td><em>Salix spp.</em></td>
<td>Jenkins et al. 2003</td>
<td>Nationwide</td>
<td>generalized</td>
<td>70</td>
</tr>
<tr>
<td><em>Tsuga heterophylla</em></td>
<td>Gholz et al. 1979</td>
<td>Pacific Northwest</td>
<td>regional</td>
<td>78</td>
</tr>
<tr>
<td><em>Umbellularia californica</em></td>
<td>Coltrin 2010</td>
<td>Study site</td>
<td>site-specific</td>
<td>61</td>
</tr>
<tr>
<td>Other hardwoods</td>
<td>Jenkins et al. 2003</td>
<td>Nationwide</td>
<td>generalized</td>
<td>56</td>
</tr>
</tbody>
</table>
Tree and Stand-level Biomass Estimations

The inventory was applied to both sets of equations to derive two estimates of aboveground biomass. Total metric tons per hectare (Mg ha\(^{-1}\)) were calculated for each species in order to determine the difference in biomass estimations between each set of equations. Mg ha\(^{-1}\) was also calculated for all species combined at the study site using both sets of equations. For each plot, biomass of each tree was calculated and individual tree biomass values were then summed to provide a plot-level value. The plot to plot variance and standard error of each prediction was calculated as follows (Avery and Burkhart 2002):

1] \[
\text{Variance} = \frac{\sum_{i=1}^{n}(x - \bar{x})^2}{n-1}
\]

where

\(x = \) plot biomass

\(\bar{x} = \) mean plot biomass

\(n = \) sample size

2] \[
\text{Standard error} = \sqrt{\frac{\text{variance}}{n} \times \left(\frac{N-n}{N}\right)}
\]

where

\(n = \) sample size

\(N = \) population size
Test for Difference of Biomass Estimations

Freese (1960) outlined a relatively simple and accurate method to test differences between biomass estimates. The estimate from the site-specific and regional equations is assumed to be the “standard technique” for estimating biomass, while the generalized equations are assumed to be a “new technique” for estimating biomass. With this method, accuracy of the new technique is compared with the standard technique using a chi-square test:

\[
1) \; x^2 = \frac{\sum_{i=1}^{n} (x_i - \mu_i)^2}{\sigma^2}
\]

where

- \(x^2\) = chi-square value
- \(x_i\) = the value of the \(i^{th}\) observational unit as estimated by the new technique
- \(\mu_i\) = the value of the \(i^{th}\) observational unit as estimated by the standard technique
- \(n\) = the number of units observed
- \(\sigma^2\) = level of required accuracy

CCAR’s protocols do not give any guidance regarding the level of required accuracy (\(\sigma^2\)) that would be acceptable with the use of alternative biomass equations. Hazard and Berger (1972) studied tree volume estimations using Freese’s (1960) methods. In their study, a standard of 10% was set as an index of variation between the standard technique and the new technique. Due to a potential carbon trading market with
monetary values associated with biomass estimates, a higher level of 5% was used in this study as an index of variation between each biomass estimate.

**Biomass Distribution Comparison**

Total biomass estimates of similar forest types were obtained to compare with the estimate at the study site. The Forest Inventory and Analysis database was queried to obtain average total aboveground biomass estimates of live trees for similar forest types on the North Coast of California.

**CCAR’s Sampling Error Protocols**

CCAR’s Forest Project Reporting Protocols of 2007 provide sampling error guidelines that are used to help forest managers determine the sampling intensity needed for biomass estimates. CCAR desires that the biomass estimates have a high level of statistical confidence. Therefore, they have set deductions to biomass based on size of the half width of the 90% confidence intervals relative to the mean biomass estimate. For example, if the half width confidence level about the mean is greater than 20%, then CCAR will not accept the biomass estimate. If the half width confidence interval is greater than 10%, then a biomass deduction of 20% is required. The sampling scheme in this study used 65 0.04 ha plots on a total of 148 ha to obtain a mean biomass estimate. The sampling error associated with the estimate was calculated in order to determine if the sampling intensity was sufficient for CCAR’s purposes, and to determine if biomass deductions would be warranted.
RESULTS

Tree and Stand-level Biomass Estimations

Calculations of total biomass for each species using both sets of equations are presented in Table 3. For species where a site or regional equation was found, the percentage difference of predicted biomass from the generalized equations ranged from -40.3% to 28.8%. The regional equations for Douglas-fir and tanoak predicted higher biomass than the generalized equations at a percentage difference of 4.5% and 28.8%, respectively (Table 3). The site-specific bay-laurel equation was 6.7% higher than the generalized equation. These three species combined accounted for more than 80% of the basal area at the study site. For these species, regional and site-specific equations consistently predicted higher biomass across the diameter range studied (Figures 2, 3). Regional equations for madrone and red alder predicted 7.5% and 18% higher biomass, respectively. Regional equations for bigleaf maple, grand fir, and hemlock all predicted 40.3%, 3.6% and 2.6% less biomass than the generalized equations, respectively. Total stand biomass predictions and standard errors using both sets of equations for each plot in the inventory was calculated (Table 4). Site-specific and regional equations predicted 26.4 Mg ha\(^{-1}\) more biomass than the generalized equations.

Test for Difference of Biomass Estimations

After examining the data no consistent bias was found between estimates from the new technique compared to the standard technique. The chi-square test for difference assuming no consistent bias was 1485 (df = 65), which was higher than the chi-square
Table 3. Biomass predictions for each species located at the study site.

<table>
<thead>
<tr>
<th>Species</th>
<th>Basal Area (%)</th>
<th>Site-specific and Regional Equations</th>
<th>Generalized Equations</th>
<th>Difference(^a) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abies grandis</td>
<td>7.9</td>
<td>19.4</td>
<td>20.1</td>
<td>-3.6</td>
</tr>
<tr>
<td>Acer macrophyllum</td>
<td>2.7</td>
<td>7.4</td>
<td>11.1</td>
<td>-40.3</td>
</tr>
<tr>
<td>Alnus rubra</td>
<td>7.8</td>
<td>20.5</td>
<td>17.1</td>
<td>18.0</td>
</tr>
<tr>
<td>Arbutus menziesii</td>
<td>0.3</td>
<td>0.8</td>
<td>0.7</td>
<td>7.5</td>
</tr>
<tr>
<td>Lithocarpus densiflorus</td>
<td>24.9</td>
<td>76.4</td>
<td>57.2</td>
<td>28.8</td>
</tr>
<tr>
<td>Psuedotsuga menziesii</td>
<td>36</td>
<td>114.6</td>
<td>109.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Sequoia sempervirens</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Salix spp.</td>
<td>0.3</td>
<td>0.6</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>Tsuga heterophylla</td>
<td>0.4</td>
<td>1.0</td>
<td>1.1</td>
<td>-2.6</td>
</tr>
<tr>
<td>Umbellularia californica</td>
<td>18.7</td>
<td>50.2</td>
<td>47.0</td>
<td>6.7</td>
</tr>
<tr>
<td>Other hardwoods</td>
<td>0.8</td>
<td>1.2</td>
<td>1.2</td>
<td>-</td>
</tr>
</tbody>
</table>

*Note: the same equations were used for Salix spp., Sequoia sempervirens and the ‘other hardwoods’ group.
\(a\) The percent difference of biomass is the site and regional equation estimate minus the generalized equation estimate divided by the average of the two estimates.
Figure 2. Biomass predictions from two equations for Douglas-fir.
Figure 3. Biomass predictions from the site-specific bay-laurel equation, the regional tanoak equation, and the generalized mixed hardwood equation.
Table 4. Biomass per hectare, standard errors, and 90% confidence intervals for both 1) the site-specific and regional equations and 2) the generalized equations.

<table>
<thead>
<tr>
<th></th>
<th>Site-specific and Regional Equations</th>
<th>Generalized Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Biomass</td>
<td>292.3</td>
<td>265.9</td>
</tr>
<tr>
<td>Biomass Std. Error</td>
<td>19.2</td>
<td>18.0</td>
</tr>
<tr>
<td>Lower 90% Confidence Interval</td>
<td>260.3</td>
<td>235.9</td>
</tr>
<tr>
<td>Upper 90% Confidence Interval</td>
<td>324.3</td>
<td>295.9</td>
</tr>
</tbody>
</table>
tabular value of 84.82 at the 0.95 probability level (df = 65). This suggests that the generalized equations do not meet the stated accuracy requirements of being within 5% (15 Mg ha\(^{-1}\)) of the estimate from the site-specific and regional equations, and therefore they are significantly different estimates.

**Biomass Distribution Comparison**

The stand-level biomass estimation was compared with other various forest stands (Table 5). Total biomass is similar to biomass predictions from the Forest Inventory and Analysis database for similar forest types within nearby areas.

**CCAR’s Sampling Error Protocols**

In this study, a total of 2.6 ha out of 148 ha were sampled, resulting in a half width 90% confidence intervals around the mean at 11.0% for the site-specific and regional equations, and 11.3% for the generalized equations recommended by CCAR. The sampling errors are within the required error of less than 20% as described by CCAR. However, at a sampling error of 11%, a 20% biomass deduction is required under the protocols. Under this protocol, the biomass estimate using the site-specific and regional equations would be reduced to 233.8 Mg ha\(^{-1}\) and the generalized equations to 212.7 Mg ha\(^{-1}\).
Table 5. Total aboveground biomass estimates and basal area of the study site and similar forest types.

<table>
<thead>
<tr>
<th>Forest Type</th>
<th>Location</th>
<th>Source</th>
<th>Biomass Mg ha(^{-1})</th>
<th>Basal Area m(^2) ha(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas-fir/tanoak/bay-laurel</td>
<td>North Coast Range, CA</td>
<td>Current author: Site/regional equations</td>
<td>292.3</td>
<td>40.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>National generalized equations</td>
<td>265.9</td>
<td>40.1</td>
</tr>
<tr>
<td>Douglas-fir</td>
<td>Humboldt County, CA</td>
<td>USDA Forest Service (2009)</td>
<td>288.1</td>
<td>39.0</td>
</tr>
<tr>
<td>Tanoak</td>
<td>Humboldt County, CA</td>
<td>USDA Forest Service (2009)</td>
<td>252.5</td>
<td>43.0</td>
</tr>
</tbody>
</table>
DISCUSSION

The regional and site-specific equations for Douglas-fir, tanoak, and bay-laurel all predicted higher biomass than the generalized equations. This may have been the reason why the total biomass prediction on a stand level was higher than with the equations provided by Jenkins et al. (2003). In Jenkins et al. (2003), the main factor that was taken into consideration for the grouping of species was similarities of phylogenetic relationships and taxonomical characteristics. The 20 species that were used to construct the ‘mixed hardwood’ equation were almost exclusively built from eastern United States hardwoods, and may not be similar to tanoak or bay-laurel in this sense. The regional equation for Douglas-fir was built from sites in Washington and Oregon (Gholz et al. 1979). However, the generalized Douglas-fir equation provided by Jenkins et al. (2003) was built from sites across the Pacific Northwest and the interior Rocky Mountains. Perhaps the growth characteristics between coastal and interior Douglas-fir influences the allometric relationship of dbh and aboveground biomass, and is the reason for the discrepancies of biomass estimates from each equation.

Another factor that Jenkins et al. (2003) included in grouping species together were the wood specific gravities. The ‘mixed hardwood’ group was comprised of specific gravities that ranged from 0.32 to 0.64, and averaged 0.45. In an unpublished study of bay-laurel biomass conducted at the L.W. Schatz Demonstration Tree Farm the average specific gravities ranged from 0.45 to 0.62, and averaged 0.52. The higher specific gravity in bay-laurel may be the reason why the equation predicted slightly higher biomass than the ‘mixed hardwood’ equation across the entire diameter range.
studied. The regional tanoak equation provided by Snell and Little (1983) calculated total tree biomass by using an equation for crown biomass and an equation for bole volume. Bole volume was then converted to bole weight by applying a known average specific gravity of 0.67 (U.S. Forest Products Laboratory, 1974). The high specific gravity of tanoak may be the most obvious reason why the tanoak equation predicts nearly 30% more biomass than the generalized ‘mixed hardwood’ equation (Table 3). It is interesting to see how sensitive biomass estimates can become in an individual species based on a single measurement of specific gravity, and how that can carry over to the biomass estimation of an entire stand. This reason alone may be why the biomass estimate from the site-specific and regional equations is significantly higher than the generalized equations.

Case and Hall (2008) found that for some species, increasing levels of equation generalization produced higher average prediction errors. However, they also found that for 5 out of 10 boreal species studied in west-central Canada some generalized equations produced no significant differences in biomass predictions than site-specific or regional equations. Combinations of these factors seem to be apparent in this study. National generalized equations seem to work well at predicting biomass for Douglas-fir, western hemlock, grand fir, and bay-laurel. However the generalized equations seem to poorly reflect accurate biomass predictions for tanoak, red alder and bigleaf maple when compared to regional equation predictions.

The analysis of the difference between the two biomass estimates using the chi-square test revealed a shortcoming in CCAR’s forestry protocols. As stated by Freese (1960), when determining if a new technique can be used as an accurate method to
estimate a variable in place of a standard technique, a level of desired accuracy is required. In this study, the assumption was made that the generalized equations would need to be within 5% of the biomass estimate from the site-specific and regional equations, which is roughly 15 Mg ha\(^{-1}\). There may be a monetary value associated with biomass estimates in the near future with a carbon trading market. 15 Mg ha\(^{-1}\) was suggested in this study because any amount more seemed like a reasonably substantial amount of biomass to be unaccounted for. However, this is a decision that CCAR policy makers may want to consider when accepting forestlands for carbon stock registration. It was observed in this study that the use of generalized equations did not accurately predict biomass at the study site. Given differences in the allometric relationships of dbh and aboveground biomass between species, stand structures, regions and/or sites, CCAR should adopt a policy that uses biomass equations with the least amount of generalization. By doing this, the most accurate estimates of total stand biomass can be obtained.

The sampling error with both sets of biomass estimations at the study site met the maximum 90% confidence intervals that were required by CCAR. However, a 20% deduction would be required from each biomass estimate. The number of sample plots needed at the study site in order to reduce the sampling error to 5% or less was calculated (Figure 4). For both sets of equations, nearly 300 0.04 ha sample plots would be needed for the sampling error to be at 5%, a level sufficient not to require deductions.

Other sampling schemes, such as stratified sampling, may be applicable in order to reduce the sampling error without the need for more measurements from new plots. However, interpretation from recent aerial photos of the study site and time spent in the
Figure 4. The sampling error percentage at the 90% confidence intervals around the mean estimate is presented. The dotted line represents the site-specific and regional equations, and the dashed line represents the generalized equations.
field reveals that there are no areas that could be reasonably stratified. The dominate species (Douglas-fir, tanoak, and bay-laurel) are mixed together throughout the property, providing insufficient requirements for stratified sampling. Stratified sampling would be the better alternative if there were stands of pure conifers and(or) hardwoods, which would reduce the variability of the sampling scheme and decrease the sampling error.

Another problem associated with CCAR’s biomass deduction guidelines is the cost to the landowner of increased sampling intensity. The labor costs associated with an increased sample of inventory plots may outweigh the benefit of having no biomass deductions taken from the biomass estimate. Further, the biomass deduction guidelines make quantifying heterogeneous forest stands much more expensive to sample than homogeneous stands. When given a stand with multiple species and size/age classes, the variability between plots can increase which would require the landowner to obtain more sample plots to reduce the sampling error. This may be a disadvantage to landowners and consulting foresters who are trying to maximize potential profit by registering carbon stocks with CCAR.

Policy makers for CCAR may want to consider the impact that the use of different types of biomass equation generalization may have on quantifying biomass and carbon in a forest stand. Further, protocols need to be developed that state the required accuracy of biomass predictions from using sets of biomass equations with increasing levels of equation generalization. However, CCAR may want to impose the use of equations with the least amount of generalization.

In order to obtain reasonable biomass estimates on stand levels, further biomass data needs to be collected to accommodate for a range of species, diameters, site
qualities, and stand qualities. Until a more comprehensive list of such equations are
developed, organizations such as CCAR are going to be faced with inaccurate biomass
and carbon estimates of given forest types.


Schatz, G. 2007. Personal Communication. 14345 Maple Creek Route, Korbel, CA 95550.


