EVALUATION OF TOTAL ABOVEGROUND BIOMASS AND TOTAL MERCHANTABLE BIOMASS IN MISSOURI

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Abstract.—In recent years, the state of Missouri has been converting to biomass weight rather than volume as the standard measurement of wood for buying and selling sawtimber. Therefore, there is a need to identify accurate and precise methods of estimating whole tree biomass and merchantable biomass of harvested trees as well as total standing biomass of live timber for resource assessments and silvicultural planning. In this study, we compared the traditional whole tree diameter-based biomass model currently used with alternative model forms fitted to tree data collected from four southeast Missouri species. Additionally, we reassessed each nonlinear model with total tree height and crown ratio included as covariates. Finally, we assessed the best model identified from the aforementioned analyses for estimation of merchantable biomass. Results of the analysis yielded several nonlinear models for estimating aboveground tree biomass with relatively high precision and low bias. The optimal model was chosen based upon precision and bias of estimation for all four species and was shown to produce precise estimates of merchantable biomass as well as total aboveground biomass for each species.

INTRODUCTION

The calculation of tree biomass is a fairly new concept to the forest products industry in Missouri. Traditionally, the industry has focused on volume estimation, generally in scaled board feet. In the late 2000s, a number of industry pressures pushed a change to buying and selling wood by weight. This change is common in the forest industry nationwide. Additionally there has been an interest in the estimation of carbon content of wood in standing and harvested trees. The equations generally used for biomass and carbon estimation are less precise than those used to estimate volume in Missouri forests. This disparity in precision is primarily an artifact of exclusive use of diameter at breast height (d.b.h.) as a covariate in biomass equations combined with regression coefficient estimates derived from sampled trees in other regions of the United States. The importance of biomass/weight estimation for the Missouri forest products industry highlights a need to derive more precise methods of estimating biomass for Missouri tree species.

Currently the most common method for estimating total aboveground tree biomass is the diameter-based nonlinear model provided by Jenkins et al. (2003). One advantage to this model is that it provides estimates of biomass using only one covariate (d.b.h.). This means that biomass estimates can be derived with minimal effort and cost to forest managers and loggers alike. However, the generalized nature of this method can often lead to inflated estimates and low precision of estimation for individual species. Additionally, most Missouri hardwood species utilize the same set of coefficient estimates based on the hardwood species grouping conducted by Jenkins et al. (2003), which reduces the flexibility of biomass estimation between individual hardwood species and species groups found in Missouri.

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Table 1.—Summary statistics by species for sampled trees

Species	N	d.b.h. (cm)	Total Height (m)	Merchantable Height (m)	Total Weight Green (kg)	Total Weight Dry (kg)	Merchantable Weight Green (kg)	Merchantable Weight Dry (kg)
Hickory	33	29.6	16.9	8.2	847.7	548.3	437.5	281.7
White oak	60	34.9	17.8	8.3	1271.9	809.7	630.3	400.7
Black oak	63	35.8	17.5	9.4	1249.4	743.6	771.6	457.3
Post oak	59	33.8	15.5	6.6	934.6	591.5	487.2	307.5

In this study we collected a local data set of total aboveground biomass and merchantable biomass to evaluate the published equation (Jenkins et al. 2003) commonly used to estimate biomass in Missouri. We subsequently used the same data set to refit the model and compare it to several other common model forms for estimation of aboveground tree biomass. Due to the time and expense of collecting biomass data sets, relatively few studies have been conducted that compare biomass estimation methods using covariates other than d.b.h. Therefore, we analyzed the effect of introducing height and crown ratio as additional covariates into each nonlinear model form. Finally, we refit the recommended model from the aforementioned analyses for estimation of merchantable biomass/weight using both d.b.h. and merchantable height as covariates. The last stage of the analysis was particularly important for gauging the usefulness of our recommended biomass model for the Missouri forest products industry.

METHODS

This study is part of a larger biomass harvesting project conducted at the University of Missouri in the School of Natural Resources in collaboration with the Missouri Forest Product Association and the U.S. Forest Service, State and Private Forestry. The Missouri Forest Products Association assisted in identifying a suitable site for sampling 220 trees with a diameter at breast height between 8 and 30 inches. The sample included at least 50 trees in each of four sample groups: white oak (*Quercus alba* L.), black oak (*Quercus velutina* Lam.), post oak (*Quercus stellata* Wangenh.), and hickories (*Carya* spp.). Attempts were made to sample evenly across diameter classes from the minimum tree size up to the largest tree found at the site. Table 1 lists the summary statistics of the sample trees.

Each sample tree was marked and d.b.h., total tree height, and crown ratio were measured on standing trees. Trees were then felled by a professional master logger, who cut the stump as close to the ground as could be safely accomplished. The whole tree with tops and leaves was skidded onto the road for further processing. The Missouri Forest Products Association obtained the use of a Volvo™ front-end loader with a load cell so the entire aboveground portion of the tree could be weighed at once (Fig. 1). The operator was careful to assure full suspension and minimal movement during the measurement.

After the whole tree was measured, branches and leaves were removed and the total merchantable portion of the stem was weighed. If the tree was bucked further at the logger's preference, we weighed each log as well. A disk from the bottom end of each log was removed and weighed green in the field using an electronic scale. These disks were used to obtain moisture content on the day of felling and oven-dry weight for each tree. Oven-dry weight for total biomass and merchantable biomass was estimated using the average moisture content measured from the individual disks cut from each tree. Because of logistics, only one site was sampled near Potosi, MO. Specific gravity was determined using standard methods (Bowyer et al. 2003).

Figure 1.—Front-end loader with a tree fully suspended for weighting.

ANALYSIS

The motivation for this study was to evaluate published biomass equations for use in Missouri and to then use a variety of model forms to produce equations to predict whole tree aboveground biomass and merchantable biomass for the sampled trees. To start the analysis we used the Jenkins et al. (2003) equation to predict aboveground whole tree biomass for each tree and compared it to the weight measurements in the field.

Many of the widely-used equations for aboveground biomass of U.S. trees use diameter as the sole tree measurement for estimation. Aboveground biomass equations have been developed in both linear and nonlinear forms, greatly dependent upon intended scale of use and the combination of region and tree species for which it was derived.

Common National-scale Model Form

Previous work by Jenkins et al. (2003) yielded a set of generalized allometric regression equations for estimating total tree biomass using tree inventory data for U.S. forests at the national scale. One of the most widely used aboveground woody biomass equations has the following form (Jenkins et al. 2003, Jenkins et al. 2004):

$$bm = \exp(\beta_0 + \beta_1 \ln d.b.h.)$$

where
bm = total aboveground biomass (kg) for trees 2.5 cm and larger in d.b.h.
d.b.h. = diameter at breast height (cm)
exp = exponential function
ln = natural logarithm.

The first step in our analysis was to estimate aboveground biomass separately for each of the four species using this equation. We assessed each species separately throughout the analysis in order to compare the performance of all models between species and to assess any significant changes to estimates of aboveground biomass with the inclusion of additional variables such as height and crown ratio. Because our species of interest only included hickory and oak species, the aboveground biomass equation used the same regression coefficients for all four species: β_0 = -2.0127 and β_1 = 2.4342 (from Table 4 in Jenkins et al. 2003).

Comparison with Other Common Model Forms

The first step to determining an appropriate model form for estimating aboveground biomass for southeast Missouri hardwood species was to compare the model form used by Jenkins et al. (2003) to several other common model forms within the United States. We ultimately compared six model forms using d.b.h. as a covariate. These included three nonlinear model forms in addition to Jenkins et al. (2003) and two linear model forms. Many of the alternative models did not have coefficient estimates available for the species of interest in our study. Therefore, a comparison based on existing coefficient estimates for each model was not possible. Instead, we fit each model to our collected tree data using the R statistical package (R Foundation for Statistical Computing, Vienna, Austria). For all analyses we fit the models separately for each species, thereby deriving species-specific coefficient estimates for each model. Resulting models were validated and compared using summary statistics of precision and bias as well as residual plots to identify species- and model-specific trends in estimation of aboveground tree biomass.

Influence of Height Measurements in Nonlinear Model Forms

A common characteristic of many aboveground tree biomass models is the exclusive use of d.b.h. as a covariate. Recall that the initial comparison of alternative models described in the previous section preserved this characteristic to assess the prediction capabilities of the models when fit specifically to tree measurements for the four species of interest. One of the objectives of this study was to analyze the influence of height on prediction of aboveground tree biomass when included in the models. We were particularly interested in assessing the influence of height as a multiplier for d.b.h. squared (dbh^2). Our interest in this use of height comes from the similar use of height in many traditional volume equations based on the concept of a simplified cylindrical measurement of the tree stem. One of the most common volume equations using this concept takes the following form (Hahn 1984):

$$V = \beta_0 + \beta_1 * dbh^2 * ht$$

Where
V = gross volume
ht = merchantable height (m).

We know from past studies and analyses of forest data, such as from U.S. Forest Inventory and Analysis (FIA), that aboveground forest biomass is highly correlated with aboveground volume (Chojnacky 2012, Goerndt et al. 2012). Therefore, in all cases where the original aboveground biomass model included a covariate of dbh^2, we included total tree height as a multiplier to dbh^2. Due to issues of overlapping model form between alternative models, we added height as an additional covariate for models that did not initially include dbh^2.

Effects of Crown Ratio

The primary reason for assessing the influence of crown characteristics in aboveground biomass models was to detect differences in model fit between the four species of interest. This is particularly important from a stand dynamics aspect as some hardwood species (e.g., post oak) tend to reach a height apex at a relatively young age. They can, therefore, produce trees of varying age and specific gravity with only moderate variation in both d.b.h. and height, depending upon crown closure and competition within the stand. Therefore, following the inclusion of total height into the biomass models, crown ratio was included as an additional covariate to test for significant model effects and to assess any noticeable changes in prediction of aboveground biomass between the different species. The crown ratio metric used for this study was calculated as follows:

$$CR = \frac{ht}{HCB}$$

where CR = crown ratio (%), *HCB* = height to crown base, and *ht* = total tree height (m).

Merchantable Biomass Estimation

Analyzing the influence of height in the estimation of total aboveground biomass provided valuable information as to which model form was most optimal for estimating aboveground biomass across the four species in this study. In order to expand usability of this model form to merchantable biomass, the model form was refit for each species using merchantable height and d.b.h. to estimate merchantable biomass weight. Although merchantable height can be approximated from a ground measurement on standing trees, in this analysis we calculated merchantable height as a summation of the lengths of merchantable logs cut from each tree. The observed merchantable biomass weights used to fit the models were derived from the summation of green weights of merchantable logs per tree and adjusted using the average moisture content (%) by species as with total aboveground dry biomass.

Model Validation

Each model was validated by using summary statistics that were calculated based upon the species-level validation and included relative root mean squared error (RRMSE) and relative bias (RB) calculated as follows:

$$RRMSE_s = \frac{\sqrt{\frac{1}{R}\sum_{r=1}^{R}(\hat{Y}_{iP} - \hat{Y}_{iO})^2}}{\bar{Y}_{iO}}$$

where

$RRMSE_i$ = the relative root mean squared error for species *s,*

R is the number of trees sampled for species *s*,

$\hat{Y}_{iP}$ is the predicted aboveground biomass for tree *i,* and

$\hat{Y}_{iO}$ is the observed aboveground biomass for county *i*.

Similarly, overall bias was assessed using relative bias for species *s* calculated as:

$$RB_s = \frac{1}{R}\sum_{r=1}^{R}\left(\frac{\hat{Y}_{iP} - \hat{Y}_{iO}}{\bar{Y}_{iO}}\right)$$

In addition to the aforementioned summary statistics, models were also validated and compared using residual plots. This enabled us to visually assess prediction bias and trends in prediction as observed values increased, and to see outliers which may affect model fit and coefficient estimation.

RESULTS AND DISCUSSION

Common Diameter-based Nonlinear Model Form

Recall that the coefficients applied to the common aboveground biomass model and obtained from the Jenkins paper (see Table 4 in Jenkins et al. 2003) were β_0 = -2.0127 and β_1 = 2.4342. Predicted values from this model produced RRMSE estimates of 27.9 for hickory, 37.2 for white oak, 41.2 for black oak, and 69.9 for post oak. This model also produced relative bias (RB) estimates of 1.5 for hickory, 8.9 for white oak, 25.7 for black oak, and 36.1 for post oak. The summary statistics reflected a relatively low level of precision and relatively high bias using the original model, particularly for black oak and post oak. Error associated with these estimates is better understood by observing residual plots (Fig. 2).

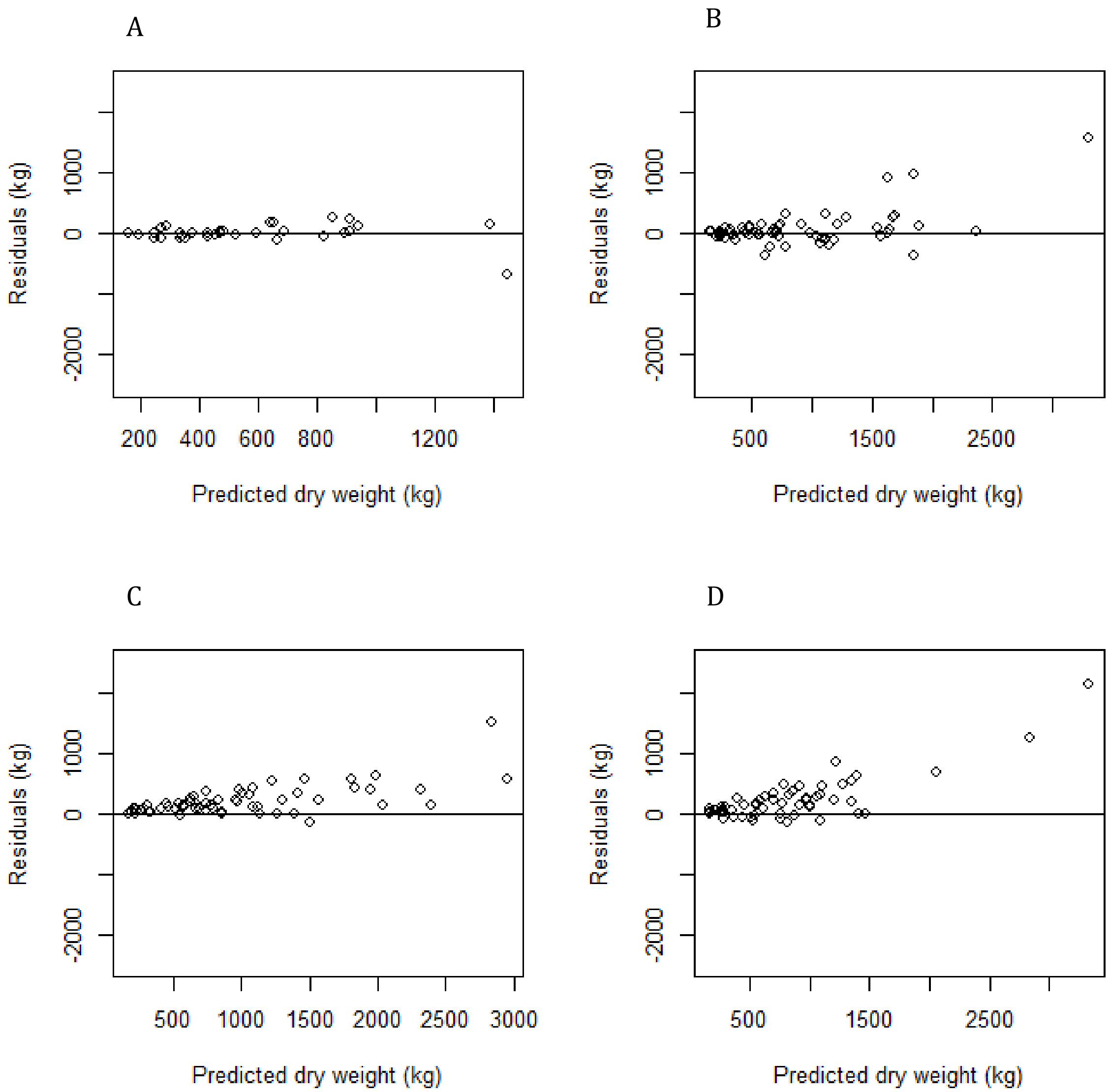

Figure 2.—Residuals of prediction of aboveground biomass by species using model form and hardwood coefficient estimates from Jenkins et al. (2003) for hickory (A), white oak (B), black oak (C), and post oak (D).

The original model for hardwoods from Jenkins et al. (2003) has a tendency to overestimate aboveground biomass for the four species of interest. This effect was least noticeable for hickory, which does not show obvious overestimation until about the 75th quartile of predicted biomass values. For black oak and post oak, overestimation begins at very low predicted values and increases as the predicted value increases. In addition to a lack of sensitivity to the individual hardwood species, another probable reason for this tendency is variation in the range of tree sizes observed in our data compared to that of the data used to develop the model. The data used to develop the model relied heavily upon measurements from eastern forests which, due to climate and soil conditions, tend to have greater height growth relative to d.b.h. compared to many hardwood species in Missouri. This possibility corresponds well to the results obtained from fitting the model to our data, as an assumption of greater height relative to d.b.h. would lead to compounded overestimation as predicted values increase. This assessment of the original diameter model reinforced the need to refit the model to our measurement data and to compare the results to several other forms of the model.

Comparison with Other Common Diameter-based Model Forms

The models chosen for comparison to the original diameter-based model from Jenkins et al. (2003) represent model forms developed in several regions of the United States and Canada (Jenkins et al. 2004). Each model form uses some derivation of d.b.h. as its only covariate. Unlike the model from Jenkins et al. (2003), it was not possible to assess many of the alternative models using predetermined coefficients due to a lack of available coefficient estimates for the species of interest in this study. Therefore, this analysis focused on a refitting of the Jenkins et al. (2003) model (hereafter referred to as Model A) to our data for each of the four species and comparing it to several alternative model forms also fitted to our data. In all, we compared predictions from four nonlinear models and two linear models. Table 2 shows the coefficient estimates for each model form (hereafter referred to as Model A through Model F) fitted to our tree data by species.

Note that the model form was maintained for each fitted model, regardless of whether or not all coefficients were statistically significant. Most of the coefficient estimates lacking significance were intercepts, which is understandable due to the logic of aboveground biomass passing through the origin with respect to d.b.h. Model E had the greatest number of nonsignificant coefficients. Calculation of variance inflation factors (VIF) for Model E indicated high multicollinearity for the coefficients associated with d.b.h. and $(d.b.h.)^2$. This likely influenced the significance of coefficients for this model because multicollinearity can make estimates of coefficient standard error inaccurate, though it has no effect on the prediction capabilities of the model. Table 3 shows the summary statistics for precision and bias for each model by species.

Fitting Model A to our data drastically improved the precision and bias of prediction compared to the original coefficient estimates from Jenkins et al. (2003). Additionally, Models A, B, and D produce estimates that are very similar, to the point that RRMSE and RB are nearly indistinguishable between these models. Model C, which uses coefficients for both d.b.h. and $(d.b.h.)^2$, consistently outperforms the other models with regard to precision, though it does not do quite as well in terms of bias. However, with the maximum difference between estimates being about 4 percent for RRMSE and about 2 percent for RB, the models are fairly comparable. Although summary statistics indicate the general performance of the models, analysis of residuals is much more revealing of the key differences in prediction between the models. For illustration of residual plots, we chose to focus on hickory, as it was the species with the greatest variation in precision and bias (Fig. 3).

Table 2.—Coefficient estimates for alternative diameter-based aboveground tree biomass models fitted to the tree data for our four species of interest

Model	Model form	Hickory			White oak			Black oak			Post oak		
		β_0	β_1	β_2	β_0	β_1	β_2	β_0	β_1	β_2	β_0	β_1	β_2
	Nonlinear												
A	$bm = \exp(\beta_0 + \beta_1 * \ln(dbh))$	-3.39	2.82		-0.09*	1.89		-1.67	2.28		0.33*	1.71	
B	$bm = \exp(\ln(\beta_0) + \beta_1 * \ln(dbh))$	0.02*	3.01		0.91	1.89		0.14	2.36		1.38	1.71	
C	$bm = \exp(\beta_0 + \beta_1 * dbh + \beta_2 * \ln(dbh^2))$	5.79	0.11	-0.46*	-7.76	-0.07	2.35	-7.1	-0.04	2.12	-7.54	-0.07	2.29
D	$bm = \exp(\beta_0 + \beta_1 * \ln(dbh^2))$	-3.39	1.41		-0.09*	0.95		-1.66	1.14		0.33*	0.86	
	Linear												
E	$bm = \beta_0 + \beta_1 * dbh + \beta_2 * dbh^2$	1222.41	-91.69	2.21	-772.56	43.76	0.04*	-74.91*	-2.64*	0.66	-661.76	40.76	-0.09*
F	$bm = \beta_0 + \beta_1 * dbh^2$	-166.85	0.76		-3.78*	0.61		-121.89	0.62		58.61*	0.43	

Values marked with * are not statistically significant.
Equations from Goldsmith and Hocker 1978; Goltz et al. 1979; Hahn 1984; Jenkins et al. 2003; Jenkins et al. 2004; Raile, 1981; Ruark and Bockheim 1988.

Table 3.—Summary statistics for all diameter-based models by species

	Hickory			White oak			Black oak			Post oak		
Model	N	RRMSE	RB	N	RRMSE	RB	N	RRMSE	RB	N	RRMSE	RB
A	33	26.82	-2.11	60	28.72	1.44	63	24.23	0.72	59	32.61	1.57
B	33	26.82	-2.11	60	28.72	1.44	63	24.23	0.72	59	32.61	1.57
C	33	24.11	-4.56	60	26.49	-0.45	63	23.77	-2.81	59	30.01	-0.57
D	33	26.82	-2.11	60	28.72	1.44	63	24.23	0.71	59	32.61	1.57
E	33	26.34	-4.32	60	27.48	<0.01	63	24.14	-2.13	59	30.97	<0.01
F	33	29.61	-3.91	60	28.87	<0.01	63	24.12	-2.14	59	33.49	<0.01

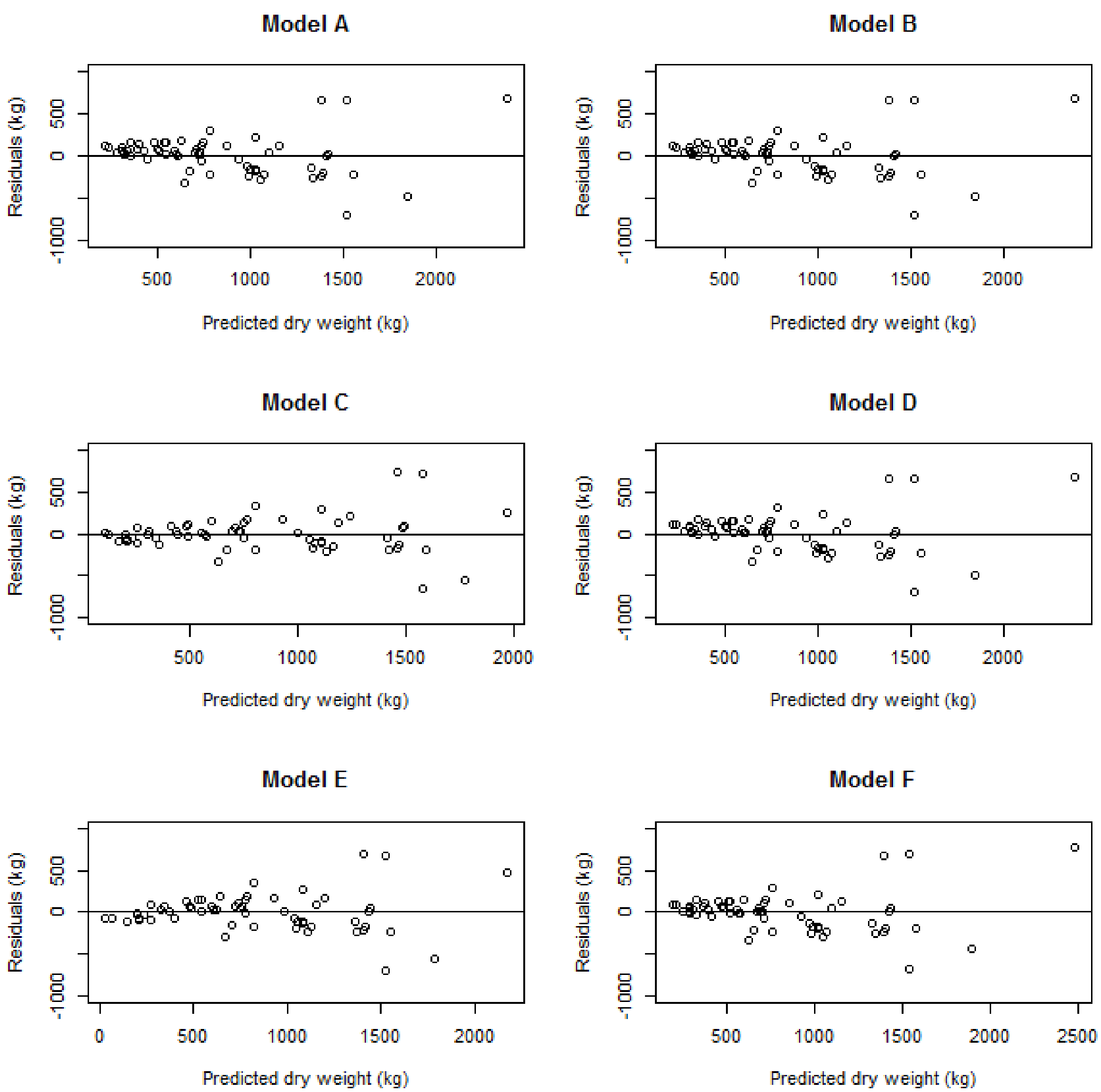

Figure 3.—Residuals of prediction of aboveground biomass for hickory using diameter-based model forms listed in Table 2.

There is a tendency for most models to overestimate for low predicted values; however, Model E appears to actually underestimate instead. Model C was the only model that did not appear to overestimate or underestimate for low predicted values. Additionally, Model C stood out from the other models in that it produced a more even distribution of predicted values, as well as a tighter arrangement of residuals compared to many of the other models. The linear models (Models E and F) tended to have the widest arrangement of residuals with regard to relatively extreme values.

Although the linear models performed reasonably well with regard to prediction of aboveground biomass using d.b.h., we opted to drop these models for the remainder of the analysis. Linear models can be unreliable when predicting values for trees that are beyond the size range of the trees originally used when creating the models because forest attributes, such as volume and aboveground biomass, are often inherently nonlinear in nature (hence the prevalence of nonlinear models in the literature). Nonlinearity can cause transformed linear models such as Models E and F to lose precision and accuracy when covariate values are not represented by the range of values in the data set used to develop the model. Nonlinear models are often more robust to extrapolation of this kind, in part due to the greater ability of nonlinear regression to produce reliable estimates of coefficients with relatively small data sets.

Influence of Height in Nonlinear Models

As previously stated, there were two general strategies regarding inclusion of total height into the nonlinear models for aboveground biomass. The first strategy applies to Models A and B in which height (ht) is added into the model as a separate covariate. The second strategy applies to Models C and D and consists of including height as a multiplier to $(\text{d.b.h.})^2$. Recall that this strategy stems from a desire to mimic the use of height in traditional volume equations under the assumption that the volume and aboveground woody biomass are highly correlated. Table 4 shows the coefficient estimates for each nonlinear model form utilizing total tree height.

As with the original diameter-based models, the most common coefficient to show nonsignificance was the intercept. However, with black oak several models had nonsignificant coefficients. For Models A and B, the coefficient for height was not statistically significant for black oak, indicating that height was not very influential for these model forms. We postulate that low variation in the black oak sample could be a likely cause for this. Simply put, the black oak sample used for the study displayed lower variation of height relative to diameter than some of the other species, in which case height as a separate coefficient would not provide much additional information regarding aboveground woody biomass after accounting for d.b.h. A similar effect existed in the post oak sample, which ultimately influenced the results of the models when crown ratio was included as a covariate, as will be shown in the next section. Table 5 shows the summary statistics for precision and bias for each model by species.

The nonlinear models that included height generally yielded greater precision for most species when compared to the diameter-based models. Even though Models A and B showed nonsignificance for the height coefficient in the case of black oak, there was still a slight improvement in precision. The change in relative bias between the diameter-based models and models including height was somewhat more sporadic. Notably, the RB for all models except Model C showed an increase in relative bias for hickory. This was in contrast to the general tendency of the models to produce

Table 4.—Coefficient estimates for alternative nonlinear aboveground tree biomass models fitted to the tree data for our four species of interest using both d.b.h. and height

		Hickory			White Oak			Black Oak			Post Oak		
Model	Model Form	β_0	β_1	β_2	β_0	β_1	β_2	β_0	β_1	β_2	β_0	β_1	β_2
	Nonlinear												
A	$bm = \exp(\beta_0 + \beta_1 * \ln(dbh) + \beta_2 * \ln(ht))$	-5.19	2.65	0.82	-3.03	1.72	1.21	-2.17	2.14	0.35*	-1.15*	1.46	0.86
B	$bm = \exp(\ln(\beta_0) + \beta_1 * \ln(dbh) + \beta_2 * \ln(ht))$	0.01*	2.66	0.82	0.05*	1.72	1.21	0.11	2.14	0.35*	0.32*	1.46	0.86
C	$bm = \exp(\beta_0 + \beta_1 * dbh + \beta_2 * \ln(dbh^2 * ht))$	-1.18*	0.04	0.63	-4.75	-0.02	1.19	-1.04*	0.02*	0.71	-5.96	-0.03	1.38
D	$bm = \exp(\beta_0 + \beta_1 * \ln(dbh^2 * ht))$	-5.65	1.23		-2.46	0.91		-2.82	0.93		-0.98*	0.75	

Values marked with * are not statistically significant.

Table 5.—Summary statistics for all diameter and height models by species

	Hickory			White oak			Black oak			Post oak		
Model	N	RRMSE[a]	RB[b]	N	RRMSE	RB	N	RRMSE	RB	N	RRMSE	RB
A	33	23.06	-3.31	60	22.16	0.09	63	23.78	0.64	59	30.84	1.84
B	33	23.06	-3.31	60	22.16	0.09	63	24.78	0.64	59	30.84	1.84
C	33	21.25	-2.41	60	21.85	-0.27	63	24.7	0.93	59	29.08	0.88
D	33	24.23	-3.52	60	22.65	0.34	63	24.99	0.54	59	30.87	1.84

[a] RRMSE=relative root mean squared error.
[b] RB=relative bias.

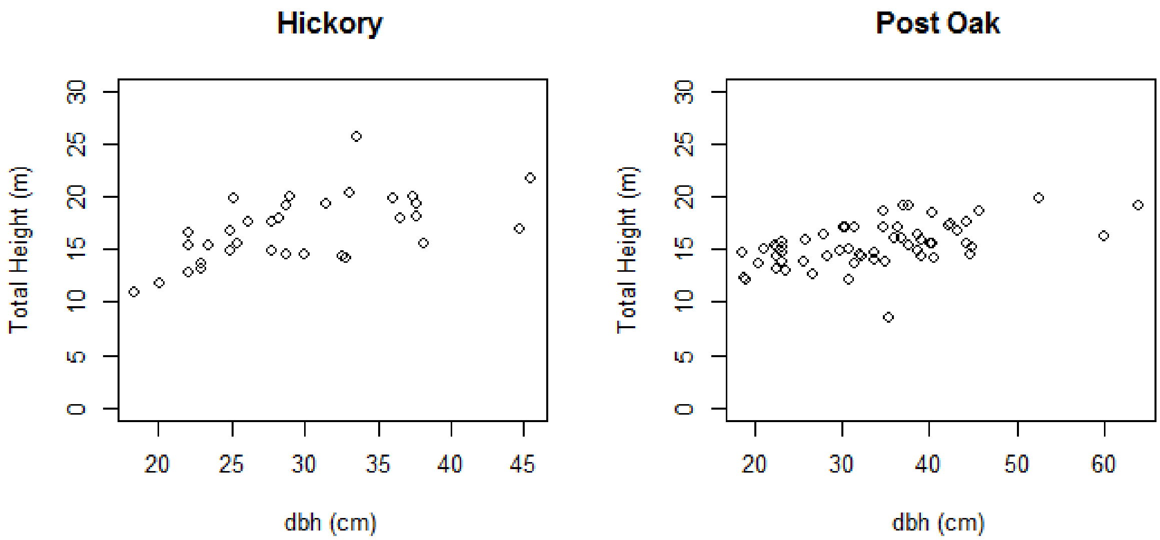

Figure 4.—Scatterplots of total height versus d.b.h. for hickory and post oak based on the sample data for this study.

lower RB for most species in the study. The primary reason for an increase in RB pertained to the relationship between height and d.b.h. in the sample for hickory used in this study. To illustrate how the relationship between d.b.h. and height can vary among species, Figure 4 shows scatterplots of total height to d.b.h. for hickory and post oak.

Hickory displays much greater variability with regard to the correlation between total height and d.b.h. The correlation between d.b.h. and height for post oak is quite linear and shows very little variation from low to high observed d.b.h. In contrast, for hickory height increases very quickly at low d.b.h. values but then plateaus at d.b.h. values greater than 25 cm. This particular trend in height versus d.b.h. for hickory likely contributed to the increased RB observed in Table 4, which is an artefact of including height as a covariate in the models. Note, however, that the inclusion of height had very little negative effect on the RB of Model C, which when combined with the superior performance of this model form for diameter-based estimation of aboveground biomass creates a strong argument for the use of Model C as a preferred model form for selected Missouri hardwood species.

Influence of Crown Ratio in Nonlinear Models

Including crown ratio as a covariate generally resulted in most nonlinear model forms performing poorly when estimating aboveground woody biomass. The only exception was with the estimation of aboveground biomass for black oak and post oak. For black oak, crown ratio was only significant in Model C. For post oak, crown ratio was statistically significant in each of the nonlinear model forms. To explain this occurrence, we must once again refer to the differences in growth patterns between the different species.

Recall from Figure 3 that post oak had a very small slope for the linear relationship between total height and d.b.h. This was most likely an artifact of the tendencies of post oak to reach a height and d.b.h. apex at a fairly young age. In short, the range of ages for the post oak trees sampled in this study had much greater variability than the d.b.h. and height ranges would indicate, creating a situation where trees of similar volume have very different biomass weights due to higher specific gravity for older trees. One variable that can help to explain differences between older and younger trees of similar size is crown ratio, due to the occurrence of relatively smaller crowns for older trees

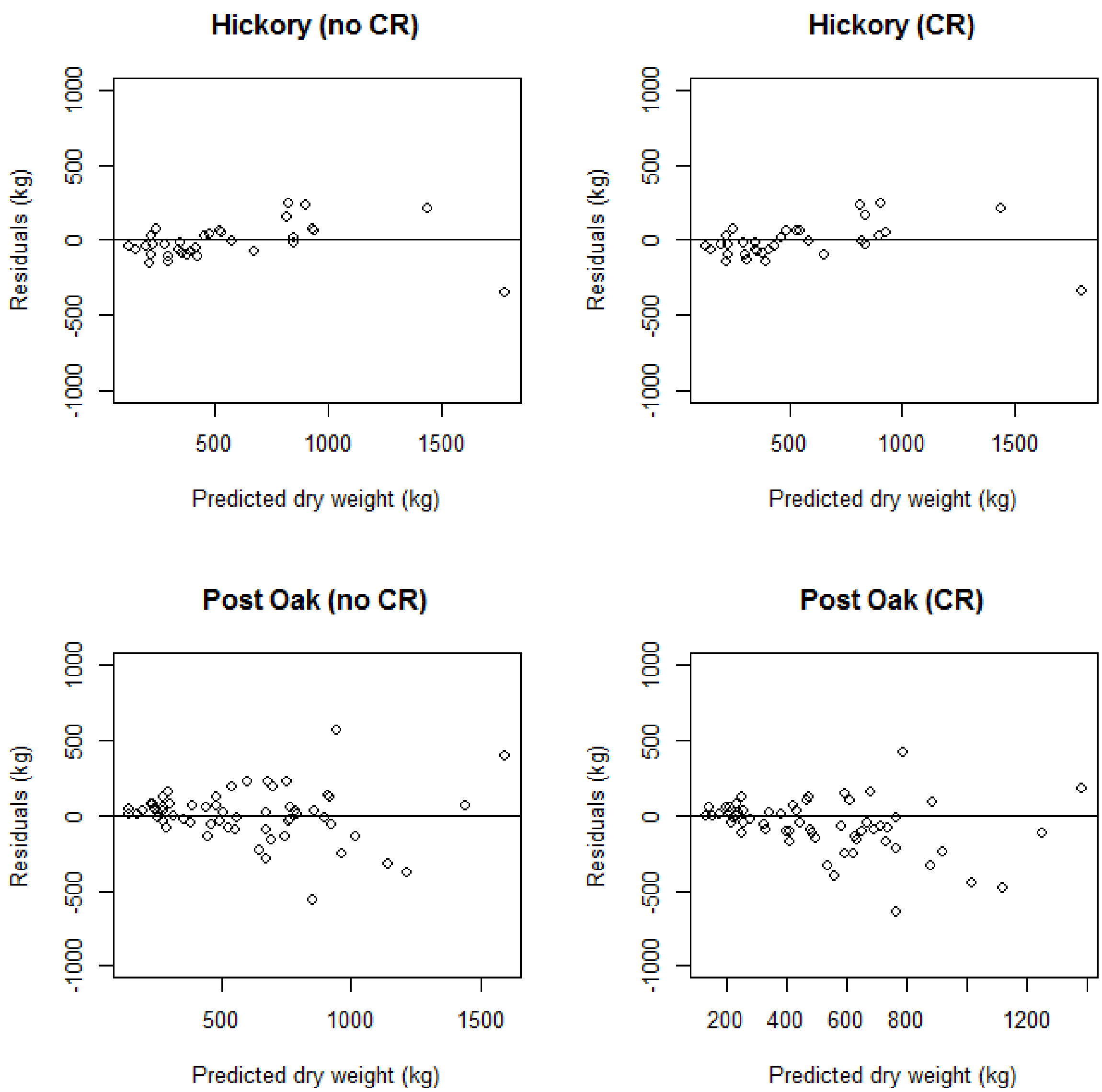

Figure 5.—Residual plots of estimates for aboveground biomass for hickory and post oak using Model C with and without crown ratio (CR) as a covariate.

that have spent much of their lifespan in closed canopy conditions. To visualize the effect of crown ratio on estimation of aboveground biomass for post oak, it is useful to compare residuals between post oak and one of the species that did not have crown ratio as a significant variable. Figure 5 shows residual plots for Model C with and without crown ratio as a covariate for hickory and post oak.

The difference between the residual plots with and without the inclusion of CR was quite subtle but revealed the variation in how CR influenced estimation of aboveground biomass between the two species. Most importantly, notice that the inclusion of CR in Model C for post oak slightly reduced bias at low predicted values. Additionally, it reduced some of the more extreme residuals for high predicted values observed from the model excluding CR. This demonstrated that CR is statistically significant for post oak primarily because it provided information that is useful in estimating aboveground biomass for trees that are at either the low end or the high end of the range of d.b.h. and heights for the sample of that species. This compliments the argument that a full understanding of aboveground woody biomass weight for post oak could go beyond a simple measure of volume based on d.b.h. and height alone.

Best Overall Model for Estimating Aboveground Biomass for Selected Species

We showed that the diameter-based model form by Jenkins et al. (2003) can produce fairly precise and accurate estimates of aboveground woody biomass for selected hardwood species if fit specifically to tree data from those species. However, we also showed that other common model forms may perform even better if fit using the same data. The model form that consistently performed the best overall with regard to precision and bias was Model C. This model consistently outperformed all other models with regard to precision whether using only d.b.h. as a covariate or incorporating height as a multiplier to $(d.b.h.)^2$. While this model did not always produce the lowest bias, it produced RB values well within acceptable tolerances and was the only nonlinear model that showed a decrease rather than an increase in RB with the inclusion of height as a covariate. Although all nonlinear models performed fairly well based on our tree data, Model C would be the recommended model form to use for these four species whether using only d.b.h. or d.b.h. and height combined.

Application of Optimal Model for Merchantable Biomass

The analyses indicated that of all the model forms assessed in this study, the Model C form was optimal with regard to both precision and bias. Therefore, it was logical to assess this model form for estimation of merchantable woody biomass. Note that CR was omitted from this particular analysis as CR had minimal effect on estimation of total aboveground woody biomass, and models for estimating merchantable biomass should be tailored to use measurements that can be taken by loggers on merchantable logs obtained from felled trees. Recall that for this version of Model C, total tree height was replaced by merchantable height measured as a sum of merchantable log lengths cut from each tree. Table 6 shows the coefficient estimates and summary statistics for the final model of merchantable biomass by species.

White oak showed the poorest fit for the merchantable biomass model as indicated by the low statistical significance of the coefficient for d.b.h. as well as higher RRMSE and RB than any other species. For the other species, the merchantable biomass model actually yielded considerably lower RRMSE and RB than the total aboveground biomass counterpart models using the Model C form. This was not entirely surprising given that a biomass estimate based solely upon merchantable stem should have high correlation with the traditional height x $d.b.h.^2$ method of volume estimation without additional variation caused by inclusion of tops, branches, and leaves. The under performance of the model for white oak compared to the other species was most likely caused by

Table 6.—Coefficient estimates and summary statistics for the final model of merchantable biomass by species

	Coefficient estimates			Summary statistics		
Species	β_0	β_1	β_2	N	RRMSE[a]	RB[b]
Hickory	-0.49*[c]	0.023	0.61	33	12.49	0.21
White oak	-0.66*	0.001*	0.71	60	22.95	1.42
Black oak	0.53*	0.019	0.51	63	16.15	1.27
Post oak	-1.85	0.007	0.82	59	15.67	0.17

[a] RRMSE=relative root mean squared error.
[b] RB= relative bias.
[c] Values marked with * are not statistically significant.

inconsistencies in taper of the merchantable stems. This was most apparent in the contrast with post oak, which typically has very little taper by comparison. This study has shown that traditional nonlinear models forms can be applied to major Missouri hardwood species to derive relatively precise and accurate estimates of both total aboveground biomass and merchantable biomass. For estimated model coefficients for predicting merchantable biomass in oven-dry pounds using d.b.h. measured in inches and merchantable height measured in feet, please refer to the Appendix.

CONCLUSION

The goal of this study was to compare the traditional model for estimating aboveground woody biomass with estimates derived from the same model form refit to tree data taken in an intensive inventory for southeast Missouri. Additionally, it was our objective to compare estimates from the refit standard model to other model forms fit to the same tree data for estimating both total aboveground biomass and merchantable biomass.

Comparisons of summary statistics and residuals from both nonlinear and linear diameter-based models indicated that refitting traditional model forms to data collected from Missouri hardwood species improved upon precision and accuracy of estimates from the original model of Jenkins et al. (2003). The inclusion of height into the nonlinear model forms generally resulted in somewhat higher precision of estimation for total aboveground biomass, though bias increased slightly for some species. Increase in bias was mainly an issue for hickory, most likely due to particular trends in d.b.h. vs. height for this species group. The only species that benefited from the inclusion of CR with regard to estimation of biomass was post oak.

Although the refitting of the Model A form showed considerable improvement over the coefficient estimates provided by Jenkins et al. (2003), the analysis indicated that the Model C form performed the best overall for all species with the inclusion of height as a covariate. The resulting models for merchantable biomass showed considerable improvement in both precision and bias when compared to the counterpart models for total aboveground biomass for most species. This study has shown that many traditional nonlinear tree biomass equations can be used to obtain precise and accurate estimates of both total aboveground biomass and merchantable biomass when fit specifically to Missouri hardwood species. Additionally, the resulting models from this study provide practical tools for the forest products industry of Missouri to efficiently estimate harvested biomass prior to sale at a precision similar to volume estimation.

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APPENDIX

Coefficient estimates for the final model of merchantable biomass in ovendry pounds by species using d.b.h. in inches and merchantable height in feet

Species	Coefficient estimates		
	β_0	β_1	β_2
Hickory	0.70177	0.05791	0.60755
White oak	0.61557	0.00373	0.71159
Black oak	1.67079	0.04796	0.51286
Post oak	-0.50714	0.01655	0.81549

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