PREDICTING THE COVER-UP OF DEAD BRANCHES USING A SIMPLE SINGLE REGRESSOR EQUATION

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Abstract—Information on the effects of branch diameter on branch occlusion is necessary for building models capable of forecasting the effect of management decisions on tree or log grade. We investigated the relationship between branch size and subsequent branch occlusion through diameter growth with special attention toward the development of a simple single regressor equation for use in future hardwood stem quality models. Data were obtained from 21 boards representing 3 logs of the first 21 feet of one cherrybark oak originating from a planted stand north of Vicksburg, MS. Double cross-validation methods were used to evaluate fitted models. A non-linear model form ($Y = a^{*}BK_{max}^{\ b}$, where Y = overwood, BK_{max} = maximum branch-knot diameter and a and b are parameters) provided the best fit. The model explained approximately 50 percent of the variation in overwood.

INTRODUCTION

Silviculturists have long realized the importance of tree or log grade. However, the implications of silvicultural activities on stem structure have been largely overlooked. This is particularly the case of recent large-scale replanting efforts in the Lower Mississippi Alluvial Valley (King and Keeland 1999, Twedt and Wilson 2002), where many monospecific plantations lacking natural analogs are being created. Unlike some softwood products, grade production in hardwood trees is a more important factor in valuation than volume because of the great differential between the highest and lowest grades of lumber or veneer products produced. For example, the price differential between red oak FAS and 1F alone and FAS and 2A alone was 219 percent and 264 percent in March of 2005, respectively (Hardwood Market Report, 3/05/05). Therefore, understanding the impacts of silvicultural activities on the production of hardwood tree grade is critical.

Experimental methods of acquiring causal information regarding the impacts of management activities on tree structure are needed, and in some cases are underway (Clatterbuck and others 1987, Oliver and others 1990). Complementary techniques that can expedite acquisition of needed information are necessary. Stem analysis techniques combined with modeling methods can improve our understanding in the interim, and help guide current and future land management decisions.

As gross crown dimensions are proportional to and determinants of tree growth (Assman 1970, Rennolls 1994), the number and size of branches within the crown are major determinants of stem structure and, therefore, wood quality. Wood quality is heavily affected by the development of first-order branches within the crown, particularly the self-pruning and subsequent occlusion of branches as crown recession occurs (Makinen 1998, Makinen and Colin 1998, Makinen and Makela 2003). Thus, a logical first step is to evaluate the effects of variable branch sizes on the stem diameter needed for branch occlusion.

Information on the effects of branch diameter on branch occlusion is necessary for building models capable of forecasting the effect of management decisions on tree or log grade. However, little is known regarding the relationship between branch size and the occlusion of that branch through diameter growth following crown recession. The knowledge gap is particularly large for hardwoods, including highly valuable species such as cherrybark oak (*Quercus pagoda* Raf.). Models combining growth and development of stem structure, including internal characteristics, are in development (Maguire and others

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1994, Makela and Makinen 2003). However, researchers have focused primarily on conifer species [e.g. Norway spruce (*Picea abies* (L.) Karst), Scots pine (*P. sylvestris* L.) and Loblolly pine (*P. taeda* L.)].

The primary objective of this research was to quantify the relationship between branch size and subsequent branch occlusion through diameter growth. Special attention was paid to the development of a simple single regressor equation for use in future hardwood stem quality models.

METHODS

Data

Data were obtained from 21 boards representing 3 logs of the first 21 feet of one cherrybark oak. The tree originated from a stand of planted cherrybark oak on land owned by Anderson-Tully Company, north of Vicksburg, MS (322553N, 0904306W). The tree was blown over in a local windstorm event in 2002, but the bole remained intact. Tree diameter at breast height (dbh) was 41 cm and total height was 31 m at age 36 years. Three logs, representing the merchantable portion of the tree were removed for sawing.

Each log end was divided into quarters and marked for reassembly following sawing. All boards were flat sawn in the field using a Wood-Mizer (Wood-Mizer Products Inc., Indianapolis, IN) portable band saw with a 2mm kerf. The first cut for each log followed the log pith. Boards were carried to the laboratory and the logs were reassembled. Distance from the pith to each board face was recorded. Mean sawn board thickness was 2.82 cm with a range of 2.3 to 4.6 cm.

Branch-knots were numbered and mapped along 3 axes according to board-face location, height from base of tree, and distance from the centerline of each board (board centerline corresponded to initial quarter lines drawn for reassembly). In addition, branch-knot diameter was recorded at each location. Branch-knots retained a unique identifier among sequential boards to chart the development of each branch. For each branch, maximum diameter and stem radius at the point where a branch no longer appeared (hereafter referred to as overwood) were calculated for development of simple predictive equations.

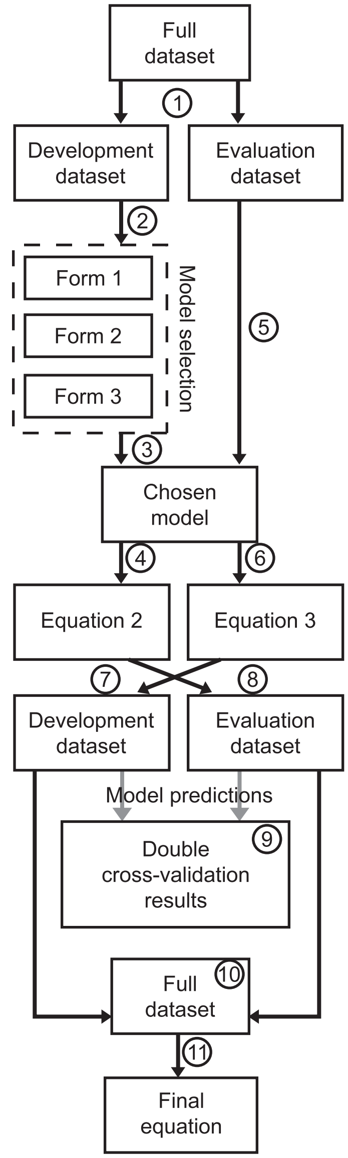

Figure 1—Flowchart illustration of model development and evaluation.

Model Building and Evaluation

Branch-knot mapping produced a total of 287 points and 105 unique branches for the 21-foot length. Only branches that could be followed from inception at the pith were used for model-building and model evaluation (n = 66). Figure 1 illustrates the analysis procedure. Data were randomly split into two datasets. One dataset was used for model fitting and parameterization (hereafter known as the development dataset). A holdout dataset was used for model evaluation (hereafter known as the evaluation dataset). Observed data in the development dataset were fitted to each model form (table 1) using the PROC REG and PROC NLIN procedures (SAS Institute Inc. 1989). Ordinary least-squares were utilized for parameter estimation. Mean square error (MSE), error sum of squares (SSE), coefficient of determination (R2) and the PRESS statistic were used to evaluate the appropriateness of each fitted model and choose the “best” performer.

Table 1—Summary statistics for each fitted model of branch-knot diameter and overwood

Statistic	Model form: $Y = Y_0 + aX$	$Y = a\ (1\text{-}e^{-bX})$	$Y = aX^b$
R	0.61	0.63	0.68
R^2	0.37	0.39	0.46
a	0.12	9.5	3.49
SE{*a*}	0.03	0.87	0.65
b		0.17	0.29
SE{*b*}		0.05	0.06
Y_0	5.16		
SE{Y_0}	0.66		
MSE	7.54	7.33	6.48
SSE	233.6	227.28	200.95
PRESS	269.54	254.22	219.84
SEE	2.75	2.71	2.55

Note: Empty cells are a result of incomplete alignment of parameter labels.

Three biologically reasonable candidate model forms consisting of one regressor, maximum branch-knot diameter achieved (BK_{max}) were proposed:

Model Form (1) $Y = Y_o + a^* BK_{\max}$

Model Form (2) $Y = a\left(1 - e^{-b * BK\max}\right)$

Model Form (3) $Y = a^* BK_{\max}{}^{b}$

where

Y = overwood
Y_0, a, and b are parameters

The predictive capability of the chosen model was evaluated. The developed model was used to predict each case in the evaluation dataset and the mean squared prediction error (MSPR) (Neter and others 1996) was calculated with:

$$\text{MSPR} = \frac{\sum_{i=1}^{n}\left(Yi - \hat{Y}i\right)^2}{n} \tag{1}$$

where

Yi = the value of the response variable in the ith validation case
$\hat{Y}i$ = the predicted value for the ith validation case based on the development dataset
n = the number of cases in the evaluation dataset

Comparison of the MSPR with MSE of the model fit with the development dataset can be used as indication of the predictive ability of the model. The mean ($\bar{e}$) of the prediction errors for all cases of the evaluation dataset was computed as an estimate of model prediction bias (Zhang 1997). In addition, the model was quantitatively tested by a double cross-validation procedure (Neter and others 1996, Zhang 1997). Following the evaluation of the initial model, the evaluation dataset was used to reparameterize the model. The reparameterized model was used to predict each case from the development dataset and the same metrics were calculated and compared. Cross-validation is considered an effective method for model evaluation and obtaining nearly unbiased estimators of prediction error (Neter and others 1996, Zhang 1997). Final estimation of model parameters were derived from the full (n = 66) dataset (Neter and others 1996).

RESULTS

Model Selection

No significant evidence was observed for problems of unequal error variances. Residual analysis resulted in no significant trends in the plots of residuals against the predictions. Therefore the assumptions of least-squares were satisfied.

The linear model $Y = Y_o + a^* BK_{\max}$ and non-linear models $Y = a\left(1 - e^{-b*BK\max}\right)$ and $Y = a^* BK_{\max}{}^{b}$ were fitted to the development dataset. Regression analyses revealed that the model $Y = a^* BK_{\max}{}^{b}$ fit the development dataset best (table 1). The linear model $Y = Y_o + a^* BK_{\max}$ was the poorest fit. The correlation coefficient and coefficient of determination was highest for $Y = a^* BK_{\max}{}^{b}$ and the MSE, SSE and PRESS statistic were lowest (table 1). The standard error of the estimate was also smaller for the $Y = a^* BK_{\max}{}^{b}$ model (table 1). The model chosen was $Y = a^* BK_{\max}{}^{b}$.

Model Evaluation

Examination of the residuals from the regression solution of the chosen model revealed no heteroscedasticity. All parameter estimates were statistically significant at $\alpha = 0.05$. The fitted model resulted in the following equation:

$$\text{Overwood} = 3.49 ^* \; BK_{\max}{}^{0.29} \tag{2}$$

The SSE for the model fitted with the development dataset was 200.95 (table 2). The PRESS statistic (219.84) was reasonably close to the SSE and supports the validity of the fitted regression model and of MSE as an indicator of the predictive capability of this model (Neter and others 1996). The initial fitted model resulted in a significant moderate relationship with only moderate predictive power (R = 0.68, $R^2 = 0.46$, P < 0.001) (fig. 2A).

Using equation (2), each case in the evaluation dataset was used to predict overwood (fig. 2B). Calculated mean prediction error was -0.36 cm and MSPR was 4.85 (table 2). MSPR of the evaluation dataset was comparable with MSE of the development dataset suggesting that MSE based on the development dataset is a valid indicator of the predictive capability of the model.

Reparameterization of the model using the evaluation dataset resulted in the following equation:

$$\text{Overwood} = 2.83 ^* \; BK_{\max}{}^{0.35} \tag{3}$$

The SSE and PRESS statistic were 152.96 and 167.94, respectively (table 2). Similar to the model fitted to the development dataset, the model fitted to the evaluation dataset ([equation (3)] indicated a significant moderate relationship with moderate predictive power (R = 0.74, $R^2 = 0.54$, P < 0.001) (fig. 3A). However, the model fit was slightly improved over the model fit to the development dataset. Using equation (3), each case in the development dataset was used to predict overwood (fig. 3B). Calculated mean prediction error was 0.33 cm and MSPR was 6.32 (table 2).

Parameterization of the model using the full dataset resulted in the final equation:

$$\text{Overwood} = 3.17 ^* \; BK_{\max}{}^{0.32} \tag{4}$$

The final model was similar to the previous model fits and indicated a significant relationship with moderate predictive power (R = 0.70, $R^2 = 0.50$, P < 0.001) (table 2, fig. 4).

Table 2—Double cross-validation summary for the fitted nonlinear model form $Y = aX^b$ for branch-knot diameter and overwood

Statistic	Model-building dataset	Validation dataset	Full dataset
a	3.49	2.83	3.17
SE{*a*}	0.65	0.53	0.42
b	0.29	0.35	0.32
SE{*b*}	0.06	0.06	0.04
SSE	200.95	152.96	357.59
PRESS	219.84	167.94	374.18
MSE	6.48	4.93	5.59
MSPR	6.32	4.85	
R^2	0.46	0.54	0.5
R	0.68	0.74	0.7
SEE	2.55	2.22	2.36
$\bar{e}$	0.33	-0.36	

Note: Empty cells are a result of not calculating some metrics for the full dataset.

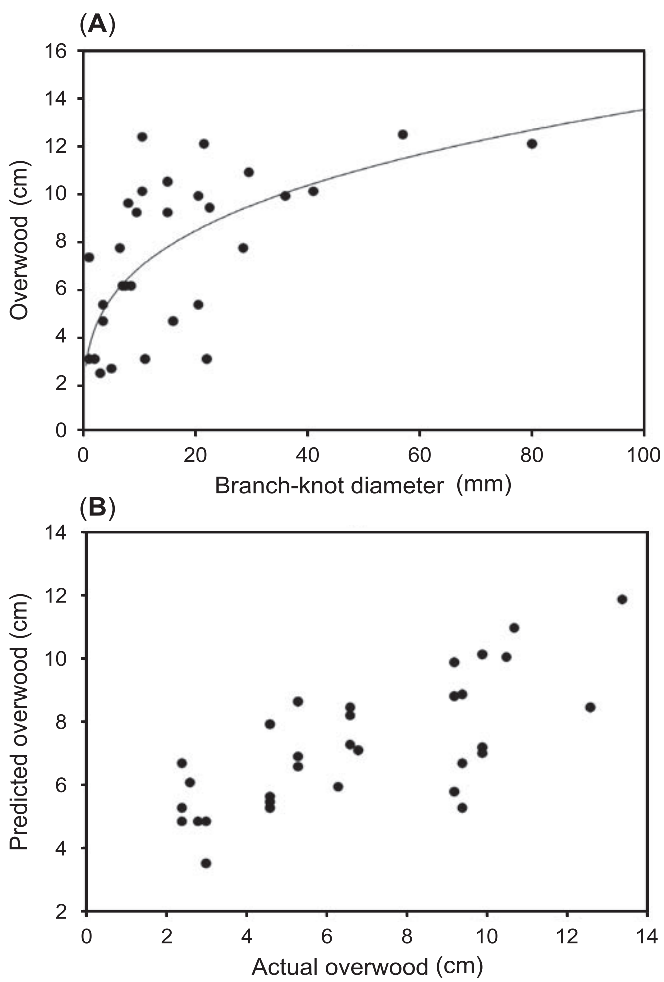

Figure 2—Branch-knot diameter and overwood with nonlinear model fitted to the model-building dataset (A) and actual by predicted overwood (B) using validation dataset for cherrybark oak planted in Vicksburg, MS.

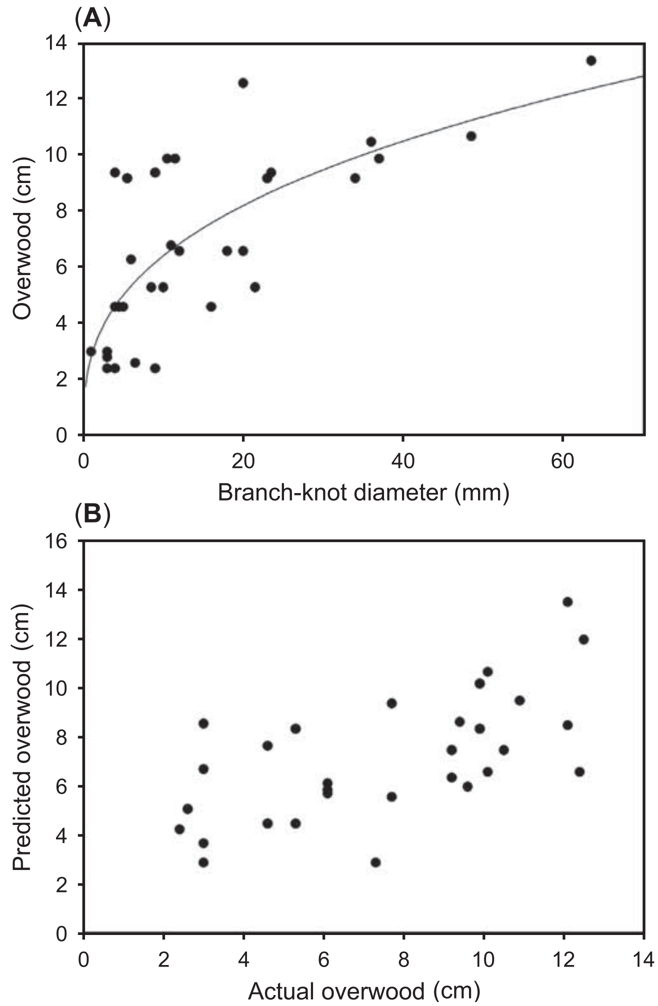

Figure 3—Branch-knot diameter and overwood with nonlinear model fitted to the validation dataset (A) and actual by predicted overwood (B) using model-building dataset for cherrybark oak planted in Vicksburg, MS.

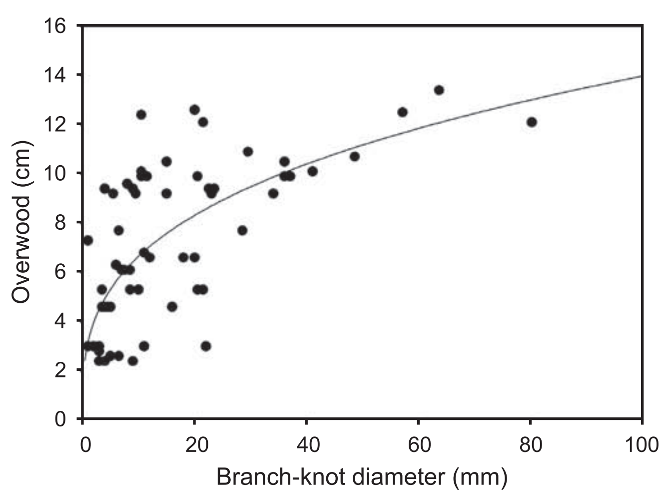

Figure 4—Branch-knot diameter and overwood with nonlinear model fitted to the full dataset for cherrybark oak planted in Vicksburg, MS.

DISCUSSION AND CONCLUSION

The model presented in this study will be used in the development of future models for forecasting stem quality in hardwoods as a result of silvicultural decisions. Although the predictive power is intermediate, this equation, to the authors' knowledge, represents the first attempt of its kind to quantify the relationship between branch size and branch occlusion in cherrybark oak. As a result, limited information exists regarding insights into the relation of branch size to overwood.

The final equation explained only 50 percent of the variation in the full dataset. A share of the unexplained variation may be explained by the constraints of the data collection methodology. The methodology involves very low longitudinal resolution (2.3 to 4.6 cm). That is, branch-knot observations were only available on cut board faces. As a result, accurate measures were unavailable for some branches. For example, a branch may have been completely occluded 0.5 cm within a 4 cm board. The recorded measure of occlusion would include the actual 0.5 cm and the error of the additional 3.5 cm of the cut board. The use of computer tomography (CT), such as that used by Moberg (2001), may be the only method capable of reducing this type of error. However, such equipment is often not available. Additionally, the resolution obtained through CT-scan image analysis makes it difficult to capture accurate small branch-knot observations (Gronlund 1995, Oja 1999).

Some of the unexplained variation in the model may be due to differences in the length of the residual dead branch following breakage from the stem. One key assumption in this model is that pruning of dead branches happens in a static manner. This assumption may or may not be valid. However, incorporation of variables to describe or predict the variation in branch breakage or length of branch stub is quite complex. This complexity was not considered when the model was developed and evaluated.

By removing the temporal aspect from the dataset and not attempting to predict occlusion rates, the developed model should have application outside of the tree in which the data was collected. Furthermore, by focusing on a linear measure of wood required to completely occlude a given branch, the effect of site, crown position and growth rate should be removed. However, as the dataset only consisted of occluded branches from within one tree, further tests are required to evaluate model predictions from a completely independent dataset. In addition, model performance should also be evaluated when incorporating data from different sites and stem development histories.

The results from this study represent one planted tree. Relationships may vary between plantation and natural stand development. Variable stand density may also impact this relationship. As such, additional datasets are desired for future analyses and to further test this quantification of the relationship between branch size and branch occlusion.

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