# A TECHNIQUE FOR PREDICTING CLEAR-WOOD PRODUCTION IN HARDWOOD STEMS: A MODEL FOR EVALUATING HARDWOOD PLANTATION DEVELOPMENT AND MANAGEMENT

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**Abstract.**—The management of artificial hardwood stands suffers from a paucity of information. As a result, many managers and scientists turn to conventional pine plantation management as a source for informing silvicultural decisions. Such an approach when managing hardwoods ignores the development occurring in natural hardwood stands, which produce stems prized for their growth and form. Contrary to a volumetric focus, stem quality is extremely important in the valuation of hardwood stands. The monetary value of a stand is directly related to the quality of individual stems within that stand. Growing a hardwood bole that is clear of branches, knots, and defects, or growing "clear wood," can significantly increase the return on a hardwood plantation investment. We investigated an approach to forecast the impact of hardwood plantation establishment and management decisions on the production of "clear wood." A model was developed that predicts, through a series of simultaneous equations, the growth and development of first-order branches and subsequent branch occlusion. Our investigation focused on cherrybark oak (*Quercus pagoda*), an economically valuable southern bottomland species. The resultant model provides the user with output regarding stem quality. Users then can evaluate the impact of decisions such as initial spacing, species composition, and plantation arrangement on hardwood log quality. This approach may be expanded to other economically important species. Therefore, we briefly discuss the data requirements for expanding this approach to other species or species groups. In addition, we explore some of the possible uses for this tool in future research and management planning.

## INTRODUCTION

Multiple challenges continue to plague silviculturists' attempts to naturally regenerate and promote the development of high-quality hardwoods such as oak (*Quercus* spp.) (Loftis and McGee 1993, Oswalt and others 2006). Many landowners and foresters turn to artificial regeneration techniques to satisfy oak establishment objectives and to meet demand for hardwood forest products; accordingly, hardwood plantings apparently have increased. In addition, governmental cost-share programs such as the Wetland Reserve Program and the Conservation Reserve Program are contributing to the increase in hardwood planting and hardwood plantation establishment (King and Keeland 1999, Devall and others 2001, Gardiner and others 2004). Consequently, increasing attention and efforts are being directed toward the development of prescriptions for artificially regenerated hardwood stands (Lockhart and others 2006).

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Artificial hardwood stand management suffers from a lack of credible scientific information. The myriad of different species with different site requirements and growth habits makes establishing and managing hardwood plantations more complex than with single-species pine (*Pinus* spp.) plantations. The importance of stem quality introduces an additional complicating variable. Numerous forest growth and yield models have been developed for modeling pure and mixed stands (Peng 2000, Porté and Bartelink 2002). Generally, the focus of these models is volumetric in nature; that is, they forecast tree or stand level metrics such as volume/unit-area, diameter distributions, stem density/unit-area, or basal area/unit-area, metrics from which individual stem quality cannot be quantified. Few models have focused on forecasting measures of stem quality. Simple linear (Ernst and Marquis 1979, Myers and others 1986) and nonlinear regression (Dale and Brisbin 1985) and discriminant function (Lyon and Reed 1987, Belli and others 1993) equations have been used to predict tree or log grades and/or to predict tree/log grade distributions. None of the solutions has been ideal due to the focus on subjective discrete classification variables. In addition, these models often assume no change in stem defect over time; they assume only changes in log or tree diameter. As a result, these models are limited in usefulness.

To develop a model without the constraints of traditional log/tree grading systems, we investigated an approach to forecast the impact of hardwood plantation establishment and management decisions on the production of "clear wood." Through a series of simultaneous equations, our model predicts the growth and development of first-order branches and subsequent branch occlusion. Our investigation focused on cherrybark oak (*Quercus pagoda* Raf.), an economically valuable southern bottomland hardwood. In contrast to most stand and individual tree scale models, the resultant model provides the user with output regarding stem quality. The development of a model to predict specific tree or log grades was not the objective of this work. Rather, the purpose was to produce a model that can be used as a decision support tool. Model-users have the capability to evaluate the impact of decisions such as initial spacing, species composition, and plantation arrangement on hardwood log quality.

## MODELING APPROACH

The primary objective of this work is to develop a model that can be used to evaluate the impacts of various silvicultural decisions on the development of stem quality. The overall problem has been dissected into three issues: 1) predicting the amount of overwood that is necessary for dead branch occlusion through subsequent diameter growth; 2) predicting branch population dynamics within the live crown; and 3) incorporating 1 and 2 into a model for evaluating the effects of various silvicultural decisions on the development of clear wood. Initially, the effort is to predict either a positive or negative impact on clear-wood production through altering stand level parameters impacted by different management decisions.

The intention of the modeling activity is to develop a model of the crown system dynamics of bottomland oaks that, when incorporated within an individual tree growth model, can be used to predict branch and knot characteristics with enough accuracy to evaluate potential tree or log quality. Additionally, we attempt to develop the model in such a way that will allow relatively easy interaction between land managers and the model while allowing a certain degree of flexibility that allows land managers to adapt the model to local conditions.

Several key points in the objectives statement warrant elaboration. First, *crown system dynamics* refers to the birth, growth, development, and death of first-order branches that make up the living crown of the modeled tree. The model, therefore, tracks the conception of first-order branches within the crown, subsequent branch growth and branch death as crown rise occurs due to competition. Crown characteristics, such as crown surface area, crown volume, crown diameter, and crown shape are calculated and used as metrics to compare model results with other modeling efforts and empirical data.

Second, bottomland oaks refers to species from the genus *Quercus*, in particular cherrybark oak. This modeling activity is in pursuit of a mixed-species model that can accommodate natural stands. Yet, it is important to note that the immediate objective is to develop a model that will accurately reflect the stem-quality development of monospecific plantations and planted two-species mixtures. Upon satisfactory development of such a model, the additional information needed to model the spatial and competitive variation found in natural stands will be incorporated.

*Easy* interaction is imperative to allow natural resource managers with very little or no modeling experience access to the predictive powers of the developed model. It is extremely important that resource managers be able to use the model as a tool for an additional level of sophistication in their planning process, Finally, the ability for the model to be *adapted* to reflect local conditions, through the use of local knowledge of site indices, is essential.

## BRANCH OCCLUSION MODEL

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).

A logical first step is to evaluate the effects of variable branch sizes on the stem diameter needed for branch occlusion through diameter growth following crown recession, but little is known regarding this relationship. The knowledge gap is particularly large for hardwoods, including highly valuable species like cherrybark oak. Models combining growth and development of stem structure, including internal characteristics, are in development (Maguire and others 1994, Makela and Makinen 2003). However, researchers have focused primarily on conifer species (e.g., Norway spruce [*Picea abies* (L.) Karst], Scots pine [*Pinus sylvestris* L.], and loblolly pine [*Pinus taeda* L.]).

Data were obtained by mapping branch-knots from 21 boards strategically sawn from three logs of one cherrybark oak. 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 2-mm 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 three 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 were used for development of a simple predictive equation.

## CROWN ALLOMETRY MODEL

An understanding of the growth dynamics of individual first-order branches within the developing crown is integral to forecasting stem quality. Similar to the capacity to forecast branch occlusion, it is essential to have the capability of predicting not only the number of branches, but also the spatial distribution and size of branches within the live crown. It is particularly important to be able to describe the population of branches at the base of the live crown. Branches at the base of the live crown are commonly the largest branches within the crown and therefore have the greatest potential for impacting future stem quality (Oswalt and others 2006).

The goal for the crown allometry model was to produce a series of equations in which the dynamics of first-order branches within the active crown, with special focus on the branch population at the base of the live crown, could be predicted. Predictor variables of interest were gross crown metrics that could be derived from either individual tree models or common inventory data. Predictor variables were crown width (CW), crown length (CL) (referred to as "crown depth" in the case of branches not at crown base), and the base of the live crown (CB).

Data for developing equations to describe the allometry of cherrybark oak crowns were obtained from 50 trees located in four separate stands across Tennessee. Three stands were located on the Natchez Trace State Forest (NTSF) in western Tennessee (latitude: 35.781° N; longitude: 88.360° W) and one stand was located on privately owned land in Dixon Springs, TN (latitude: 36.358° N; longitude: 86.050° W). Diameter at breast height (d.b.h.) varied from 8 to 51 cm. Height varied from 6 to 30 m and stand age varied from 14 to 50 years. Before felling, total height, d.b.h., and crown metrics were collected for each tree. Crown metrics consisted of crown length (height to base of live crown subtracted from total tree height), multiple crown radii (n = 5 to 18), and height to the widest part of the live crown. All first-order branches on each felled tree were mapped according to insertion height, departure angle, and departure quadrant. Departure quadrant, which corresponded to a four-quadrant polar coordinate grid, was derived from the quadrant in which the majority of the branch was located. In addition, branch basal diameter and branch length were recorded for each branch. Mean crown width was calculated from crown radii observations. A system of equations was developed that allowed prediction of individual branch metrics.

## SYLVAN FRAMEWORK

In the late 1980s an approach to modeling forest growth, based on the three-dimensional crown characteristics of trees and stand dynamics principals to predict tree growth and development, was developed by Larsen (1991a, 1991b, 1994). This approach produced the Sylvan Stand Structure Model. Offering great flexibility, this model is dependent on individual tree distance and was designed to derive model parameters from the stand in question. The Sylvan model has successfully been applied to a wide variety of species and used to predict the development of Douglas-fir/western hemlock (*Pseudotsuga menziesii*/*Tsuga heterophylla* [Raf.] Sarg.) in the Pacific Northwest, cherrybark oak/sycamore (*Quercus* spp./*Platanus occidentalis* L.) in Arkansas, European beech (*Fagus sylvatica* L.) and Austrian pine (*Pinus nigra* Arnold) in Italy, Scots pine in Finland and upland hardwoods in Missouri (D.R. Larsen, personal communication). The Sylvan model was chosen because it offers the needed flexibility to develop site-specific and species-specific coefficients, forecasts growth of real stands, produces realistic interspecific and intraspecifc crown interaction, is largely influenced by crown size, is based on accepted stand dynamics theory, and tracks crown recession over time.

## COMPLETE MODEL

The design of the branch occlusion and crown allometry sub-models is such that the branch occlusion sub-model requires inputs from both a forest growth model and the crown allometry sub-model and the crown allometry sub-model requires inputs from a forest growth model. In combination, the forest growth model and crown allometry and branch occlusion sub-models constitute the complete wood quality model. The completed wood quality model is a set of simultaneous equations that draw inputs from the model user and the Sylvan individual tree model (Fig. 1). User inputs include a local dataset for developing customized growth model parameters for the Sylvan tree model. Second, model users define the initial plantation design by specifying species, spacing, and arrangement. In addition, users can export treelists from Sylvan at any point during the management timeline to utilize programs such as the U.S. Forest Service's Stand Visualization System (SVS) platform, which allows the user to define intermediate treatments such as thinnings. The SVS-altered treelist can be imported back into Sylvan and simulation continued.

Preliminary output from the wood quality model consists of both standard stand-level and standard tree-level metrics along with measures of knotty-wood and clear-wood production. Knotty-wood and clear-wood production can be expressed both at the stand and individual tree scale.

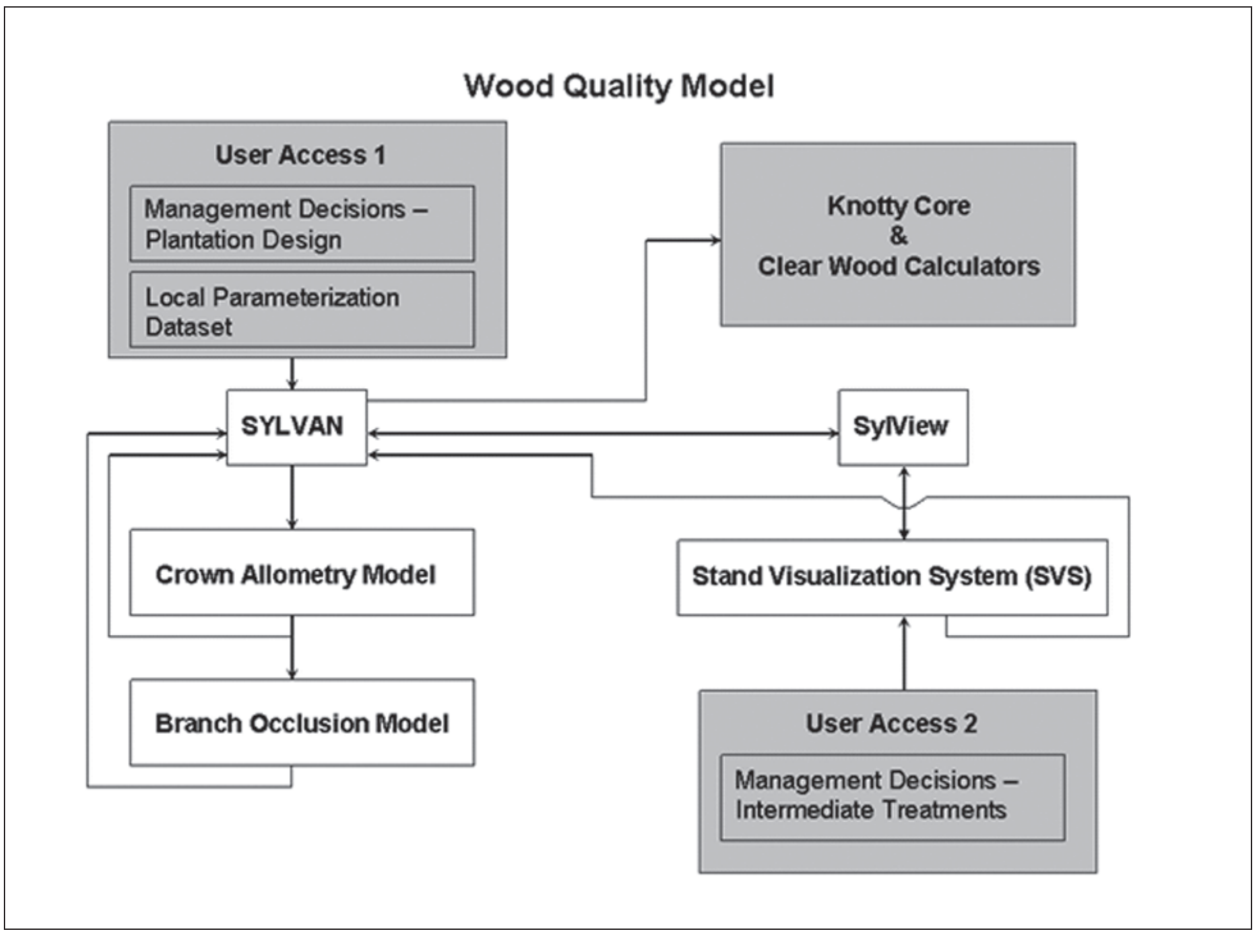


Figure 1.—Conceptual diagram of the crown allometry, branch occlusion and Sylvan models along with the knotty core and clear wood calculators, the SylView and SVS GUI's and user access points, which constitute the overall wood quality model.

The complete model is an empirical approach. Though the model may be more limited in its applicability than a mechanistic approach, empirical models generally produce more accurate predictions (Porte and Bartelink 2002). Additionally, the ability to parameterize the Sylvan model with localized tree datasets allows for increased applicability across sites. However, the branch occlusion and crown allometry equations are also empirically derived, so they would need to be re-parameterized for new species and species mixtures. Unlike for the Sylvan model, simple routines have not yet been developed for the re-parameterization of the branch occlusion and crown allometry equations with localized datasets.

## OUTCOMES AND APPLICATIONS

### RESEARCH

We are currently interested in aiding the design of plantation trials, such as identifying the most promising type of spacing and species combinations to investigate. In addition, comparisons can be made among management scenarios to fine-tune hardwood plantation management investigations. Furthermore, the wood quality model can be used to explore the relative importance of various processes, such as canopy stratification, in producing clear-wood; eventually researchers may be able to outline some general theories of how hardwood plantations develop.

### HARDWOOD PLANTATION MANAGEMENT

Following completed evaluation of the wood quality model and packaging within a user-friendly graphical user interface (GUI), forest land owners and land managers will have a decision support tool that can help guide evaluations of potential hardwood plantation management approaches. Landowners and land managers will be able to effectively compare management scenarios with regards to impacts on clear-wood production (analogous to tree grade). Information about tree quality has been missing from hardwood simulation models; the wood quality model will equip decisionmakers with a key variable for assessing potential stand value.

## CONCLUSION

The use of forested ecosystems as sinks for global carbon has gained considerable attention. Concomitantly, the reestablishment of bottomland hardwoods across the South is a priority for many organizations. As a result, reforestation and afforestation projects have increased considerably. Additionally, many landowners are interested in investing in hardwood plantations. Missing from current decision support tools is the ability to predict the quality of wood produced through the management of hardwood plantations and the impact of management decisions on individual tree quality. The hardwood quality model described in this study incorporates the much needed level of sophistication that will enable landowners and land managers to make sound decisions regarding hardwood plantations. The wood quality model can also be used by research scientists to develop sound hardwood plantation management strategies that include spacing and species assemblage recommendations.

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