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I am submitting herewith a dissertation written by Christopher Michael Oswalt entitled "Development of a Simulation System for Testing Hardwood Plantation Silviculture." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Natural Resources.

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DEVELOPMENT OF A SIMULATION SYSTEM FOR TESTING HARDWOOD PLANTATION SILVICULTURE

A Dissertation
Presented for the
Doctor of Philosophy
Degree
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Christopher Michael Oswalt
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DEDICATION

This dissertation is dedicated to my wife Sonja N. Oswalt, parents, J.Elmer and Deborah T. Oswalt, and mother-in-law Betty R. Weeks for always believing in me, inspiring me, and encouraging me to reach higher in order to achieve my goals.

This dissertation is also dedicated to the memory of Billy W. Weeks, a father-in-law, friend, spiritual guide and mentor that will be extremely missed until we meet again. Thank you for your support, love, advice and encouragement.

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ABSTRACT

Hardwood plantations are becoming increasingly important in the United States. To date, many foresters have relied on a conifer plantation model as the basis of establishing and managing hardwood plantations. The monospecific approach suggested by the conifer plantation model does not appear to provide for the development of quality hardwood logs similar to those found in natural hardwood stands. Thus, there is interest in creating mixed species plantations to simulate natural hardwood stand development.

A simulation system, CherrybarkSQ, was developed to provide a platform for investigating the impacts of mixed species management of hardwood plantations on the stem quality of cherrybark oak (*Quercus pagoda*). Stem wood quality was defined by the proportion of clear wood (without knots) grown over a knotty core expressed by a Clear Wood Index (CWI) value. The construction of CherrybarkSQ consisted of developing models for predicting first-order branch characteristics and the occlusion of first-order branches for a distance-dependent individual tree model. CherrybarkSQ tracks the production of the knotty-core and clear wood over time through relationships developed between crown length and branch diameter and branch diameter and the overwood needed to occlude the branches.

CherrybarkSQ was used to simulate the development of four hardwood plantation designs, three cherrybark oak monoculture designs (Pure, PureThin and Pure25) and a cherrybark oak and sweetgum mixed design (Mix) over a 50-year period. Among designs with similar initial stand density (Pure, PureThin and Mix), the Mix design produced the lowest CWI, an indication of greater clear wood production. The Mix plantation design

consistently out-performed the Pure and PureThin designs. The low-density Pure25 design had the lowest CWI and the largest average diameter.

The results of the CherrybarkSQ simulations indicate that when initial stand density is similar, a mixed species approach to cherrybark oak plantation management produces greater amounts of clear wood. A low-density monospecific approach produces a similar proportion of overwood, but the distribution of that overwood is on a shorter branch-free bole compared to the longer branch-free bole of trees at the greater density. The impact of hardwood plantation management decisions on clear wood or stem quality production, and therefore value, offers a great opportunity for evaluating hardwood plantations. Models and evaluations like those provided by CherrybarkSQ can assist with the interpretation, management and future development and value of mixed species plantations.

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ABSTRACT

Currently, the management of artificially regenerated 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 guiding their silvicultural decisions. This chapter outlines the need for management recommendations for artificially regenerated hardwood stands and an approach used to forecast the impact of hardwood plantation establishment and management decisions on the production of “clear wood”. A simulation system was developed that predicts, through a series of simultaneous equations, the growth and development of first-order branches and subsequent branch occlusion. This investigation focused on cherrybark oak (*Quercus pagoda* Raf.), an economically important bottomland oak species.

INTRODUCTION

Demand for hardwood sawlogs and veneer continues to grow across the eastern United States. Accordingly, the number of landowners, both private and industrial, deciding to establish hardwood plantations is increasing. This move toward hardwood plantations is due, in part, to variable success by silviculturists in naturally regenerating and promoting the development of high-quality hardwoods such as oak (*Quercus* spp.) (Oswalt et al. 2006; Loftis and McGee 1993). Additionally, interest in using hardwood plantations in the South as carbon sinks is increasing (Gardiner et al. 2004; Stanturf et al. 2004; Gardiner and Oliver 2005) as previously cleared agricultural land considered marginal for large-scale crop production is being reforested at increasing rates and scales. Furthermore, governmental cost-share programs such as the Wetland Reserve Program (WRP) and the Conservation Reserve Program (CRP) are influencing the increase in hardwood planting and hardwood plantation establishment (Gardiner et al. 2004; Devall et al. 2001; King and Keeland 1999), particularly bottomland hardwood types. As a result, increasing attention and efforts are being directed toward hardwood plantation silviculture and the development of prescriptions for artificially regenerated hardwood stands in the United States.

Plantations and plantation silviculture will play an important role in helping to satisfy the growing demand for wood products, both fiber and dimensional. Plantations account for approximately 5 percent of the global forest cover, yet provide an estimated 35 percent of global roundwood product (FAO 2001). Nearly all plantations are established as monocultures (Kelty 2006). Numerous authors have asserted that plantation forestry is an integral element needed to help diminish the impact of anthropogenic activities on natural forests (Seymour and Hunter 1999; Landsberg 2003; Kelty 2006). In fact, high-yield plantations are one element of the "management triad" that includes ecological reserves, managed natural forests and high-yield plantations (Seymour and Hunter 1999). Plantations can concentrate silvicultural activities, reducing pressures on natural forests and allowing other forested lands to be committed to ecological reserves, conservation easements and other non-extractive uses (Kelty 2006). Consequently, Landsberg (2003) emphasized the importance of plantations by noting that "the future of wood production should lie in plantation forestry."

Conifer plantation silviculture has a long history and has been widely applied. Species of interest have been primarily loblolly pine (Carter and Foster 2006), Douglas fir (Marshall and Turnblom 2005; Puettmann and Berger 2006), Scots pine (Savill et al. 2002), and radiata pine (Maclaren 1994). Conversely, while hardwood plantations have a lengthy history (Hayes 1822 per Nichols et al. 2006), widespread application has not been realized. Numerous elements are culpable (and discussed later in this chapter), however the primary point is that hardwood plantation silviculture has principally remained a research topic. With the exception of Eucalypts (Florence 2004), very little hardwood plantation silviculture information has transitioned from academic literature to management guidelines.

The increased establishment of hardwood plantations is only one element of the equation to supply quality hardwood products. A vital aspect of hardwood silviculture is to maximize all components of tree quality (i.e. tree/log grade) (Strong et al. 1995). However, hardwood plantation science, particularly in the United States, has paid little attention to investigating the influence of establishment and intermediate management decisions on stem quality. Instead, borrowing from conifer plantation science dominated by a volumetric focus, the approach appears to lean on the assumption that a quality stem is purely a function of maximizing diameter growth over time. Some anecdotal evidence suggests that this may not be the case. Producing quality hardwood stems is a function of both establishment decisions (e.g. monoculture vs. polyculture and the spatial arrangement of stems) and the individual stem development patterns created from initial establishment and intermediate operations. However, with the current situation in hardwood plantation science, many significant questions are unanswered and some have yet to be investigated. Of particular importance are questions regarding the impact of adopting a monospecific or multispecific approach on stem quality.

The importance of stem quality to the valuation of hardwood plantations, the benefits of adopting a mixed-species approach to hardwood plantation management and the framework for the development of a simulation system designed to investigate the influence of decisions regarding the establishment and management of hardwood plantations are discussed in this chapter. In addition, a description of the current situation surrounding hardwood plantation silviculture, a mixed-species approach to managing hardwood plantations, current mixed stand models and a new modeling approach are outlined. Subsequent chapters will address the development of equations to describe branch occlusion (Chapter 2) and crown allometry (Chapter 3) in cherrybark oak, the development and performance of the completed simulation system for forecasting the influence of establishment and management decisions on cherrybark oak stem quality (Chapter 4) and a case advocating a multispecific approach to hardwood plantation management in the United States (Chapter 5).

Current Situation

Presently, the management of artificially regenerated hardwood stands with a dimensional product objective, suffers from a lack of tested scientific information. A myriad of different species with different site requirements and growth habits makes establishing and managing hardwood plantations more complex than single species, pine plantations. The importance of stem quality introduces an additional variable. Without specific knowledge of hardwood development in artificially regenerated hardwood stands, many managers and scientists have turned to conventional pine plantation management as the primary source of information for guiding silvicultural decisions. The management of monocultures such as pine plantations has a very long history, dating back to as early as 1368 (Nichols et al 2006). However, utilizing the traditional conifer plantation approach in a hardwood stand ignores the developmental processes occurring in natural hardwood stands that aid in producing the stems currently prized for their growth and form. Although extensive knowledge exists regarding the development of natural hardwood stands and the differences between hardwoods and conifers are apparent, a "pine-mentality" continues to dominate hardwood plantation establishment and management because information is so sparse.

Pine plantation management is known for its volumetric focus (e.g. see Carter and Foster 2006 and Williams and Gresham 2006). Historically, demand for products such as pulpwood, particle board, structural lumber and plywood have driven the growth and management of pine plantations. As such, pine plantation science, particularly in the United States, has generally paid greater attention to developing management strategies for the optimization of fiber production, rather than approaches that center on the production of high quality stems, i.e., encouraging clear, knot-free wood. The question remains: Is this management approach appropriate for guiding silvicultural decisions concerning hardwood plantations? In this and subsequent chapters the working hypothesis is that it is not, and a more sophisticated management approach is necessary. Two elements of this hypothesis are expanded upon and evaluated; first, the need for a focus on stem quality when managing hardwood plantations and secondly the use of a mixed species approach to achieve high-quality hardwood stems grown in plantations.

Contrary to a volumetric focus, as with pine plantation management, stem quality is extremely important in the valuation of hardwood stands. The monetary value of a hardwood stand is directly related to the quality of individual stems within that stand. Consequently, a large amount of variation can exist in the value of stands with similar composition and size. For example, the value of a grade 1 log of cherrybark oak can be 5 to 6 times greater than that of a grade 3 log with similar dimensions[1]. Stubbs (1986) reported differential ratios in the value of log grades of 13:7:1 on average for grade 1, 2 and 3 logs, respectively for bottomland oak (*Quercus* spp.), ash (*Fraxinus* spp.), sweetgum (*Liquidambar styraciflua* L.) and yellow poplar (*Liriodendron tulipifera* L) combined. In addition, Meadows and Burkhardt (2002) estimated a 13 percent loss in stand value as a result of grade reductions due to epicormic branching. Accordingly, growing high grade hardwood timber can significantly increase the return on a hardwood plantation investment. Very little guiding information, however, exists. As a result, timely information is needed to help guide both future research and current management decisions in hardwood plantation silviculture.

A review of the National Hardwood Lumber Association's lumber grading specifications reveals that knots are a major grade limiting factor. Likewise, the Forest Service's tree and log grading specifications indicate major reductions for the presence of

[1] E.C. Burkhardt, personal communication

live branches or knots. Clear wood is wood developed in the absence of branches or knots and it is well understood that clear wood is the wood in a log with the most value. Therefore, high quality trees or logs can be said to have a higher proportion of clear wood. Stem quality is directly and positively related to clear wood content. The biology of clear wood production is such that crown development, branch senescence and branch occlusion are all important factors in determining the amount of clear wood a particular tree develops. Designing silvicultural prescriptions that optimize the production of clear wood in hardwood plantations is imperative to meeting future demands for high quality hardwood products. Sound clear-wood silvicultural regimes for hardwood plantations are needed.

Mixed-Stand Approach

Even though the active management of mixed species stands is just recently becoming more prevalent (Zhao et al. 2004), the benefits have long been noted. As early as 1822 foresters were advocating multispecific approaches to hardwood plantation management (Nichols et al. 2006). Specifically, Hayes (1822) suggested that hardwood stems should be planted "at about twenty feet… the plantation should then be thickened up with other sorts of trees" in order to produce quality hardwood stems (Nichols et al. 2006). Additionally, Toumey and Korstian (1937) listed numerous advantages of multispecific or "mixed crop" plantations that included 1) simplified management, 2) economic gains from multiple species, 3) simpler artificial restocking, 4) better site utilization, 5) decreased vulnerability to fungi and insects and 6) more valuable thinnings through mixtures of primary crop species and subordinate species having better prices at small diameters. Nevertheless, the common prescription for establishing hardwood plantations focuses on monspecificity and in the case of oaks, establishing single-genus stands with a mixture of oak species (Lockhart et al. 2006). Occasionally multiple species will be planted in single-species or single-genus blocks. Biologically, for all but the stems that lie in the zone of transition between species/genus, the planting pattern results in development patterns identical to monospecific stands. The only difference is scale. Although monocultures are often more economical and operationally simpler, establishing many hardwoods in monocultures or “near” monocultures ignores the processes that aid in the development of clear wood and represents poor clear-wood silviculture.

Natural cherrybark oak – sweetgum mixtures are common in stands throughout bottomland hardwoods in the South. Cherrybark oak is an extremely valuable hardwood with multiple dimensional product uses. As a result, cherrybark oak silviculture has been a focus of bottomland silviculture research for the past 3 decades (Baker and Broadfoot 1977; Bonner 1984; Miller and Burkhardt 1987; Clatterbuck and Hodges 1989; Oliver et al. 1990; Gardiner and Hodges 1998; Gazal and Kubiske 2004; Gardiner and Yeiser 2006). In addition, multiple researchers are investigating artificial reproduction techniques for this valuable species (e.g. Lockhart et al. 2000; Lockhart et al. 2003; Gardiner et al. 2004), including a case study of artificially regenerated mixtures of cherrybark oak and sweetgum (Lockhart et al. 2006). Due to the amount of research-based data and examples, this paper often cites the cherrybark oak – sweetgum mixture as an example.

Stem quality in cherrybark oak can be considered a function of two processes and the timing of each. First, to produce branch free wood, the live crown (i.e. the area of the stem with actively growing branches) must recede (or rise) before clear wood can be produced on the main bole of the stem. Second, diameter increment is needed to occlude residual dead branches left in the "wake" of the receding crown. The two processes appear to be at odds. Substantial leaf area or photosynthetic capacity is needed to produce significant diameter growth. However, according to Pressler's growth law (see Assman 1970) and the Pipe-stem model (Shinozaki et al. 1964a; 1964b) large branches are needed to carry the necessary leaf area to produce adequate increment for branch occlusion. Crown recession must slow to allow for large branches to develop. In addition, large senesced branches, once below the receded crown, require larger stem diameters for complete occlusion (Oswalt et al. *in press*). To reconcile this apparent opposition, consideration must be given to the temporal aspects of each process in conjunction.

The ideal conceptual model of development for a cherrybark oak stem for optimizing or maximizing stem quality (e.g. clear wood production) would involve both expedient crown rise subsequently followed by crown enlargement or branch extension (Figure 1.1). Adequate crown rise needs to occur to produce a significant merchantable bole length (i.e. 32+ feet). Subsequently, canopy space needs to become available for branch extension and crown expansion, which allows for adequate photosynthetic capacity to develop, resulting in increased diameter growth to speed branch occlusion. The apposite timing of these processes can materialize through four developmental pathways (DP) (pathways 1 and 2 occur in natural stands and pathways 3 and 4 in planted stands).

(DP1) Multiple stand dynamic studies have demonstrated that over time dense canopy space is often relinquished by one or more species in mixed stands through species-specific differential growth rates (Oliver 1980, Clatterbuck and Hodges 1988; Lockhart et al. 2006). Clatterbuck and Hodges (1988) determined that sweetgum in natural mixtures with cherrybark oak generally experiences decreased growth at approximately 20 years of age. They presented evidence that the reduction in sweetgum height growth commonly resulted in the relinquishment of canopy space which cherrybark oak crowns were able to capture through expansion. The timing of these two processes often follows the conceptual model described above. That is, crown expansion, a result of free canopy space, following the development of a significant merchantable bole.

(DP2) Similar to DP1, canopy space can be made available for crown expansion through both density-dependent and density-independent mortality. However, the timing of mortality events is not always optimal or beneficial to the production of quality stems. The uncertainty, particularly of irregular mortality, represents risk associated with the goal of producing clear wood.

(DP3) Through the use of intermediate treatments, such as thinnings, in densely planted monospecific stands, the necessary timing of the processes can be simulated and possibly tuned to site-specific growth rates. Yet, much like DP2, there are numerous risks. For example, such an approach requires repeated stand entry and therefore, a greater potential of damage to crop trees. In addition, the probability of epicormic branching facilitated by overexposure of clear boles in conjunction with the constricted condition of crowns before expansion is high for some species (Dimov et al. 2006; Meadows and Goelz 2002) and extremely detrimental to overall stem quality (Stubbs 1986; Meadows and Burkhardt 2001.

(DP4) Lockhart et al. (2006), through a case-study in Mississippi (instigated by the early results from Clatterbuck (1985)), demonstrated that it may be possible to mimic the natural process of DP1 in planted stands. The use of multispecific plantations as analogues for natural stands in order to mimic their patterns of development, may represent an attractive management approach to producing high-quality sawlogs of oak and other species (Oswalt et al. *in press*). This practice may be considered good clear-wood silviculture.

In order to develop reliable clear-wood silviculture prescriptions for hardwood plantations, further support for the development pathways of artificially regenerated stands described above is required. To test the validity of the above hypothesized hardwood plantation developmental pathways, a model of mixed stand development is needed that forecasts variables that can be used to quantify stem quality or some element of stem quality. The model should be based in current forest stand dynamics theory and include the ability to accurately predict crown characteristics. Such a model would allow for more long-range planning and forecasting and will offer some flexibility among different forest systems.

Current Models for Mixed Stands

The temporal aspect of forest-related research lends itself to the utilization of computer models in order to expedite the collection of evidence in support of or opposition to particular hypotheses and to guide forest management decisions. The use of quantitative models to forecast forest response to human and natural influences at multiple scales is essential to effective management. Furthermore, dynamic models of tree growth are becoming increasingly important in both ecological research and forest management planning (Shugart 1984, Liu and Ashton 1995, Jogiste 1998).

Numerous forest growth and yield models have been developed for modeling pure and mixed stands (see reviews by Peng, 2000 and Porté and Bartelink, 2002). At first, the focus was on pure, even-aged stands. Porté and Bartelink (2002) note that, historically, the complexity of interactions in mixed stands, even two-species assemblages, slowed the development of mixed stand growth models with widespread applicability. For example, two-species stands of species A and species B could differ with regard to proportional composition, stand origin, spatial pattern (anthropogenic or naturally occurring) and site conditions. However, demand for mixed stand models has only intensified over the past few decades. Support for mixed stand plantations has grown accordingly. Porté and Bartelink (2000) argue that the increasing development of mixed-species models is a result of the increased availability of computers, changing goals of forest management, the interest in incorporating causal relationships into forest models and a general shift in silvicultural focus from even-aged monospecific stands to that of mixed-species stands. Ample evidence supports their position on computational power, management goals and interest in causal relationships. However, there is little evidence that any silvicultural shift has occurred in commercial applications (Nichols et al. 2006), where a shift would have major influence on the global and national forest resource. Instead, the "shift in silvicultural focus" (Porté and Bartelink 2000) has been largely confined within the sphere of research. Nichols et al. (2006) summarized the situation with the following:

> "Within the community of mixed-species researchers, it is easy to gain the impression that there is widespread support and demand for mixed-species plantations, but this is not generally so in the case of commercial plantations for timber production."

In order to facilitate a shift from monoculture to mixed species commercial applications of plantations, especially hardwood plantations, researchers must provide evidence of benefits that outweigh any increased management complexity and/or operational costs. Support for mixed-species plantations must be based on economic arguments (Nichols et al. 2006). Currently, most arguments advocating mixed species plantations are either environmental (i.e. diversity) or based on aesthetics (i.e. "It looks more like a natural forest"). Indeed, there is a wealth of research promoting the benefits of mixed-species plantings (see review by Vanclay et al. 2006). Regardless, few attempts have been made to base the argument for mixed-species plantations on economic factors. The few papers that do reference economic gains argue for the adoption of a mixed-species plantation approach from the standpoint of gains in productivity. For the most part, conifer plantations are referenced, ignoring the gains that may be possible in hardwood plantations as a result of increased stem quality (e.g. see Nichols et al. 2006).

The primary need that exists is a forest growth model that can accommodate mixed species stands in a spatially explicit manner and produce information that can be used to assess the economic impacts of a range of plantation silviculture management scenarios. Such a model would need to accurately forecast stand development patterns. Dynamic patterns in stand development are generally explained through population dynamics (Jogiste 1998). Jogiste (1998) purported that population dynamics affect stand bole-wood growth and accumulation and therefore, stem quality. Since population dynamics differ between differing communities (Oliver and Larson 1996), such as pure-species versus mixed-species, it is reasonable to suggest that individual stem quality would be differentially affected. As such, investigations of the impact of species composition has on stem quality are important to pursue. The temporal scale of forest research dictates a modeling approach to such investigations to produce timely information.

Current Tree/Log Quality Models

Given the rarity of comprehensive long-term data on tree-grade/stem-quality, simulation modeling is a useful means of inference on long term stand dynamics including the effects of natural and planned anthropogenic disturbances. Generally, the focus of most models is volumetric in nature. That is, forecasting tree or stand level metrics such as volume unit-area^{-1}, diameter distributions, stem density unit-area^{-1} or basal area unit-area^{-1}, from which individual stem quality can not be quantified or inferred. Few models have focused on forecasting measures of stem quality.

One of the factors that may be attributed to the scarcity of stem quality models is the long used methods for quantifying stem/log/lumber quality. For the most part, stem quality has been quantified through the adoption of categorical grading systems that use discrete classification variables. The standard system for grading logs was developed by the Forest Service in the late 1940's and early 1950's (Yaussy 1991) and is nominally based on the century-old lumber grading system of the National Hardwood Lumber Association (NHLA). Very little has changed within these grading systems over time.

A handful of researchers have attempted to work within the framework of the established categorical grading systems. Simple linear (Ernst and Marquis, 1979; Myers et al. 1986) and nonlinear regression (Dale and Brisbin, 1985) and discriminant function (Lyon and Reed, 1987; Belli et al. 1993) equations have all been used to predict tree or log grades and/or to predict tree/log grade distributions. None of the solutions have been ideal. Both the regression and discriminant analysis approaches appear to have been somewhat successful. However, these attempts developed empirical models that incorporate term(s) that represent current tree or log grade to predict future stem quality. These models are only useful in predicting future tree/log grade over short temporal scales and require data to be collected when stem quality has already largely been expressed. In general, these models require data that incorporate stem quality to predict stem quality. Often the models assume no change in stem defect over time, and only assume changes in log/tree diameter. As a result, these models have limited utility.

Another approach to modeling stem quality has been to include, within prediction equations, a continuous variable as the dependent variable that describes tree/log grade. Both Ware (1964), in the 1960's, and later Yaussy (1991), in the early 1990's, supported this idea. Research has found that a simple count of tree/log defects, especially in the butt-log of the tree, is highly associated with quality. This is true regardless of the type, size or location of the defects (Yaussy, 1991). However, as Yaussy (1991) points out, it is usually faster to grade a tree than to take the time to count each individual defect. An approach is needed in order to progress toward a method that can be used to forecast aspects of stem quality and to help answer the questions concerning management of hardwood plantations, specifically oak.

According to Mäkinen and Colin (1999) the value of wood should be assessed based on the physical characteristics of the wood itself. Reliance on one particular grading-system developed at a specific point in time, long-lived or not, limits the application of any model or simulation system developed. The development of a model that links stem quality characteristics to actual wood structure, as in the case of clear wood allows for much more flexibility in defining desirable grading rules (Mäkinen and Colin 1999).

MODELING APPROACH

The primary objective of this work is the development of a set of sub-models that can be used in conjunction with a forest growth model to evaluate the impacts of various silvicultural decisions on the development of stem quality. The modeling approach presented 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 simulation system for evaluating effects of various silvicultural decisions on the development of clear wood. This effort attempts to predict either a positive or negative impact on clear wood production through altering stand level parameters as they are impacted by different management decisions.

The intention of the modeling activity above 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, the model should allow for relatively easy interaction between land managers and the model while allowing a certain degree of flexibility that will allow land managers to adapt the model to local conditions.

There are several key points in the objectives statement that warrant elaboration. First, *crown system dynamics* refers to the birth, death, growth and development of first-order branches that make up the living crown of the modeled tree. The model, therefore, tracks the initiation of first-order branches within the crown, particularly at the base of the live crown, subsequent branch growth and branch death as crown rise occurs.

Second, *bottomland oaks* refers to species from the genus *Quercus*, in particular cherrybark oak. In the long-term 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 within plantations.

Third, *easy interaction* is necessary to allow natural resource managers with very little or no modeling experience access to the predictive powers of the developed model. Model usage as a tool, to add an additional level of sophistication to planning, is extremely important to this process. Finally, the ability for the model to be *adapted* to reflect local conditions, through the use of local knowledge of site indices is imperative.

In order to develop such a model, an approach to forecast the impact of hardwood plantation establishment and management decisions on the production of clear wood was investigated. A simulation system was developed that predicts, through a series of simultaneous equations, the growth and development of first-order branches and subsequent branch occlusion. In contrast to most stand and individual tree scale models, the developed model provides the user with output regarding stem quality. The model does not predict specific tree or log grades. The purpose was to produce a model that can be used as a general decision support tool for guiding the management of hardwood plantations. Users have the capability of evaluating the potential impact of decisions such as initial spacing, species composition and plantation arrangement on the development of clear wood. Further research is required to expand this approach to other economically important species.

Branch Occlusion Sub-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). 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. Models combining growth and development of stem structure, including the internal characteristics of logs, are in development (Maguire et al. 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.)) rather than hardwoods.

Data were obtained from mapping branch-knots of 105 unique branches on 21 boards strategically sawn from 3 cherrybark oak logs representing one tree. 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 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. Maximum diameter of each branch and stem radius at the point where a branch no longer appeared were calculated for development of a simple predictive equation.

Crown Allometry Sub-Model

An understanding of the growth dynamics of individual first-order branches within the developing crown is an integral component needed for forecasting clear wood and therefore, stem quality. Similar to forecasting branch occlusion, it is essential to have the capability of predicting, not only the number of branches, but the spatial distribution and size of branches within the live crown. Being able to describe the population of branches at the base of the live crown is especially important because these are commonly the largest branches within the crown and, therefore have the greatest potential of impacting clear wood production (Oswalt et al. *in press*).

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 and 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 include 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 4 separate stands across Tennessee. Three stands were located on the Natchez Trace State Forest (NTSF) in western Tennessee (35.7812° Latitude, -88.360031° Longitude) and one stand was located on privately owned land in Dixon

Springs, Tennessee (36.35804° Latitude, -86.050209° Longitude) (See Chapter 3 for a detailed description of the study sites). Diameter at breast height (dbh) varied from 7.6 to 50.8 cm (3 to 20 inches). Height varied from 5.8 to 30.2 m (19 to 99 feet) and stand age varied from 14 to 50 years. Before felling, total height, diameter at breast height (dbh = 1.37 m), and crown metrics were collected for each tree. Crown metrics included crown length (height to base of live crown subtracted from total tree height), multiple crown radii (n = 5 – 18) and height to the widest part of the live crown. All first-order branches on each felled tree were mapped according to crown depth, departure angle and departure quadrant. Basal diameter and 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.

The CherrybarkSQ Simulation System

The design of the branch occlusion and crown allometry sub-models is such that the crown allometry sub-model requires inputs from a forest growth model and the branch occlusion sub-model requires inputs from both a forest growth model and the crown allometry sub-model. In combination, the forest growth model and crown allometry and branch occlusion sub-models constitute the complete wood quality model (Figure 1.2) or the Cherrybark Stem Quality model (CherrybarkSQ). Prior to the detailed development of CherrybarkSQ, numerous existing mixed stand growth models were reviewed for appropriateness to the a priori objectives of the finished stem quality model and fit with the anticipated branch occlusion and crown allometry sub-models. Models were specifically reviewed for appropriateness of spatial resolution (tree vs stand), inputs and outputs, data requirements for parameterization and code availability. For a detailed review of mixed stand growth models see Porté and Bartelink (2002) or Busing and Mailly (2004) for a review of individual-based models.

Due to the large number of published forest growth models, attempts were made to narrow the field of available models. Models were evaluated to determine if the following requirements were satisfied: 1) maintain spatial resolution at the tree scale, 2) maintain explicit spatial coordinates of all trees, 3) provide crown characteristics (crown base, crown width and crown length), 4) allow for interaction with the USDA Forest Service's Stand Visualization (SVS) platform, 5) supply easily accessible code, and 6) contain simplified routines for parameterizing the model to local conditions.

The model classification system developed by Porté and Bartelink (2002) (Figure 3) and subsequent review was used to aid model selection. Only models that are classified as distance dependent tree models were of interest. Stand level models were ignored because of the lack of necessary spatial information. Stand level models generally treat the canopy as a horizontally homogeneous leaf layer. As a result, stand level models would not be able to represent different planting patterns, cannot account for spatially explicit thinning treatments nor incorporate crown competition which was determined to be an important element needed in the development of CherrybarkSQ. CherrybarkSQ must incorporate individual tree information because stem quality can vary within a stand and is largely a function of the competitive environment of the individual stem throughout development. Consequently, individual-based models that simulate the performance of individual organisms in ecological systems (DeAngelis and Gross 1992) appeared more appropriate for the development of CherrybarkSQ.

Individual-based models or in this case, tree models can be classified into one of two groups (Figure 1.3), distance dependent tree models (DDTM) or distance independent tree models (DITM) (Porté and Bartelink 2002). DITM's including the gap models that simulate a forest as a group of independent patches like JABOWA (Botkin et al 1972) and JABOWA descendants (e.g. FORET, SILVA, ZELIG), do not explicitly track individual tree coordinates and therefore are not appropriate for CherrybarkSQ. Most of the popularly cited individual-based models either do not track the necessary crown variables (JABOWA, FORET, ZELIG, FORSKA, SPACE, FORMOSAIC, PICUS) or do not offer the spatial complexity (JABOWA, FORET, ZELIG, FORSKA, FIRE-BGC, PICUS) needed for the CherrybarkSQ model (see Table 1.1 for model references).

In the late 1980's an approach to modeling forest growth, based on the three-dimensional crown characteristics of trees and stand dynamics principles to predict tree growth and development was developed by Larsen (1991a, 1991b, 1994). This approach produced the Sylvan Stand Structure Model (Sylvan), an individual tree distance dependent model that offers great flexibility and was designed to derive model parameters from the stand to be projected. The Sylvan model has successfully been applied to a wide variety of species and used to predict the development of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), in the Pacific Northwest, cherrybark oak and sycamore (*Platanus occidentalis* L.) in Arkansas, European beech (*Fagus sylvatica*) and Austrian pine (*Pinus nigra* Arnold) in Italy, Scots pine (*Pinus sylvestris* L.) in Finland and upland hardwoods in Missouri[2]. The

[2] Dr. D.R. Larsen , personal communication

Sylvan model was chosen because it 1) offers the needed flexibility to develop site-specific and species-specific coefficients in a relatively simplified manner, 2) forecasts growth of real stands, 3) produces realistic crown interactions, 4) is largely influenced by crown size, 5) is based on accepted stand dynamics theory and 6) tracks crown recession over time.

The completed wood quality model consists of a set of simultaneous equations that draw inputs from the model user and the Sylvan individual tree model (Figure 1.2). The dataflow sequence begins with data collected from the stand of interest. The field data, including spatial coordinates are input into the Sylvan model and projected forward one timestep (timestep = 5 years). Following each timestep the crown allometry sub-model forecasts the characteristics of the population of branches at the base of the live crown (CB) from data derived from the Sylvan model. In the next step, the branch occlusion sub-model forecasts the diameter of the knotty-core at CB. The process is repeated until the final timestep, designated by the user. The knotty-core and clear-wood calculators derive the volume of the knotty-core and clear-wood within the stem. Knotty-wood and clear-wood production can be expressed both at the stand and individual tree scale. User inputs include: 1) a local dataset for developing customized growth model parameters for the Sylvan tree model and 2) initial plantation design that includes species, spacing and arrangement. Users can export treelists from Sylvan at any point during the management timeline in order to utilize programs such as the USDA Forest Service's Stand Visualization (SVS) platform that allows for the user to define intermediate treatments such as thinnings. The SVS-altered treelist can be imported back into Sylvan and simulation continued.

CherrybarkSQ is an empirical approach. While the model may be more limited in its applicability than by using a mechanistic approach, in general empirical models produce more accurate predictions (Porté 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 empirically derived also and would need to be re-parameterized for new species and species mixtures. Unlike 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 & APPLICATIONS

Research

One of the primary uses for CherrybarkSQ will be aiding the design of plantation trials. For example, the model can be used to evaluate what type of spacing and species assemblage combinations look most promising. In addition, comparisons can be made among variable management scenarios in order to guide 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. The model, after adapting it to other hardwood species, may eventually be used to outline general theories of how hardwood plantations develop.

Hardwood Plantation Management

Upon completed evaluation of the wood quality model and packaging within a user-friendly graphical user interface (GUI) forestland 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). Armed with tree quality information, decision-makers will possess a key variable for assessing potential stand value, information that has long been missing from hardwood simulation models.

CONCLUSION

For quite some time now researchers and forest land managers have needed a tool that would help investigate questions and help guide decisions regarding the management of hardwood plantations. Some models have been developed, but few, if any, have the capabilities of simulating hardwood tree quality or the influence of management decisions on the stem characteristics that define quality (i.e. branches, branch-knots and clear-wood). It is well known that a purely volumetric focus will not be adequate in valuing hardwood stands. The inclusion of the ability to simulate stem quality through forecasting clear-wood development within forest growth models is imperative. CherrybarkSQ takes an important step toward the development of much needed modeling tools. The developed model has the capability of not only aiding the design of future plantation research trials, but guiding decisions regarding the planning, establishment and subsequent management of hardwood plantations.

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CHAPTER 2

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/log grade or stem quality. The relationship between branch size and subsequent branch occlusion through diameter growth was investigated with special attention toward the development of a simple single regressor equation for use in future stem quality hardwood 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/log grade or stem quality. 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 hardwood plantations lacking natural analogs are being created. Unlike some softwood products, grade production or stem quality 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 differential between red oak FAS ("First and Seconds" the highest grade of hardwood lumber) and 1F alone and FAS and 2A (mid-grade lumber) 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 stem quality 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 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.)).

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 with good prediction capability for use in future hardwood stem quality models. Examples of similar models were not available in the published literature. Therefore, three biologically reasonable model forms were considered for exploration that reflected the observation that the amount of wood required to occlude a branch of a given diameter is proportional to branch diameter. Several pruning studies indicate that larger branches require greater time to occlude (Briggs 1990, O'Hara and Buckland 1996) and that the amount of wood (linear distance from the pith) needed to occlude a given branch is positively related to the diameter of the given branch. The studies by Briggs (1990) and O'Hara and Buckland

(1996), although focusing on post-pruning occlusion, developed models based on similar constructs.

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 40.9 cm (16.1 inches) and total height was 31.1 m (102 feet) 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.

Data for this analysis were limited because the branch information were recorded from 3 logs cut from one tree. More robust datasets were unavailable due to the difficulty of collecting branch occlusion information. Branch occlusion information can be collected through computer aided imaging processes, repeated measures over long periods of time or destructive sampling as in the case of the current analysis. No method produces large amounts of necessary information at a reasonable cost. Computer aided imaging, generally computer tomography or ct-scanning, is extremely costly and equipment is rarely available for scanning heavy logs. Repeated measures capable of capturing a robust dataset would require greater than 40 years of continuous data collection. Destructive sampling allows for the collection of information over a short time period at a reasonable cost. However, destructive sampling is labor intensive for the amount of data yielded.

Such a limited dataset, while offering a opportunity to further understand the relationship between branch size and branch occlusion in cherrybark oak, does present complications. For instance, because the one sampled tree was grown in a fully stocked stand with a developed midstory, the dataset contains few examples of occluded large diameter branches. These few large diameter branches may exert an inordinate amount of influence on the the relationship. A greater number of larger branches would allow for a more comprehensive analysis and allow for additional data splits for further evaluation.

Model Building and Evaluation

Branch-knot mapping produced a total of 287 points and 105 unique branches for the 6.4-meter length. Only branches that could be followed from inception at the pith were used for model-building and model evaluation (n = 66). Figure 2.1 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). Additional data splits were not considered. Observed data in the development dataset were fitted to each model form (Table 2.1) using the PROC REG and PROC NLIN procedures (SAS Institute Inc. 1989). Ordinary least-squares were utilized for parameter estimation.

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

Model Form 1) $Y = Y_0 + a*BK_{max}$

Model Form 2) $Y = a(1-e^{-b*BKmax})$

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

where

Y = Overwood

Y_0, a, and b are parameters

Each of the model forms reasonably followed the form of the expected relationship based on previous pruning studies (Briggs 1990, O'Hara and Buckland 1996). Each model form had a simple, single independent variable form. Mean square error (MSE), error sum of squares (SSE), coefficient of determination (R^2) and the PRESS statistic were used to evaluate the appropriateness of each model and to choose the "best" performer.

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:

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

where

Yi is the value of the response variable in the *i*th validation case

$\hat{Y}i$ is the predicted value for the *i*th validation case based on the development dataset

n is 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 of the prediction errors ($\bar{e}$) 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 $Y = Y_0 + a*BK_{max}$ and non-linear models $Y = a(1\text{-}e^{-b*BKmax})$ 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 2.1). The linear model $Y = Y_0 + a*BK_{max}$ 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 2.1). The standard error of the estimate was also smaller for the $Y = a*BK_{max}{}^{b}$ model (Table 2.1). The model chosen as the "best" performer 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:

Overwood = $3.49*BK_{max}{}^{0.29}$ {*Eq. 2*)

The SSE for the model fitted with the development dataset was 200.95 (Table 2.2). 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 ($R = 0.68$, $R^2 = 0.46$, $P < 0.001$) (Figure 2.2a).

Using equation 2, each case in the evaluation dataset was used to predict overwood (Figure 2.2b. Calculated mean prediction error was -0.36 cm and MSPR was 4.85 (Table 2.2). 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:

Overwood = $2.83 * BK_{max}^{0.35}$ {*Eq. 3*}

The SSE and PRESS statistic were 152.96 and 167.94, respectively (Table 2.2). 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 ($R = 0.74$, $R^2 = 0.54$, $P < 0.001$) (Figure 2.3a). 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 (Figure 2.3b). Calculated mean prediction error was 0.33 cm and MSPR was 6.32 (Table 2.2).

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

Overwood = $3.17 * BK_{max}^{0.32}$ {*Eq. 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 2.2, Figure 2.4).

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. Alternate data splits probably would have resulted in different model evaluation results from the cross-validation procedure. However, because the full dataset was used to fit the final model, the final model is representative of the data available.

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 and could be influenced by site differences, tree vigor and genetics. 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 temporal dependence from the model and not attempting to predict occlusion rates, the developed model is not limited by site dependent factors, such as site productivity. 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.

Multiple data splits were not considered in this study. As a result, the model selection process is somewhat biased by the random data split that was used. Multiple data splits may have resulted in a different model form as a “best” fit, primarily due to the limited data points in the large diameter area of the data space.

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. Further refinements are necessary due to the uncertainty of the correct model form. The dataset used for model development was limited by a low number of large branch samples. Therefore, the uncertainty in predictions from the developed model is greater for larger diameter branches. Additional data is required to reduce the uncertainty in predictions for large branch diameters because of the importance of large branches in defining overall stem quality.

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CHAPTER 3

Equations to describe branch populations and crown allometry in plantation grown cherrybark oak.

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ABSTRACT

Allometric equations were developed to describe crown and branch attributes of plantation grown cherrybark oak. The goal of this study was to develop models of first-order branch characteristics that could be applied as part of an individual tree stem quality simulation system. Models were developed for predicting first-order branch length from crown depth and height, maximum branch length for a particular crown section from the relative position of a branch within the live crown, branch diameter from branch length, branch population for a crown section from relative crown position, crown length from crown diameter and height and crown diameter from crown length, stem diameter and height.

INTRODUCTION

Several growth and yield models have been developed for hardwood species (e.g. Botkin et al. 1972; Busing 1991; Pacala et al. 1993, also see reviews by Peng, 2000 and Porté and Bartelink, 2002). Researchers have combined different models as simulation systems that can be used to help answer stand management questions, compare management scenarios and guide future research (Briggs and Fight 1992; Siitonen 1995; Mäkinen and Colin 1998). Models of wood quality must be included in order to make sound judgments based on the results of a simulation system for hardwoods. If models of wood quality are not included, false or shortsighted recommendations could be made

(Mäkinen and Colin 1999; Mäkinen et al. 2003). However, few hardwood growth models have the capability of forecasting stem quality, few models of hardwood stem quality have been produced and no simulation system that includes stem quality has been developed for hardwood species.

Demand for many hardwood timber species is driven by high-quality products such as panels, furniture and plywood. High-quality logs, free of defects such as knots, are needed for these products. As a result, stem quality (i.e. tree or log grade) is a major determinant of the value of many hardwood logs. For instance, Stubbs (1986) reported log grade value differential ratios of 13:7:1 on average for grade 1, 2 and 3 logs, respectively for bottomland hardwood species. Furthermore, Meadows and Burkhardt (2001) estimated a 13 percent loss in stand value as a result of grade reductions due to epicormic branching.

Stem growth and development is related to crown development (see Assman 1970). The tree crown is defined as that part of the tree bearing live branches and foliage (Kozlowski et al. 1991). Consequently, the growth and development of the population of branches within the crown is related to numerous characteristics of a tree, including stem size (Bartelink 1996), stem taper (Burkhart and Walton 1985) and stem quality (Pape 1999).

Direct measurement of branches within the crown over time would be costly. Fortunately, trees develop allometrically and the allometric relationships can be described with mathematical equations (Monserud and Marshall 1999). The capability, through mathematical equations, to describe the relationships among bole attributes (e.g. height, diameter, etc.), crown metrics and the branch population within the crown will provide better understanding of the growth of trees and crowns and their impact on stand development. Allometric relationships explain the proportionality between the relative growth of two parts of a plant (X and Y): $dy/y = b(dx/x)$ which, when integrated results in $Y = aX^b$. The form of the equation is generally logarithmic. The logarithmic transformation allows for the use of linear regression and mitigates the tendency for the variance of the dependent variable to increase with increasing tree size (Baskerville 1972; Sprugel 1983; Monserund and Marshall 1999).

Allometric relationships have been documented in many hardwood species (Niklas 1994; Bragg 2001; Bechtold 2003; Jenkins et al. 2003). The relationship between crown radius or crown diameter and diameter at breast height (dbh) has been a focus of forest science for some time (see Bechtold 2003). However, no work relevant to allometric relations in either plantation-grown hardwoods or the relationship among crown metrics and branch population dynamics has been published.

Recently, some researchers have begun to develop equations to describe individual branch birth, development and senescence within the live crown of many conifer species (Mäkinen 1998; Mäkinen and Colin 1998; Mäkinen and Colin 1999; Mäkinen et al. 2003). Particularly, researchers in Fennoscandia have developed models of branch populations and branch characteristics (Maguire et al 1994; Mäkinen and Colin 1998; Mäkinen and Colin 1998; Mäkinen et al. 2003) and developed simulation systems that include models of stem quality (e.g. MOTTI (Salminen and Hynynen 2001)).

Mäkinen et al. (2003), Colin and Houllier (1991, 1992), Vestøl and Høibø (2000) and Moberg (2001) published empirical models of branch and/or knot development for Norway spruce. Mäkinen and Colin (1999) have described branch populations within

Scots pine crowns. Umeki and Kikuzawa (2000) published models describing the branch population dynamics within *Betula plataphylla* crowns in Japan. In the United States Maguire and Hann (1989) developed equations for predicting sapwood area at the base of the live crown of Douglas-fir and Gilmore (2001) presented models of branch population dynamics within *Larix* spp.

Similar branch equations have yet to be developed for most hardwoods, particularly oak (*Quercus*) species. The ability to describe the relationship between gross crown metrics and the branch population within the crown will advance hardwood growth and development model sophistication.

The aim of this study was to develop allometric equations to predict crown attributes of plantation grown cherrybark oak from readily available and easily obtained tree measurements (e.g. height, diameter, crown length). Furthermore, this study was designed to develop equations to describe the branch population in cherrybark oak crowns, particularly at the base of the live crown. The developed equations are for use within an individually-based wood quality simulation system currently under development. Of particular interest are equations for predicting branch length, branch basal diameter, crown length and crown diameter.

METHODS and MATERIALS

Study Locations

Data were collected from four planted stands of cherrybark oak located across Tennessee. Three stands were located on the Natchez Trace State Forest (NTSF) in western Tennessee and one stand (Beasley stand) was located on privately owned land in Dixon Springs, Tennessee (Figure 3.1). Sample stands were chosen to represent a chronosesquence of known cherrybark oak plantations. Stand age ranged from approximately 5 years to 50 years. All stands were planted as monocultures on approximately 9 x 9 ft. spacing. With the exception of the Beasley stand, all stands contained volunteer stems of other species, mostly sweetgum.

Focus trees (FT) were identified in each stand: NTSF Scarce Creek 1 (n = 16), NTSF Scarce Creek 2 (n = 14), NTSF Bailey (n = 12) and Beasley (n = 8). Focus trees were selected in such a way that the diameter distribution of the sampled trees was similar to the diameter distribution of the sampled stand. Focus trees were primarily selected from the dominant and co-dominant crown classes. Each FT selected had full, healthy crowns and was directly competing with neighboring tree crowns on at least three sides (ie. not open-grown). Due to requirements for destructive sampling of trees, the number of FT selected in each stand were limited by land owner specifications and differed according to landowner. Data were collected at the tree level, the neighborhood level and individual branch level for each focus tree.

Data Collection

Tree Level

Plots were dissected into 4 quadrants according to cardinal directions radiating from the FT. Before felling, total height, diameter at breast height (dbh = 1.37 m), and crown metrics were collected for each FT. Crown metrics included crown length (height to base of live crown subtracted from total tree height), multiple crown radii (n = 5 – 18) and height to the widest part of the live crown and were measured using a Haglöf Vertex Hypsometer (Haglöf Sweden Inc.). After felling, radial disks were removed from each FT at the stump, defined as 15 cm above ground level, dbh and 1.22 m thereafter for the reminder of the stem. Age, diameter inside bark (dib), diameter outside bark (dob), heartwood diameter, sapwood width and bark width were collected for each disk.

Neighborhood Level

The neighborhood of each FT was characterized and mapped for quantifying local competition. Total height, dbh, crown metrics and azimuth and distance from the FT were collected for each competing neighbor tree in each of the 4 quadrants. Competing neighbor trees were defined as adjacent trees with crowns directly competing (visibly touching) with any part of the crown of the FT in all directions.

Individual Branch Level

All first-order branches for each FT were mapped according to insertion height, departure angle and departure quadrant. Departure quadrant was derived from the quadrant in which the majority of the branch was located. In addition, branch basal diameter and branch length was recorded for each first-order branch. Samples of 4-5 branches were removed from each FT for stem analysis. Radial disks were removed at 1 foot intervals from each sampled branch. Disks were sanded and age and diameter were recorded for each radial disk.

Data Analyses

Equations were developed to describe individual first-order branch length (BL) as a function of crown depth (CD), individual branch diameter (BD) as a function of BL, crown length (CL) as a function of total height (H), CL as a function of DBH (measured at 1.37 m above groundline) DBH as a function of CL, DBH as a function of crown diameter (CW) and CW as a function of CL and localized competition (see Table 3.1 for variable definitions). Data were randomly split into two datasets referred to hereafter as the development and evaluation datasests (Table 3.2). The development data were used for model-fitting and parameter estimation. The evaluation dataset was used for cross-validation and calculation of prediction error statistics. Branch length, maximum BL (BLmax), BD, and CL were log-normally distributed and therefore were log transformed for inclusion into models. The logarithmic transformation allows for the use of standard least-squares regression techniques (Sprugel 1983) and generally increases statistical validity by homogenizing the variance in the sample space (Baskerville 1972). Multiple model forms were explored in order to identify the best equations for predicting each dependent variable. The objective was to identify models that offered the best predictions of each of the dependent variables of interest. Thus the model forms considered follows work by Assman (1970), Maguire and Hann (1989), Colin and Houllier (1991), Colin and Houllier (1992), Mäkinen and Colin (1999), Umeki and Kikuzawa (2000), Vestøl and Høibø (2000), Gilmore (2001), Moberg (2001), and Mäkinen et al. (2003).

Branch population models were developed for three developmental stages of the sampled cherrybark oak FT's (n = 50). Each FT was classified into one of three categories, small sawtimber, pole or sapling, according to the developmental stage of the originating stand as defined by mean stand dbh; ≥ 10 inches and < 16 inches for small sawtimber, ≥ 5 inches and < 10 inches for pole-size stands and < 5 inches for sapling stands. The branch population of each crown was segmented by relative crown position (RCP). Relative crown position was a discrete variable assigned by determining the location of a particular branch within 20 possible equal vertically distributed sections of live crown. Mean branch population was calculated according to RCP and developmental stage. Cubic models were then fit for each developmental stage in order to develop predictive models of branch population within the live crown.

Model root mean square error (RMSE), Press RMSE and the coefficient of determination (R^2) statistic were used to evaluate the appropriateness of each fitted model and choose the "best" performer. In addition, in order to examine the performance of the developed models the following error statistics were calculated: (1) mean error ($E = \sum(y_i - \hat{y}_i)/n$); (2) mean absolute error ($|E| = \sum|y_i - \hat{y}_i|/n$); and (3) mean squared error ($E^2 = \sum(y_i - \hat{y}_i)^2/n$), where y_i is a measured observation, $\hat{y}_i$ is a predicted observation and n is the number of observations. Measured and predicted values were transformed to the original scale before calculating error statistics. Log transformed variables were back-transformed with the addition of a correction term, $C = \exp(\mathrm{SEE}^2/2)$, where $\mathrm{SEE} = \sqrt{[\sum(\log y_i - \log \hat{y}_i)^2/n\text{-}2)]}$, to account for the bias caused by the log transformation. The branch population dataset was not split due to a low sample number. Therefore, error statistics for the branch population models were calculated using the same data used to develop the models.

RESULTS AND DISCUSSION

Branch Length, Diameter and Population

Equations, parameters, parameter standard errors and model-fit statistics are presented in Table 3.3 for BL and BD and Table 3.4 for branch population. The best predictor of BL was a three parameter model that included both CD and HT as predictor variables, $log(BL) = b_0 + b_1(log(CD)) + b_2HT$ (eq. 2). The three parameter model (eq. 2) explained approximately 72 percent of the variation in BL ($P < 0.0001$) and all parameters were significant. Mitchell (1969; 1975) published a two parameter model for Douglas-fir in the form of equation 1, with CD as the only predictor variable. Equation 1, with only CD as an independent variable in the regression, resulted in a slightly lower coefficient of determination (0.67) and higher RMSE and Press RMSE (0.4634 and 0.4639, respectively). It is unknown whether the inclusion of the additional variable HT would improve Mitchell's BL model as in the case with cherrybark oak in this study. Cherrybark oak maintains a decurrent growth habit unlike Douglas-fir. Branch length growth is not as strongly regulated by the "leader" in decurrent crowns as it is in crowns with an excurrent growth habit. Branches on species with a decurrent growth habit will therefore continue to produce uninhibited primary growth proportional to height growth. Crown form may account for the increased model performance with the inclusion of HT as an explanatory variable. RCD alone was a poor predictor of BL (eq. 3).

An excurrent growth habit has allowed for the development of models that could ignore predicting BL, instead predicting BD directly from CD or DBH measurements (Mäkinen and Colin 1998) in numerous conifer species. Similarly models have been developed to predict maximum BD from whorl number in uninodal species (Mäkinen and Song 2002) which directly correlates to CD. Although BD could be predicted from CD in the case of cherrybark oak, there was a decrease in model performance (reduction in R^2 from 0.93 to 0.64) from the model used to predict BD from BL. If measured BL is available, BD predictions will have less associated error.

Branch diameter prediction equations were produced using a two-parameter and a three-parameter model. Both models included BL and one model included CD as a predictor variable (Table 3.3). No improvement was observed with the addition of the additional variable in the three-parameter model. As a result, the two-parameter model was determined to be optimal, explaining 93 percent of the variation in the BL data. The BL-BD model (eq. 5) is similar to conventional height-diameter equations. However, the relationship of the untransformed variables is more linear (Figure 3.2). The log transformation is needed, however, to satisfy the assumptions of least squares regression (Sprugel 1983).

Most of the references of branch population models are for use with conifer species such as Douglas-fir and Scots pine and center on predicting the number of branches within individual whorls (Ishii and McDowell 2002; Mäkelä and Mäkinen 2003; Mäkinen and Mäkelä 2003). The growth patterns of branches within decurrent crowns such as oak, does not allow for similar models. Instead, the crown must be segmented to produce an analogous predictor variable. RCP is similar to whorl number in that the segment of the crown is identified according to its position relative to the apex or crown base.

The branch population models (Table 3.4) produced in this study are to be used for trees in stands of small sawtimber (eq. 15), poles (eq. 16) and saplings (eq. 17) only. The coefficient of determination was highest for the pole BPop model (R^2 = 0.82) followed by the small sawtimber and sapling models (R^2 = 0.81 and 0.66, respectively). All three models displayed moderate predictive capabilities according to the prediction coefficient of determination (Table 3.5). In addition, each of the BPop models resulted in low prediction errors. It should be noted that the branch population dataset was not split in two (development and evaluation) due to the low sample number.

Crown Length and Diameter

The majority of available gross crown metric models have been developed with data from either conifer plantations (Maguire et al. 1994), mixed natural conifer stands (Bigging and Gill 1997), mixed natural hardwood stands (Bechtold 2002) or from open-grown tree studies (Goelz 1996). To the author's knowledge, no crown allometric models have been developed or are in the literature for plantation-grown hardwood.

Four crown length models were developed (Table 3.3) and tested (Table 3.5). Equations 7 and 8 are 2-parameter models including only HT as a predictor variable, whereas equation 9 is a 3-parameter model including CW and HT and equation 10 is a cubic model relating only HT to CL. The 3-parameter model (eq. 9) preformed best. The coefficient of determination for eq. 9 ($R^2 = 0.74$) was a significant improvement over that of eqs. 7, 8 and 10 ($R^2 = 0.49$, 0.56, and 0.59, respectively). In addition, the evaluation of eq. 9 resulted in the smallest e, MAD, MSEP and the largest prediction coefficient of determination (Table 3.5).

Terminology used by modelers in the United States refer to crown diameter models derived from stand-grown trees as "largest crown width" (LCW) models (Hann 1997). The models developed in this study therefore, resemble LCW models. However, the crown diameter models here are referred to simply as crown width (CW) models.

The relationship between crown diameter and stem diameter has been well established (Dawkins 1963; Hetherington 1967; Hann 1997; Hann 1999; Bechtold 2003; Hemery et al. 2005). Improvements to predictive models of CW, over simply using stem diameter or DBH, have included localized basal area competition (Bragg 2001), total height and crown length (Moeur 1981), vertical crown ratio (Bechtold 2002) and geographic referencing (Paine and Hann 1982). The top performing CW model in this study included three predictor variables, CL, HT and DBH (Table 3.3, eq. 14). The coefficient of determination for eq. 14 was 0.80, which is an improvement over the relationships reported by Bechtold (2002) for most hardwoods. The models reported by Bechtold (2002) are also for stand-grown trees but are more complex five-parameter models. Here, the inclusion of CL only slightly improved model performance over the model with only HT and DBH (eq. 13) that resulted in a coefficient of determination of 0.77. The model with only HT as a predictor variable proved to be a poor predictor of CW (R^2 = 0.13), while the model including only DBH resulted in a coefficient of determination of 0.55. The prediction error, mean absolute difference and mean square error of prediction for eq. 14 were all small (Table 3.5). In addition, the prediction coefficient of determination (0.77) indicates that the model is a fair predictor of new data from the evaluation dataset.

Crown diameter models were not improved when a competition index, such as Hegyi's (1974), was included. This could be an artifact of the relatively homogenous environment created by a plantation. Although the competition index did vary from tree to tree, the gradient of competitive environments surrounding individual crowns in natural mixed stands is likely much more varied.

CONCLUSION

Maximum performance for the BL, BD, CL and CW models were eqs. 2, 5, 9 and 14, respectively. These models can be used for predicting both gross crown dimensions from commonly measured tree characteristics and individual first-order branch characteristics from gross crown metrics. In addition, branch populations can be predicted for stems of different developmental stages from relative crown depth information. While the models developed here are limited to cherrybark oak, the relationships can be used to begin to develop general developmental patterns within the crowns of decurrent hardwood species.

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CHAPTER 4

Impacts of different plantation designs on the yield of even-aged cherrybark oak in plantations: Results from a hardwood plantation simulation system.

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ABSTRACT

A simulation system was developed by incorporating a branch occlusion model crown allometry models within the framework of a distance-dependent individual tree model. The simulation system, CherrybarkSQ, was developed to investigate the impact of plantation design on the development of clear wood within cherrybark oak stems. Of particular interest was the difference, if any, between pure and mixed species designs of similar density. After simulations of 10 timesteps, approximately 50 years, the mixed species design resulted in trees with a higher proportion of clear wood than the pure design of the same initial planting density. In addition, a widely-spaced pure cherrybark oak plantation produced more clear wood per tree than pure plantations at a denser spacing.

INTRODUCTION

Hardwood plantations, particularly those containing oak, have considerable potential to satisfy an increasing demand for quality hardwood products, for restoring degraded bottomland hardwood landscapes (Stanturf et al., 1998, Stanturf et al. 2001, Lockhart et al. 2006), and increasing available habitat for some wildlife species (Twedt et al. 1999, Twedt and Wilson 2002). Hardwood plantations can also be used within a carbon credit trading market system (Gardiner et al. 2004; Stanturf et al. 2004; Gardiner and Oliver 2005) as part of carbon sequestration plans, which are being adopted by numerous energy producing companies. As a result, numerous agencies have recently reported increases in the area of land being planted and the number of hardwood plantations being established. The successful establishment of bottomland hardwood seedlings has become a considerable focus in the forest ecology and forest management literature (Meadows and Stanturf 1997, Gardiner and Hodges 1998, Stanturf et al., 1998, Gardiner and Yeiser 2006).

Persistent complications with naturally regenerating some hardwoods species, the increased interest in hardwood plantations for satisfying wildlife and/or timber objectives, afforestation of former agricultural lands, and governmental cost-share programs promoting the planting of hardwoods, particularly within the Lower Mississippi Alluvial Valley, have highlighted the absence of or inadequacies of silvicultural prescriptions for artificial hardwood stands (Lockhart et al. 2006, Oswalt et al. in press[a], Oswalt et al. in press [b]). The impact of early plantation establishment decisions on the future quality of the planted hardwoods is poorly understood. The most common hardwood plantation prescription, borrowed from conifer plantation science, results in monospecific or in the case of oak (*Quercus* spp.), single-genus stands. There is little evidence, anecdotal or empirical, that suggests such a “pine-mentality” produces high-quality (excellent tree/log grade) hardwood stems with large volumes of clear wood. The anecdotal evidence that does exist suggests the opposite. That is, pure hardwood plantations may result in poor quality stems or a high ratio of knotty wood volume to clear wood volume.

The tree crown, because it is responsible for the vast majority of the photosynthetic capacity of the tree (Kramer et al. 1997), is a determinant of the rate of tree growth. The tree crown plays an important role in determining tree form, including the bole of the tree (Larson 1963). The crown is the location where the majority of the competition for aboveground space and light occurs. Each crown within the same canopy influences the growth and development of neighboring crowns. The size and shape of a tree's crown is largely determined by the space in which it develops. Consequently, the growth and form of the tree bole is influenced by canopy space dynamics.

Canopy space dynamics are in part dictated by the growth habit of the tree crowns that make up the canopy and the interactions over time between and among crowns. The interaction between crowns of different growth habits, excurrent and decurrent, will be disparate from that of the interaction between crowns of the same habit. The differential impact is the result of variable levels of interspecific and intraspecific competition (Canham et al. 2004). More specifically, single-habit canopies may lead to constricted crown width development and therefore smaller crowns with less photosynthetic capacity. There is little crown differentiation or stratification when the same species grows at the same rate on the same site as happens in a monoculture. Bole diameter growth is therefore, reduced in single-habit canopies compared to multi-habit canopies (DeBell et al. 1997, Menalled et al. 1998, Binkley 2003, Forrester et al. 2004).

The single growth habit canopy space created by monospecific hardwood plantations and the multi-habit canopy space created by multispecific hardwood plantations will impact bole and crown development differentially. Crowns impact developing boles including the development of internal wood characteristics. More specifically, multispecific hardwood plantations may result in greater production of clear wood than in monospecific hardwood plantations of the same density.

A simulation system, comprised of an individual tree model, crown allometric equations (Chapter 3) and a branch occlusion equation (Chapter 2), was used to evaluate the supposition that mixed species hardwood plantations of cherrybark oak and sweetgum would result in 1) greater average diameter breast height, 2) larger average cherrybark oak crown width, 3) smaller average individual stem knotty core volume, 4) greater average individual stem volume and 5) greater clear wood production than monospecific plantations with the same planting density of cherrybark oak only.

METHODS

Simulation System

The simulation system, referred to as the Cherrybark oak Stem Quality simulation system or CherrybarkSQ, consists of three main components. First, the Sylvan Stand Structure Model (Larsen 1991a, 1991b, 1994) or Sylvan, is an individual tree distance dependent model that projects forest growth based on the three-dimensional crown characteristics of trees. Sylvan is driven by crown size and change according to general principals of stand dynamics (Oliver and Larson 1996) in order to predict tree growth and development. Sylvan grows trees as a function of tree crown size and competition from neighboring tree crowns (Larsen 1991a, 1991b, 1994). The Sylvan model utilizes species-specific information, plantation design and site-specific growth rates to produce stem height, stem diameter, stem profiles, crown base, crown height and crown width for each tree at 5-year timesteps in the modeled plantation. The Sylvan model was chosen because it offered the needed flexibility to develop site-specific and species-specific coefficients in a relatively simplified manner, forecasts growth of real stands, produces realistic interspecific and intraspecific crown interactions, is largely influenced by crown size, is based on accepted stand dynamics theory and tracks crown recession over time. Most well-established forest growth models are not appropriate for the CherrybarkSQ system (see discussion in Chapter 1). Second, equations to describe branch population dynamics and crown allometry in plantation-grown cherrybark oak were developed (Chapter 3). Crown allometry and branch equations utilize the metrics produced by the Sylvan model in order to predict branch populations and individual branch characteristics for each tree. Lastly, a branch occlusion model was developed (Chapter 2) to predict the overwood necessary to encapsulate branches of variable basal diameters following crown recession. The coordinated models represent the simulation system used to evaluate the development of clear wood in the cherrybark oak stems in each simulated stand.

SYLVAN Parameterization

For this investigation, data were collected from two stands: a 50 year old pure cherrybark oak plantation on the Natchez Trace State Park in west Tennessee and a 24 year old mixed cherrybark oak / sweetgum plantation on the Noxubee Wildlife Refuge outside Starkville, Mississippi. Both stands were planted on a 2.74 x 2.74 meter spacing. The mixed stand was planted with alternating rows of sweetgum only and rows of alternating sweetgum and cherrybark oak. The planting pattern of the mixed stand resulted in a sweetgum stem adjacent to each cherrybark oak on all sides. Data from both the pure and mixed stands were used to parameterize the Sylvan model (see Larsen 1991a, 1991b, 1994) creating two different parameter sets. Parameter sets, based on stem analysis data collected at the pure site and repeated measurements at the mixed site, slightly differed according to growth rate (see Appendix B for a detailed description of the parameterization procedures). The pure stand had a site index, base age 50, for oak of approximately 110 feet and the location of the mixed stand had a site index for oak of approximately 105 feet (Clatterbuck 1987).

Simulations

Each simulated stand was one acre in size. Simulations were run 10 timesteps (timestep = 5 years) from a starting age of 10 years resulting in an age of 60 years at the completion of the simulation. Ten simulations were run for each plantation design, five simulations per parameter set, and means calculated for each timestep. Mean diameter at breast height (dbh), total height, crown length, crown width, stem volume, knotty core volume (Figure 4.1) and clear wood index (CWI) were calculated for each design. Stem volume was calculated using linear regression equations developed by the US Forest Service Southern Research Station Forest Inventory and Analysis program (Zarnoch et al. 2003) and tested to be the best volume equations available for cherrybark oak in the south by Oswalt and Saunders (In Press). Knotty core volume was estimated by summing the calculated volume of each knotty core segment calculated as the volume of the frustum of a cone. Knotty core segments were defined by the knotty core diameter (KCD) calculated at each timestep for the base of the live crown. Knotty core diameter was estimated using the equation $KCD = 3.17(BD^{0.32})$ developed in Chapter 2. Figure 4.2 depicts the estimation of the knotty core volume. An index of the proportion of knotty core volume to total stem volume (CWI) was calculated to indicate the fraction of stem volume that is comprised of clear wood. The index ranges from 0 to ∞ with lower CWI values representing greater proportions of clear wood (see Appendix A for a detailed description of the simulation procedures and calculation of CWI).

Four plantation designs were developed for comparison: (1) densely spaced monospecific cherrybark oak plantation with no intermediate treatments, (2) densely spaced monospecific cherrybark oak plantation thinned at age 20, (3) widely spaced monospecific cherrybark oak plantation with no intermediate treatments and (4) a multispecific cherrybark oak/sweetgum plantation arranged to mimic documented stand development patterns (Clatterbuck and Hodges 1988). Designs 1, 2, 3, and 4 are referred to hereafter as Pure, PureThin, Pure25 and Mix, respectively. The Pure design consisted of a pure cherrybark oak plantation on 2.74 x 2.74 meter (9 x 9 foot) spacing. The PureThin design consisted of the same initial plantation design as the Pure design, but was selectively thinned after timestep 2 (approximately 20 years of age). The thinning treatments reduced basal area an average of 29 percent for each model run. The Pure25 design is a cherrybark oak plantation on 7.62 x 7.62 meter (25 x 25 foot) spacing. The Mix design consists of a cherrybark oak/sweetgum mixture planted on a 2.74 x 2.74 meter spacing. The Mix plantation was designed to place a sweetgum adjacent to each cherrybark oak on 8 sides. Figure 4.3 shows the layout of each plantation management design.

Simple one-way analysis of variance (Proc GLM, SAS 2000) was used to detect differences among plantation designs for mortality, diameter, mean tree knotty core volume, mean stem volume, crown width, crown length, and individual CWI. Tukey's procedure was used for post-ANOVA mean separation to detect differences between plantation designs. The same procedures were used to detect differences between species in the Mix plantation design for mortality, crown width, diameter and height.

Sensitivity Analysis

The knotty core diameter equation was developed with limited information due to the difficulty in obtaining a more robust dataset (see Chapter 2). Therefore, an analysis is required that examines the impact of altering the parameters of the knotty core diameter equation. A brute force sensitivity analysis was used to investigate the impact of the knotty core diameter equation on the results of the CherrybarkSQ system. Specifically, the sensitivity analysis examined the impact on the clear wood index for each plantation design.

The CherrybarkSQ simulation system was rerun with the scaling exponent of the knotty core diameter equation altered to ± one standard error (scaling exponent = 0.32, SE = 0.04). The results of the Sylvan model runs used in the CherrybarkSQ simulations were also used for the sensitivity analysis to remove the stochastic components of the Sylvan model from the sensitivity analysis. Mean clear wood index was calculated for one standard error above and below the scaling exponent for each plantation design and timestep. The influence of branch diameter on knotty core diameter along the range of ± one standard error of the scaling exponent was quantified to better understand the importance of the knotty core diameter equation.

RESULTS

Mix Design – Differences Between Species

Initial (pre-simulation, timestep 0) stem characteristics are presented in Table 4.1 and post-simulation (timestep 10) stem characteristics are presented in Table 4.2. Mortality was greatest for sweetgum ($P < 0.0001$) and primarily occurred at or after timestep 8 (Figure 4.4). Mean cherrybark oak dbh was consistently greater than sweetgum (Figure 4.5a) and at the end of the simulation period was three times larger on average ($P < 0.0001$) with cherrybark oak and sweetgum dbh averaging 52.8 and 17.1 cm, respectively. Average cherrybark oak crown width was also consistently larger than average sweetgum crown width (Figure 4.5b). Following the simulation period, cherrybark oak crown length averaged 9.02 meters while sweetgum crown length averaged only 1.10 meters. Mean sweetgum crown length declined over time. Mean height was greatest for cherrybark oak (Figure 4.5c) at the end of the simulation period.

Comparison of Plantation Designs

Mortality was limited in the simulations of the Mix design and almost absent in the results from the simulations of the Pure25 management scenario (Figure 4.6). The Mix design resulted in an average of 22 cherrybark oak trees succumbing to density-dependent mortality and an average of 2 cherrybark oaks were lost over 10 timesteps in the Pure25 scenario. Cherrybark oak mortality in the PureThin design, as a result of the reduced density following the simulated thinning at timestep 2, was limited compared to the Pure design. Thinning removed on average 240 stems from each of the PureThin cherrybark oak plantations. Cherrybark oak mortality following simulated thinning averaged 142 stems. The greatest estimated cherrybark oak mortality among all simulated plantation designs occurred for the Pure scenario, averaging 427 stems ($P < 0.0001$) (Figure 4.7).

Mean dbh of cherrybark oak following 10 timesteps (estimated 50 years) was greatest for the Pure25 design followed by the Mix, PureThin and Pure designs ($P < 0.0001$). Mean dbh was 73, 53, 43, and 38 cm for the Pure25, Mix, PureThin and Pure designs, respectively (Figure 4.8). Mean dbh began to diverge among designs at timestep

3 as dbh growth slowed in the Pure plantations as compared to the remaining three designs (Figure 4.9). At the completion of the simulation timeframe the trajectory of mean dbh for the Pure25 design and the Mix design was still increasing, while the trajectory of mean dbh for the Pure PureThin designs were stabilizing.

The Pure25 plantation design resulted in the greatest average crown length (Figure 4.10a) and average crown width (Figure 4.10b) ($P < 0.0001$ and $P < 0.0001$, respectively). The mean crown length and crown width for the Pure25 design was 14.78 and 10.24 m, respectively. The Mix plantation design resulted in the second largest crown length and crown width. The mean crown length and crown width for the Mix design was 11.28 and 9.02 m, respectively. Separation in mean crown length and mean crown width among plantation designs occurred following 2 timesteps (Figure 4.11a and 4.11b, respectively). Both crown length and crown width for the Mix design were on an increasing course after 10 timesteps. No difference was found in mean crown width between the Pure and PureThin designs after 10 timesteps (full simulation period) with means of 7.35 and 6.98 m, respectively. However, each design differed from the other in mean crown length (Figure 4.10a) after 10 timesteps.

The pattern of the development of crown base branch diameter (Figure 4.12) resembled the pattern of crown length development. The Pure25 design had the largest average branch diameter produced at the base of the live crown, 79 mm ($P < 0.0001$) (Figure 4.13). Separation among the plantation designs with respect to crown base branch diameter appeared as early as timestep 2 (Figure 4.12). An increase in average branch diameter occurred following the simulated thinning treatment in the PureThin design. However, the increasing trajectory was not sustained. The Mix plantation design resulted in the second largest mean branch diameter, 65 mm. The PureThin and Pure designs have a mean branch diameter of 61 and 56 mm, respectively after 10 timesteps (Figure 4.13).

Average individual stem volume following simulation was greatest for the Pure25 design followed by the Mix, PureThin and Pure designs ($P < 0.0001$). Mean individual stem volume averaged 6.77, 3.53, 2.28 and 1.83 m^3 $stem^{-1}$ for the Pure25, Mix, PureThin and Pure designs, respectively (Figure 4.14a). Average stand volume was greatest for the Pure25 design followed by the PureThin, Mix and Pure designs (Figure 4.14b). The stand volume for the Pure and PureThin designs is distributed among a significantly greater number of stems (Figure 4.7). As a result mean individual stem volume over time was significantly less for the Pure and PureThin plantation designs ($P < 0.0001$) than for the Pure25 and Mix designs.

The total stand and mean individual stem knotty core volume differed among plantation designs ($P = 0.021$). The Pure25 had the lowest average stand knotty core volume. The Mix design had the second lowest average stand knotty core volume followed by the PureThin and Pure designs. The simulated thinning reduced the average stand knotty core volume by an average of 66 cubic feet.

Mean CWI following the full simulation period, 10 timesteps, was highest for the Pure design ($P < 0.0001$) (Figure 4.15). The Pure design averaged .58 followed by the PureThin, Mix and Pure25 designs with average values of .47, .36 and .23, respectively. The simulated thinning of the PureThin design significantly reduced the average CWI from timestep 2 (pre-thinning) to timestep 3 (post-thinning) (Figure 4.16). CWI for the Pure25 plantation design became fairly stable after approximately 5 or 6 timesteps. The

Pure and PureThin designs stabilized near the end of the simulation period. Disparately, the Mix plantation design was on a consistent decline from timestep 7 to timestep 10.

Sensitivity Analysis

The sensitivity analysis illustrates the importance of the knotty core diameter equation. Altering the scaling exponent of the knotty core diameter equation by ± one standard error resulted in changes in the final CWI value reported for each plantation design. For example, the range of CWI for the Mix design was 0.48 to 0.27 (Figure 4.17). As the scaling exponent increased the final CWI value, following 10 timesteps, increased. Thus as the scaling exponent increased clear wood volume per tree decreased.

The influence of the scaling exponent was dependent upon branch diameter. The scaling exponent of the knotty core diameter equation did not have an influence on the predicted knotty core diameter for smaller branch diameters (Figure 4.18). However, as branch diameter increased the influence of the scaling exponent was visible in larger values of the exponent. The knotty core diameter equation was more sensitive to changes in the scaling exponent when the branch diameter used to predict the knotty core was large.

DISCUSSION

Conventional approaches to modeling wood quality have relied on an assumed relationship between the current state of the wood and current tree and stand metrics. Such an approach is contrary to the hypothesis that tree structure, including internal wood properties, is gradually formed during growth and development. As a result, both the current state of a stem and the historical development of that stem are needed to predict current properties of wood quality (Kantola et al. 2007). The history of the development of the stand greatly influences the quality of wood within the member stems. The CherrybarkSQ simulation system incorporates the history of individual stem development as influenced by the development of the stand in which the stem is located. As a result, more accurate assessments of stem quality can be made.

The results from the simulations of the Mix plantation design resemble the developmental patterns of natural cherrybark/sweetgum mixtures that have been reported by Clatterbuck and Hodges (1988) and mixed plantations of cherrybark and sweetgum described by Lockhart et al. (2006). The primary exception is that of the height-age curves (Figure 4.4d) of the simulated cherrybark oak and sweetgum. Both Clatterbuck and Hodges (1988) and Lockhart et al. (2006) described scenarios in which sweetgum height growth increased at a greater rate than cherrybark oak before age 20. At or near age 20, cherrybark height equaled that of sweetgum and outpaced sweetgum height growth thereafter. Mean cherrybark height for the simulated Mix plantation design was consistently greater than the mean height of sweetgum. One possible reason could be that the initial height and crown size (crown length and width) of the cherrybark was greater than that of the sweetgum in the simulated stands.

A height growth pattern that is more consistent with previous studies may result from simulations where the cherrybark oak and sweetgum are similar in size. The treelist used for the CherrybarkSQ simulations reflects size differentials that existed in the stands measured for parameterizing the Sylvan model. The superior growth of sweetgum during the juvenile stages of development is not apparent in the simulation results. Increased separation between the simulated height-age curves of cherrybark oak and sweetgum does, however, begin to become readily apparent between age 20 and 25 (timesteps 3 and 4). Although some dissimilarity was documented between the simulations and the literature with respect to the height-age relationship, the pattern of crown development of the Mix simulations corresponds closely with previous studies (Clatterbuck and Hodges 1988, Aust 1985, Lockhart et al. 2006). Aust (1985) reported, for pure natural cherrybark oak stands, cherrybark oak crown lengths smaller than crown lengths reported by Clatterbuck (1985) for natural mixtures of similar ages and from similar sites.

The increase in cherrybark oak crown width is accompanied by a decrease in sweetgum crown width (Figure 4.5b). The development of the crowns of both species is from growth-habit mediated crown differentiation. Lateral crown expansion is greatest at a higher point within the crown in cherrybark oak than in sweetgum because of the decurrent growth habit of cherrybark and the excurrent habit of sweetgum. Additionally, the spreading decurrent growth habit facilitates the capture of free canopy space created by the tight, non-spreading crowns of the sweetgum. This dynamic, in combination with differences in the growth curves of cherrybark and sweetgum, allows cherrybark oak crowns to slowly capture canopy space relegating sweetgum stems to a subordinate position in the canopy. The slow capture of canopy space by cherrybark oak crowns coupled with the additional stand density supplied by sweetgum generates a developmental pattern that gives support to the development of cherrybark oak clear wood. The same pattern may be present in other hardwood monocultures.

Crown width development in the Mix design simulations resulted in much larger crowns than in simulations of the Pure design. The average crown width resulting from the Mix design approached that of the low-density Pure25 design indicating that the increased canopy space created by the decline of the sweetgum allowed cherrybark crowns to develop as if they were in a low-density environment. This low-density environment is similar to the Pure25 design following approximately 20-25 years. Crown widths in the Mix design may not develop to a similar width in the Pure25 design because even with full relinquishment of canopy space by the planted sweetgum, the cherrybark stems were spaced 18 feet apart as compared to 25 feet apart in the Pure25 design.

Comparison of results from the simulations of the Mix plantation design and the Pure design suggests that multispecific hardwood plantations result in greater production of clear wood than in monospecific hardwood plantations of the same density. One explanation for the difference in clear wood is that the different patterns of crown development between the Pure plantation design and that of the Mix design plays an important role. The Mix plantation design resulted in a lower CWI, indicating a higher percentage of clear wood and significantly less knotty core volume at the tree and stand level than the Pure design. Even though the Pure design resulted in greater total stand volume, the volume is distributed over more stems. Thus mean volume per cherrybark oak stem following the simulation period is considerably more for the Mix design. An effect of greater stem density is that any clear wood that is produced is also distributed among many more trees and may result in a higher production to yield ratio.

CherrybarkSQ simulations of the PureThin design indicate that a thinning at approximately age 20 (2 timesteps) increases crown size and subsequently increases diameter over that of the Pure design. Although tree size increased from the simulated thinning and the average tree CWI decreased, the PureThin design produced less clear wood, as indicated by average tree CWI, than the Mix plantation design. Total stand volume minus stand knotty core volume for the PureThin plantation design was slightly greater in clear wood volume than the Mix design. However, much like the Pure design, the volume is distributed across over twice as many stems as in the Mix design. The PureThin design would result in a higher production to yield ratio, similar to the comparison between the Mix and Pure designs. In addition, the radial depth of harvestable clear wood would be much greater with the Mix design. One implication would be greater clear wood yield per tree and increased dimensional product opportunities.

The low density monospecific management scenario of the Pure25 plantation design appeared to produce the greatest amount of clear wood, as indicated by mean tree CWI. The simulations resulted in low mean tree CWI, high mean individual stem volume, high stand volume, low stand level knotty core volume and low mean individual stem knotty core volume. Simulations of the low density design resulted in the largest crown size and consequently the largest mean branch size at the base of the live crown.

The distribution of clear wood on stems from the Pure25 design differs from the distributional pattern of clear wood on stems from the Mix design. Stems from both designs had similar heights at the end of the simulation period. Crown length, however, was greater for the Pure25 design, by approximately 3.5 meters. Clear wood was distributed over a shorter merchantable bole on stems from the Pure25 design than stems from the Mix design. The result was short-fat merchantable boles for the Pure25 design and taller merchantable lengths for the Mix design. This pattern is similar to the "restricted" and "unrestricted" growth pattern described by Clatterbuck and Hodges (1988).

The addition of the Pure25 design into the comparisons of plantation management scenarios indicates that diameter is the driving factor in the production of clear wood in the CherrybarkSQ model. Accordingly, because diameter growth is influenced by crown size in the Sylvan model, crown size plays an important role in the development of clear wood in the CherrybarkSQ model. The inclusion of the Pure25 design also indicates that the equation within CherrybarkSQ regulating knotty core diameter may be underestimating the impact of branch size on the knotty core. The relationship between branch size and knotty core diameter (overwood in chapter 2) is based on limited data. Additional longitudinal stem analysis data, such as used in chapter 2, is needed to improve the quantification of the relationship.

The relationship between branch diameter at crown base and crown size has been established for cherrybark oak (Chapter 3). CherrybarkSQ relies on this correlation to estimate the basal diameter of branches at the base of the live crown and subsequently the upper end knotty core diameter at each timestep. Crown size significantly influences knotty core volume within CherrybarkSQ. Therefore, temporal crown dynamics should be accurately modeled. The Sylvan model, used to produce gross crown metrics for CherrybarkSQ, is largely based on the crown and has been shown to produce good estimates. CherrybarkSQ should reasonably predict knotty core volume. However, this research represents the first application of Sylvan to cherrybark oak plantations. Several more cherrybark oak plantations should be tested to further evaluate the simulation system.

CONCLUSION

Simulations from the CherrybarkSQ simulation system illustrated the differential development between monospecific and multispecific hardwood plantations. The data analyzed from the simulations indicates that mixed species plantations will result in greater average diameter breast height of cherrybark oak, larger average cherrybark oak crown width, greater average individual stem volume of cherrybark oak and greater clear wood production in cherrybark oak than monospecific plantations with the same planting density of cherrybark oak only. However, the mixed species design did not produce smaller knotty core volume. Instead the Pure design simulation resulted in smaller average knotty core volume than the mixed species design. Even though the mixed species design had a smaller knotty core volume, the limited diameter growth caused by restricted crowns did not allow accumulation of clear wood on stems in the Pure plantations.

When comparing the Mix design to that of the Pure design, the simulations showed that larger crowns developed in the Mix design, the Pure design restricted crown width development. Restricted crown development negatively impacted diameter growth. In turn, the limited diameter growth in the Pure design restricted clear wood development on the exterior of the knotty core. Restricted crown development may be overcome by low-density plantation designs.

The CherrybarkSQ simulations aid in the understanding of the dynamics of cherrybark oak plantations. Furthermore, some generalizations from these simulations can be made about the development of pure hardwood plantations, regardless of species.

Restricted crown development that resulted from monospecificity lead to constrained diameter growth and therefore, limited development of clear wood on the exterior of the knotty core. Although the results of the CherrybarkSQ simulations for the various plantation designs in this study generally support the suggestion that a multispecific approach is appropriate for cherrybark oak plantations than monospecific, more research is necessary. Multiple plantation trials are needed that test variable species mixtures and spacing designs. In addition, rotation-length data is required to further evaluate the CherrybarkSQ model.

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CHAPTER 5

A case for a mixed-species approach to managing cherrybark oak plantations for optimizing stem quality.

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A case for a mixed-species approach to managing cherrybark oak plantations for optimizing stem quality.

ABSTRACT

Plantations will occupy an increasing proportion of the landscape in the future. This is particularly true for temperate hardwood plantations in the southern United States as reflected by the recent increases in afforestation activities in the Lower Mississippi Alluvial Valley. Hardwood plantation management has been constrained by limited information. The result has been reliance on a traditional pine plantation silviculture derived from over a half-century of pine plantation science. An alternative to monoculture management is necessary. That alternative is a multispecies management approach. Although mixed species plantations have a long history and some convincing research exists, little operational or commercial adoption has been realized. A value added approach should increase the utilization of mixed species hardwood plantations. Mixed species hardwood plantations have been shown to result in higher quality stems of some economically important species than monocultures. The increase in stem quality improves stand-level value. The knowledge that a multispecific approach to hardwood plantation management can improve stand-level value and therefore increase investment opportunities and returns should play a role in increasing research and commercial establishment of mixed species hardwood plantations.

INTRODUCTION

As early as 1822 foresters were advocating mixed-species approaches to hardwood plantation management (Nichols et al. 2006). Specifically, Hayes (1822) suggested that hardwood stems should be planted “at about twenty feet… the plantation should then be thickened up with other sorts of trees” in order to produce quality hardwood stems (Nichols et al. 2006). Additionally, Toumey and Korstian (1937) listed numerous advantages of mixed-species or “mixed crop” plantations that included 1) simplified management, 2) economic gains from multiple species, 3) simpler artificial restocking, 4) better site utilization, 5) decreased vulnerability to fungi and insects and 6) increased value of thinnings that could be realized by mixing the primary crop species with a subordinate species returning better prices at small diameters.

Shortly after Toumey and Korstian (1937) discussed the benefits of a mixed species approach, others began to question why more mixed plantations were not being established. Clear (1944) was quoted in Nichols et al. (2006) as lamenting the fact that although numerous foresters “the world over” had recognized the value of mixtures and while the “practice of raising mixed crops” had been well established, “there has been a tendency to depart from this old and well tried system and to lay down extensive areas under pure spruce and pine” (Clear 1944, Nichols et al. 2006). The movement toward a reliance on establishing monocultures appeared as a global development. Some believed, however that relying on monocultures was a departure from good silviculture. In the opinion of Toumey and Korstian (1937), “the formation of pure stands... is sometimes indicative of insufficient silvicultural knowledge on the part of the forester.”

The current situation differs little from Clear's (1944) description. While the discussion of mixed hardwood plantations has been ongoing for quite some time, widespread application has not been realized. Hardwood plantation silviculture has remained principally a research topic (Nichols et al. 2006), and a limited one with respect to temperate hardwoods of the United States. With the exception of Eucalypts (Florence 2004), very little hardwood plantation silviculture information has transitioned from academic literature to management guidelines.

An excellent example of the need for changing the management paradigm surrounding hardwood plantations in the United States, particularly the South, is illustrated by examining oak (*Quercus*) plantations. Most oak plantations are established as monocultures or coarse-grained mixtures consisting of monoculture blocks (Lockhart et al. 2006) Single species hardwood plantations do not simulate natural stands of mixed hardwood species. The intent is generally to establish plantations for timber production or carbon sequestration, restoration or mast production for wildlife (Twedt and Wilson 2002). The focus is primarily on the crop tree, oak. If mixed stands are desired, most foresters rely on natural seeding of light-seeded species from adjacent stands (Lockhart et al. 2006). Such reliance has been shown to fail to produce mixed stands beyond the plantation edge (Allen 1990). As a result, a more explicit approach to establishing mixed species or multispecific hardwood plantations is necessary.

The future of hardwood plantation management, particularly in the United States, requires a mixed-species approach. Mixed species plantation research is underway and has been reported with cherrybark oak-sweetgum (Lockhart et al, 2006), cherrybark oak-sycamore (Clatterbuck et al, 1987; Oliver et al, 1990), cherrybark oak-loblolly pine

(Clatterbuck 1989) and Nuttall oak-cottonwood (Gardiner et al, 2004). These studies have indicated that mixed-species plantations can increase the value of individual stems within the stand and the stand itself, increase carbon assimilation, satisfy societal pressures for increased diversity in plantations and decreased reliance on natural forests, and improve aesthetics. More importantly, results from this dissertation further support the adoption of a mixed-species approach to hardwood plantation management by offering an argument with significant economic implications. A mixed-species approach has the potential to positively impact stem quality by increasing the production of clear wood over monospecific stands.

The primary objective of this work was the development of a wood quality model that when combined with an individual-tree model could be utilized to evaluate cherrybark oak plantation management scenarios and explore the implications of mixed species hardwood plantation management on wood quality. The CherrybarkSQ simulation system is the primary product of this research and is a powerful tool to help managers explore cherrybark oak plantation management options. In addition, the CherrrybarkSQ system is an important tool that can be used by hardwood plantation researchers to better understand the impact of plantation arrangement and species choices on the development of high-quality hardwood stems, particularly oaks. The approach taken with the development of CherrybarkSQ can easily be adapted for developing similar systems for use with other hardwood species. The approach involved three principal components: 1) Predicting branch occlusion following first-order branch death, 2) Modeling the characteristics of first-order branches within the crown of developing cherrybark oak stems and 3) Integrating the combined branch occlusion and branch characteristics models within an individual-tree model for creating the CherrybarkSQ simulation system.

BRANCH OCCLUSION

High-quality stems are defined by high proportions of clear wood. Similarly, the principal factors causing degrade in most logs are branches and knots. Therefore, a key component to predicting the development of clear wood is understanding the relationship between branch size and branch occlusion in developing stems. The objective of Chapter 2 was the construction of a simple branch occlusion equation to be used to predict the cover-up of dead first-order branches in cherrybark oak.

The branch occlusion model developed is a power function where overwood, defined as the linear distance from the pith to the point where clear wood development begins, is a function of the maximum diameter a first-order branch achieves. Maximum branch diameter explained 50 percent of the variation in overwood in the dataset used. The dataset is limited because it represents 108 branches from three logs from one sampled tree. In addition, large diameter branches are few in the data because the sampled tree was from a densely stocked stand. The data used to develop the branch occlusion model is extremely difficult and expensive to obtain. Data must either be collected over an extended time period (e.g. 40 plus years), destructively sampled with large equipment or electronically imaged with generally unavailable equipment.

Although data limitations are apparent and the model only has moderate predictive ability, the resultant model represents the only applicable information for describing natural branch occlusion in cherrybark oak. Branch occlusion models in the scientific literature are dominated by pruning studies and primarily describe relationships in conifer species. No applicable model was found in the literature for describing branch occlusion in hardwoods, specifically oaks. In addition, the majority of the available models included variables specific to pruned stems.

BRANCH MODELING

A key to building the sophistication needed to predict clear wood production in cherrybark oak stems is a healthier comprehension of the development of individual first-order branches within the live crown. In Chapter 3 numerous relationships were explored in order to construct equations to predict the number, diameter and length of individual first-order branches. The development of branch length and branch diameter equations for first-order branches at the base of the live crown were of particular interest for the development of the CherrybarkSQ simulation system.

The resultant models can be used for predicting both gross crown dimensions from commonly measured tree characteristics and individual first-order branch characteristics from gross crown metrics. In addition, branch populations can be predicted for stems of different developmental stages from relative crown depth information. While the models developed are limited to cherrybark oak, the relationships can be used to begin to develop general developmental patterns within the crowns of decurrent hardwood species.

CHERRYBARKSQ

The CherrybarkSQ simulation system was designed to test the influence of plantation design on the production of clear wood. Chapter 3 specifically tested the hypothesis that a mixed species plantation design would result in the production of a greater amount of clear wood than a monospecific design of the same initial planting density.

Simulations from the CherrybarkSQ simulation system illustrated the differential development between monospecific and multispecific hardwood plantations. The results from the simulations indicates that mixed species plantations will result in greater average diameter breast height of cherrybark oak, larger average cherrybark oak crown width, greater average individual stem volume of cherrybark oak and greater clear wood production in cherrybark oak than monospecific plantations with the same planting density. However, the mixed species design did not produce smaller knotty core volume. Instead the Pure design simulation resulted in smaller average knotty core volume than the mixed species design. Even though the mixed species design had a smaller knotty core volume, the limited diameter growth caused by restricted crowns did not allow accumulation of clear wood on stems in the Pure plantations.

When comparing the Mix design to that of the Pure design, the simulations showed that larger crowns developed in the Mix design; the Pure design restricted crown width development. Restricted crown development negatively impacted diameter growth. In turn, the limited diameter growth in the Pure design restricted clear wood development on the exterior of the knotty core. Restricted crown development may be overcome by low-density plantation designs.

The CherrybarkSQ simulations aid in the understanding of the dynamics of cherrybark oak plantations. Furthermore, some generalizations from these simulations can be made about the development of pure hardwood plantations, regardless of species.

Restricted crown development that resulted from monospecificity lead to constrained diameter growth and therefore, limited development of clear wood on the exterior of the knotty core. Although the results of the CherrybarkSQ simulations for the various plantation designs in this study generally support the suggestion that a multispecific approach is appropriate for cherrybark oak plantations than monospecific, more research is necessary. Multiple plantation trials are needed that test variable species mixtures and spacing designs. In addition, rotation-length data is required to further evaluate the CherrybarkSQ model.

RESEARCH NEEDS

The research need for temperate hardwood plantation management is mixed species plantation trials and further studies of species interactions. Specifically, there is a large need for mixed species oak plantation trials. Such research accompanied with operational demonstrations would show industry and small private landowners that mixed species hardwood plantations are worth the investment. Only a few case studies (Clatterbuck et al. 1987, Oliver et al. 1990, Lockhart et al. 2006) could be found that investigated fine-grained mixtures of temperate hardwood species in plantations. Plantation trials designed to investigate both spacing and mixtures of various species are needed. Much like the intense silviculture research dedicated to southern pine plantations in the second half of the twentieth century (Carter and Foster 2006), robust research programs are required to investigate the numerous mixed temperate species plantation possibilities within each region of the United States. However, additional research will not fill the information gap alone. Existing research, in combination with results from new plantation trials, must be synthesized and packaged for consumption by those outside of academia, principally commercial organizations. Within the academic and forest restoration communities the impression is often presented that there is considerable support for mixed species plantations. Nichols et al. (2006) point out the naïveté of the academics and restorationists. While there may be support among a small community of forest ecologists, restoration ecologists, and research silviculturists, the private sector has yet to "buy in" to mixed species hardwood plantations.

Future plans include incorporating simulation results from CherrybarkSQ into a saw simulator with the capability of sawing each simulated three dimensional log into products. The results from a sawing simulation package can provide a more comprehensive account of product recovery with respect to the monetary value of each log. Product recovery can then be compared among plantation designs in order to predict stand value more accurately. Furthermore, the development of the capability to track individual branches within the log will furnish an additional layer of sophistication that allows sawing simulators to better utilize specific branch information in order to assess the impacts of plantation design on branch and knot development and lumber product recovery.

CONCLUSION

The key to gaining support for mixed species plantations is illustrating the increased stem quality that can be derived from a mixed species management approach. Stand monetary value is directly proportional to the quality of the stems within the given stand. Similarly, stem quality is directly proportional to proportion of the stem that is made up of clear wood. So, higher proportions of clear wood within a stem translates to higher economic value. Hardwood plantation silviculture research needs to address this relationship through investigating the impacts of management decisions on stem quality. The results of this dissertation contribute to that end.

Abundant evidence exists that a mixed species approach is optimal to that of hardwood monocultures, specifically when the crop tree is cherrybark oak. Not only does the adoption of mixed species plantation offer benefits that have significant economic implications, a mixed species approach to hardwood plantation management presents ecological and social benefits as well. A mixed species approach, when implemented correctly, facilitates canopy stratification in planted hardwood stands. With the proper knowledge of the silvical characteristics of the primary crop tree and possible component species, mixed species hardwood plantations can be designed to optimize canopy stratification and therefore, stem quality.

Broad commercial support for mixed species plantations or a multispecific approach to hardwood plantation management will require an argument with significant economic implications. Reliable financial data is not available that compares the return from production scale plantations of monocultures and mixed species plantings. Some information exists regarding short rotation biomass plantations (Whitesell et al. 1992); however this is of little use to foresters attempting to persuade landowners to invest in long-term sawtimber production via mixed species plantations.

CherrybarkSQ, which incorporates models developed to predict the occlusion of dead first-order branches (Chapter 2) and models to predict the characteristics of first-order branches within the live crown (Chapter 3), is a valuable tool for both forest land managers and hardwood plantation researchers. The results of the cherrybark oak plantation simulations from CherrybarkSQ provide persuasive information about the economic gain potential through the adoption of a mixed species management approach. The simulation results aid in revealing the usefulness of CherrybarkSQ as a tool that can help guide hardwood plantation research. Further refinements in the underlying equations, specifically the branch occlusion equation, are needed to increase the power and utility of the system. However, the approach appears to be strong with respect to the ease of adaptability to other species.

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APPENDICES

APPENDIX A – Figures and Tables

Figure 1.1 Multispecific stand development model for cherrybark oak and the impact on clear wood production.

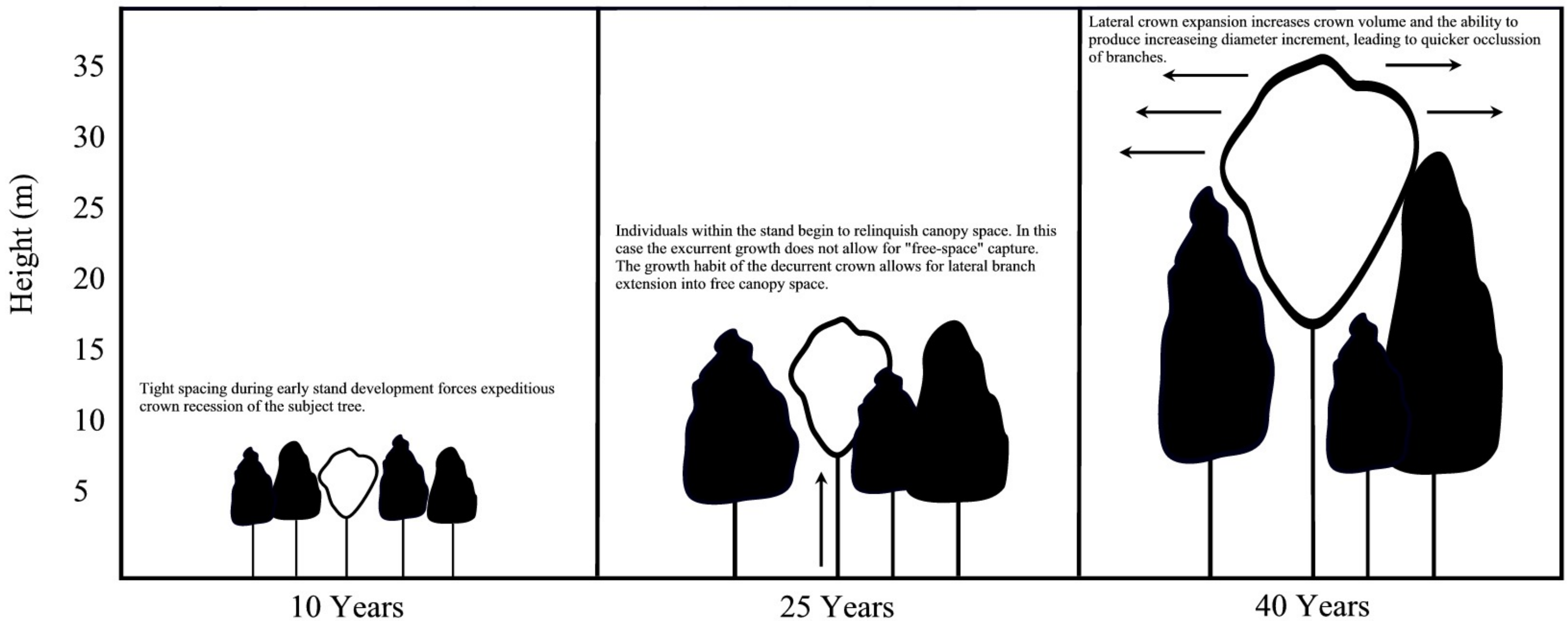


Figure 1.2 Conceptual diagram of the CherrybarkSQ model, including the Crown Allometry, Branch Occlusion and SYLVAN models along with the Knotty Core and Clear Wood calculators, the SylView and SVS graphical interfaces and user access points.

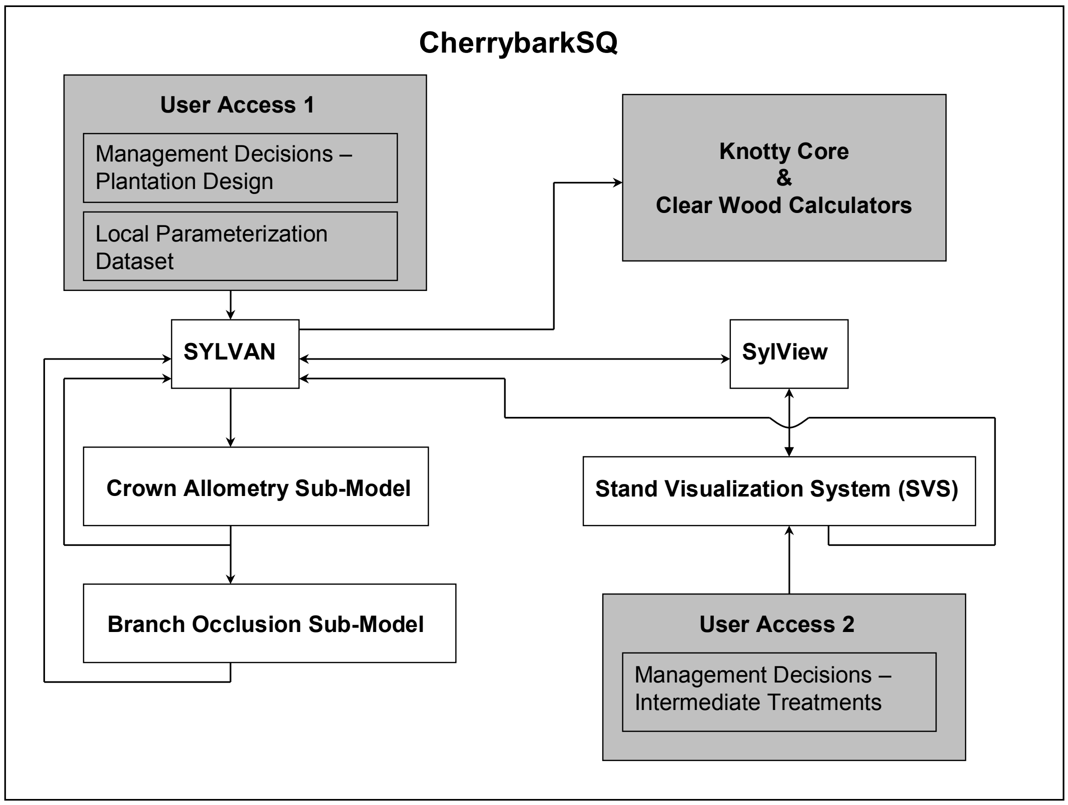


Figure 1.3 Porte and Bartelink's (2002) forest growth model classification system.

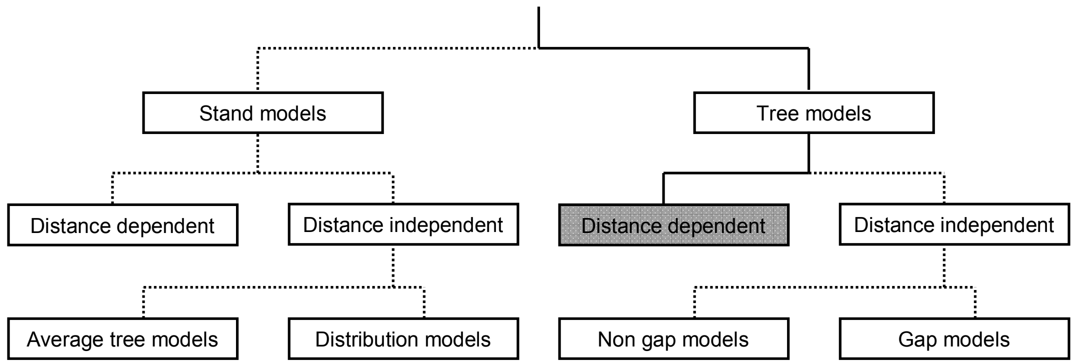


Table 1.1 References for models discussed.

Model	Reference
JABOWA	Botkin et al. (1972)
FORET	Shugart and West (1977)
SILVA	Kercher and Axelrod (1981)
ZELIG	Smith and Urban (1988)
FORSKA	Prentice and Leemans (1990)
SPACE	Busing (1991)
SORTIE	Pacala et al. (1993)
FIRE-BGC	Keane et al. (1996)
FORMOSAIC	Liu and Ashton (1998)
PICUS	Lexer and Honninger (2001)

Figure 2. 1 Flowchart illustration of model development and evaluation.

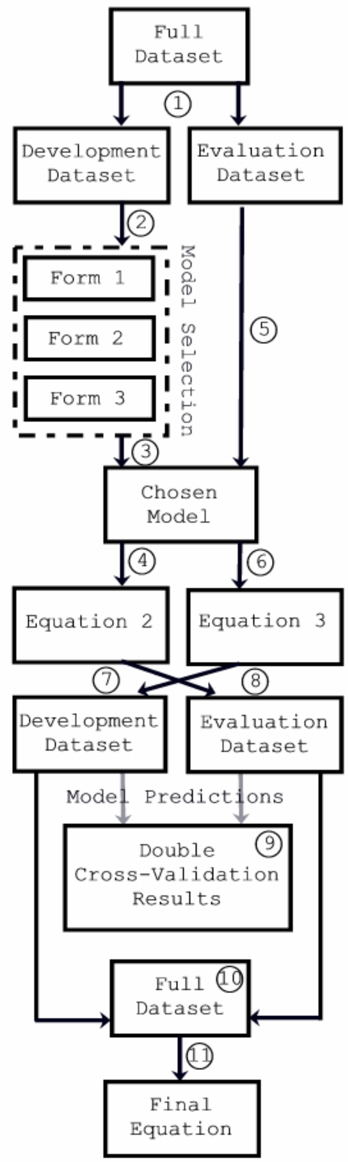


Table 2. 1 Summary statistics for each fitted model of branch-knot diameter and overwood.

	----------------- Model Form ------------------		
Statistic	$Y = Y_0 + aX$	$Y = a(1\text{-}e^{-bX})$	$Y = aX^b$
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

Figure 2. 2 Branch-knot diameter and overwood with non-linear model fitted to the model-building dataset (a) and actual by predicted overwood (b) using validation dataset for cherrybark oak planted in Vicksburg, MS.

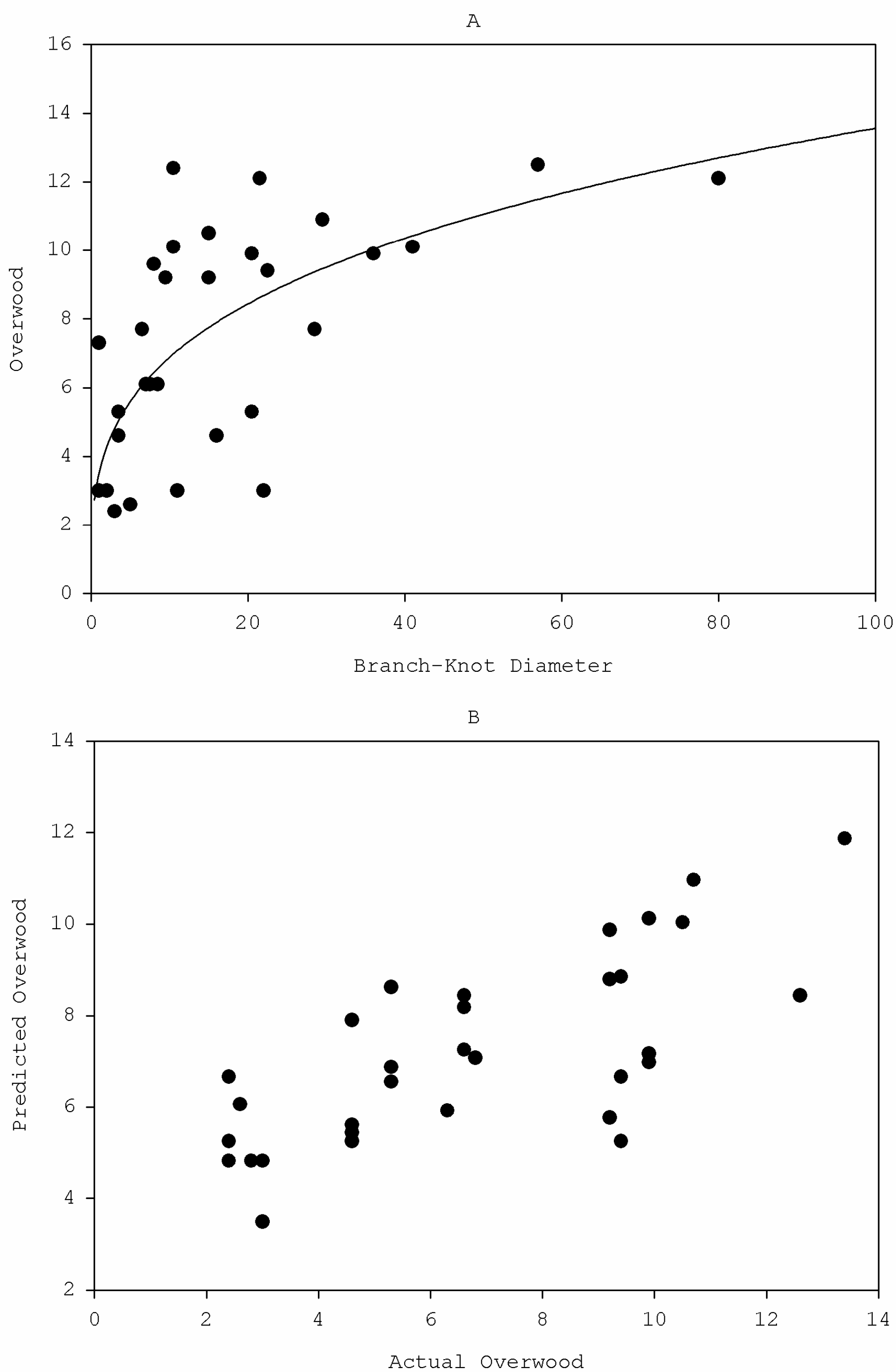


Table 2. 2 Double cross-validation summary for the fitted nonlinear model form $Y = aX^b$ for branch-knot diameter and overwood.

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	

Figure 2. 3 Branch-knot diameter and overwood with non-linear model fitted to the validation dataset (a) and actual by predicted overwood (b) using model-building dataset for cherrybark oak planted in Vicksburg, MS.

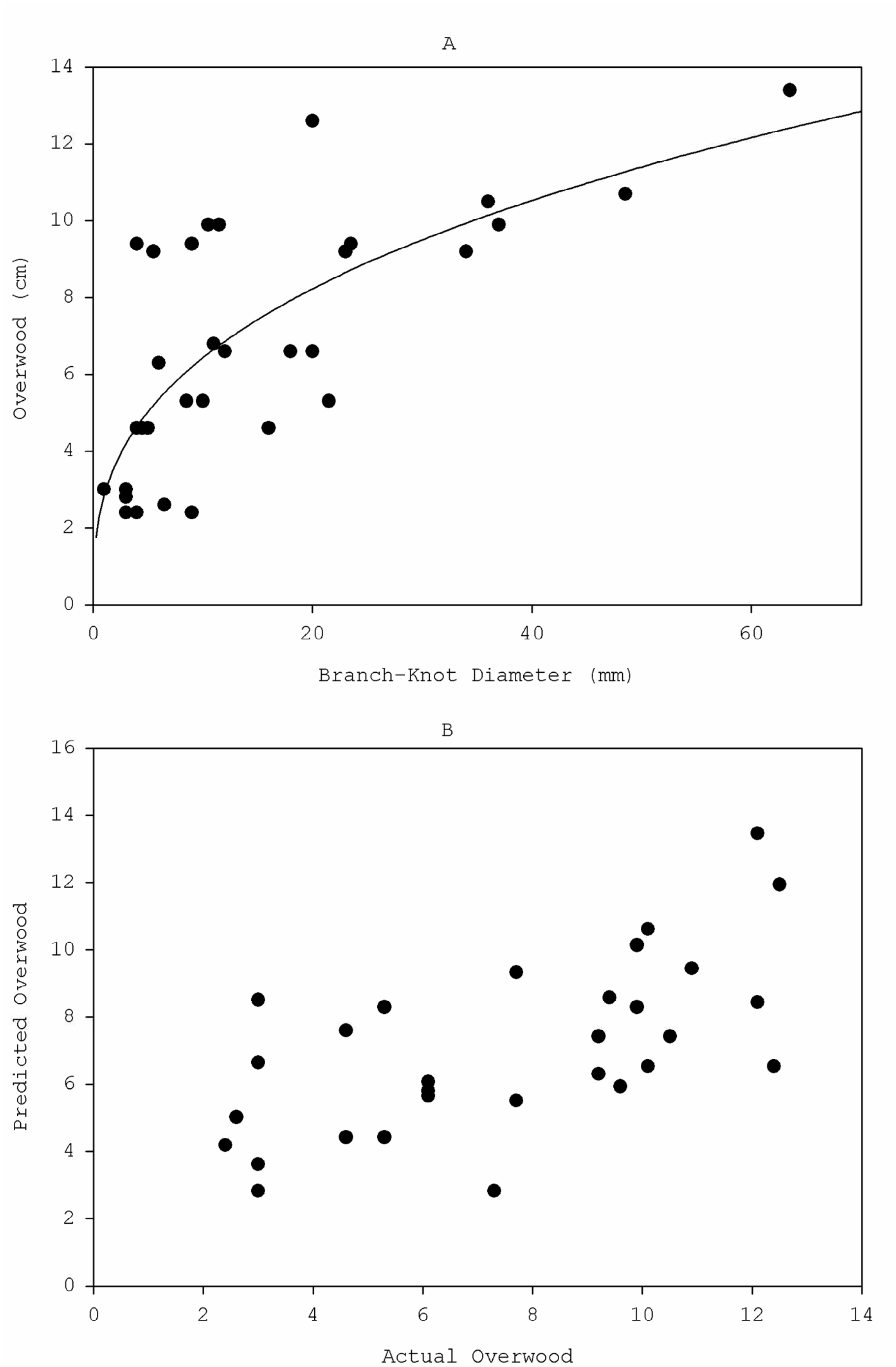


Figure 2. 4 Branch-knot diameter and overwood with non-linear model fitted to the full dataset for cherrybark oak planted in Vicksburg, MS.

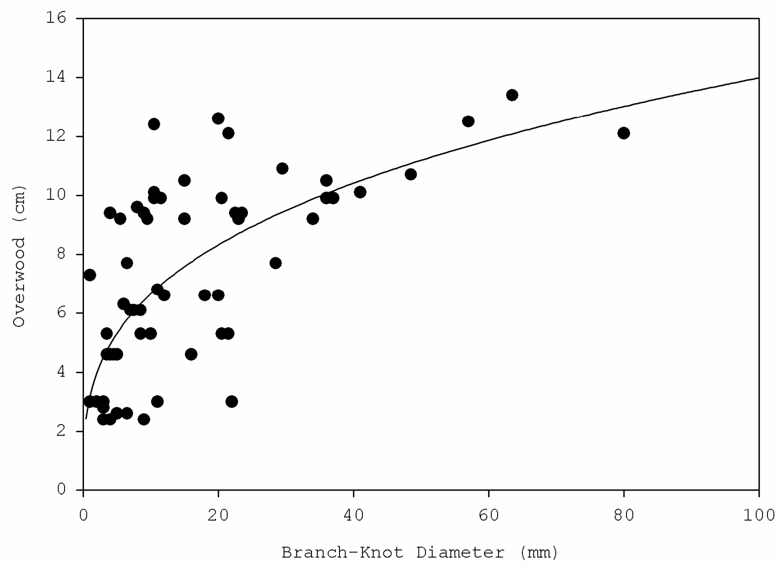


Figure 3. 1 Stand locations in Tennessee.

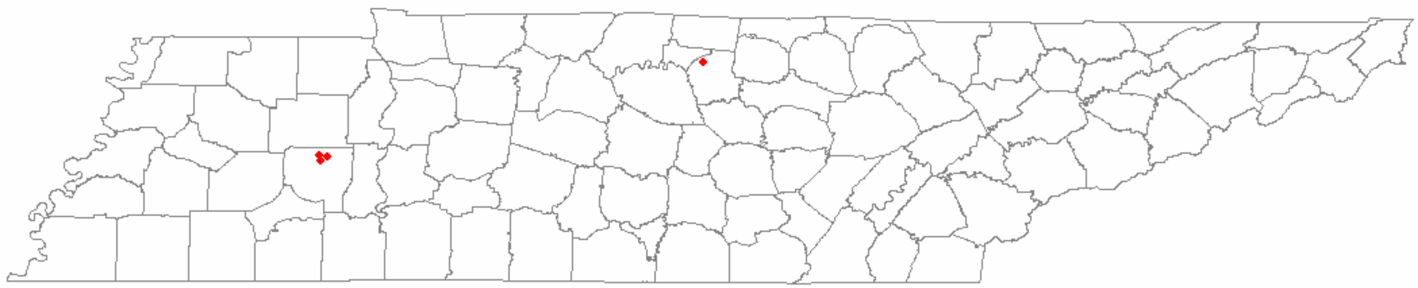


Table 3. 1 Variable definitions for Chapter 3.

Variable	Definition
BD	Branch diameter (mm)
BL	Branch Length (m)
BLmax	Maximum branch length (m)
CD	Crown depth (m)
RCD	Relative crown depth
DBH	Stem diameter at breast height (cm)
H/D	Ratio of height to diameter
CW	Crown diameter (width) (m)
HT	Height (m)
CL	Crown length (m)
RCP	Relative crown position (a variable to describe the location of a population of branches in 20 equal live-crown segments)

Table 3. 2 Descriptive statistics for each common variable use in model development and evaluation for each dataset (Development and Evaluation).

Statistic	BD (mm)	BL (m)	CD (m)	DBH (cm)	H/D Ratio	CW (m)	HT (m)	CL (m)
Development dataset								
Maximum	154.94	15.55	18.90	49.53	12.16	11.26	32.40	26.94
3rd Quartile	33.02	3.63	6.46	26.67	9.04	5.43	26.55	12.59
2nd Quartile	21.00	2.16	4.33	21.08	7.95	4.17	21.76	9.66
1st Quartile	12.70	1.19	2.47	16.51	6.77	3.19	14.63	7.22
Minimum	2.54	0.09	0.15	5.84	4.59	0.44	5.64	4.05
Mean	27.02	2.68	4.88	21.84	8.00	4.43	20.32	10.45
Std. Deviation	20.55	2.09	3.14	9.02	1.59	1.80	7.20	4.46
n	915	915	915	223	223	223	223	223
Evaluation dataset								
Maximum	124.46	10.46	16.03	43.43	12.77	9.27	31.73	23.20
3rd Quartile	32.00	3.31	5.94	28.70	9.39	5.15	27.39	13.05
2nd Quartile	20.32	2.01	4.05	22.10	8.00	3.97	23.36	0.74
1st Quartile	12.70	1.10	2.39	16.51	6.76	3.05	14.47	7.29
Minimum	3.00	0.09	0.15	3.30	4.97	0.93	5.06	2.87
Mean	25.51	2.47	4.56	22.27	8.14	4.27	20.78	10.38
Std. Deviation	19.07	1.93	2.94	9.67	1.72	1.75	7.66	4.46
n	305	305	305	74	74	74	74	74

Figure 3. 2 Relationship between untransformed branch diameter and branch length.

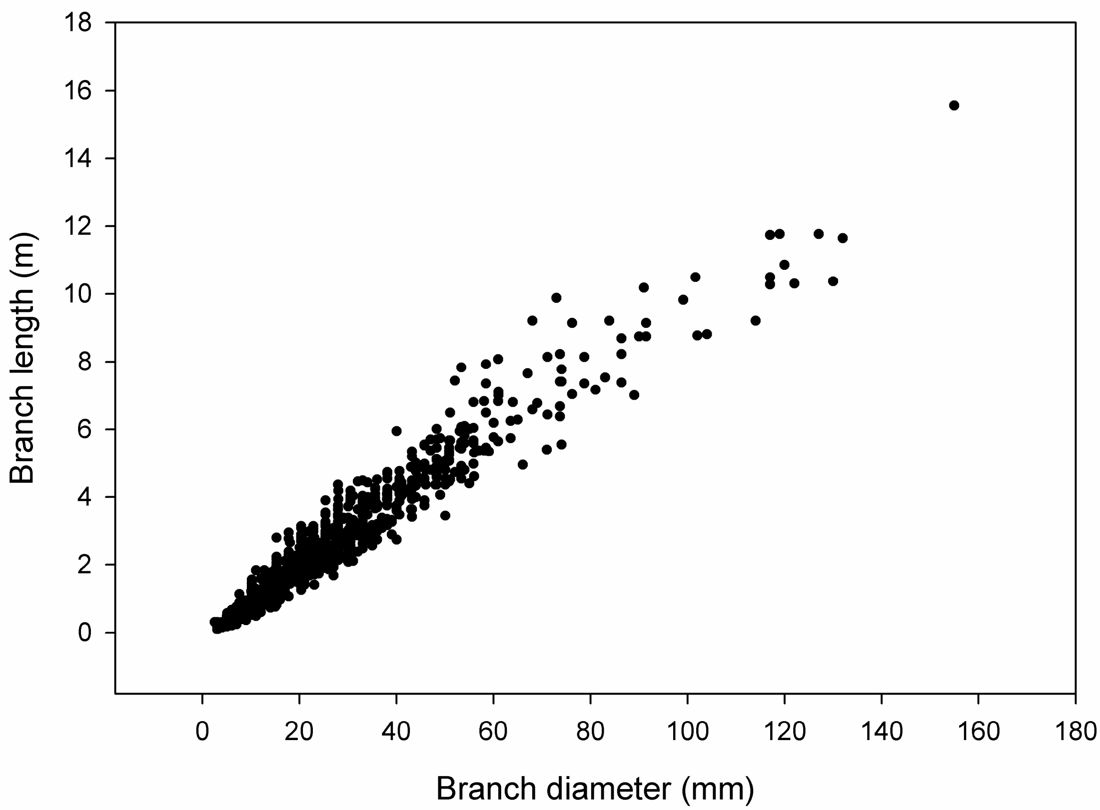


Table 3. 3 Model form, parameters (standard errors) t statistics, root mean square error (RMSE), press RMSE, coefficient of determination (R^2) and associated model P-value for model equations 1-14.

Eq.	Model Form	Parameters (SE)	*t* Ratio (p-value)	Model RMSE	Press RMSE	R^2	P-value
	Branch Length						
1	log(BL) = b0 + b1(log(CD))	b0 = -0.5853 (0.0331)	-17.66 (<0.0001)	0.4634	0.4639	0.67	<0.0001
		b1 = 0.9352 (0.0215)	43.40 (<0.0001)				
2	log(BL) = b0 + b1(log(CD)) + b2HT	b0 = -0.9071 (0.0400)	-22.71 (<0.0001)	0.4282	0.4289	0.72	<0.0001
		b1 = 0.8915 (0.0202)	44.10 (<0.0001)				
		b2 = 0.0209 (0.0017)	12.54 (<0.0001)				
3	log(BL) = b0 + b1(RCD)	b0 = -0.1129 (0.0487)	-2.32 (=0.0205)	0.6900	0.6907	0.28	<0.0001
		b1 = 1.5944 (0.0854)	18.68 (<0.0001)				
	Maximum Branch Length						
4	log(BLmax) = b0 + b1(log(CDI))	b0 = -0.0451 (0.0352)	-1.28 (=0.2007)	0.2937	0.2944	0.79	<0.0001
		b1 = 0.7904 (0.0202)	39.10 (<0.0001)				
	Branch Diameter						
5	log(BD) = b0 + b1(log(BL))	b0 = 2.4877 (0.0081)	305.33 (<0.0001)	0.1876	0.1880	0.93	<0.0001
		b1 = 0.8258 (0.0077)	107.87 (<0.0001)				
6	log(BD) = b0 + b1(log(BL)) + b2(log(CD))	b0 = 2.4658 (0.0155)	158.81 (<0.0001)	0.1874	0.1880	0.93	<0.0001
		b1 = 0.8076 (0.0134)	60.33 (<0.0001)				
		b2 = 0.0253 (0.0153)	1.66 (=0.0980)				

Table 3.3 continued.

Eq.	Model Form	Parameters (SE)	*t* Ratio (p-value)	Model RMSE	Press RMSE	R^2	P-value
	Crown Length						
7	CL = b0 + b1(HT)	b0 = 1.6466 (0.6409)	2.57 (=0.0108)	3.1907	3.2047	0.49	<0.0001
		b1 = 0.4333 (0.0297)	14.57 (<0.0001)				
8	log(CL) = b0 + b1(HT)	b0 = 1.4108 (0.0544)	25.94 (<0.0001)	0.2708	0.2716	0.56	<0.0001
		b1 = 0.0420 (0.0025)	16.64 (<0.0001)				
9	log(CL) = b0 + b1(CW) + b2(HT)	b0 = 1.1424 (0.0473)	24.15 (<0.0001)	0.2089	0.2105	0.74	<0.0001
		b1 = 0.1026 (0.0083)	12.30 (<0.0001)				
		b2 = 0.0328 (0.0021)	15.76 (<0.0001)				
10	CL = b0 + b1(HT) + b2(HT-20.32)^2 + b3(HT-20.32)^3	b0 = 3.9687 (1.4040)	2.83 (=0.0051)	2.8791		0.59	<0.0001
		b1 = 0.2478 (0.0677)	3.66 (=0.0003)				
		b2 = 0.0401 (0.0054)	7.23 (<0.0001)				
		b3 = 0.0031 (0.0031)	4.57 (<0.0001)				
	Crown Diameter						
11	CW = b0 + b1(HT)	b0 = 2.6172 (0.3384)	7.73 (<0.0001)	1.6850	1.6912	0.13	<0.0001
		b1 = 0.0891 (0.0157)	5.67 (<0.0001)				
12	CW = b0 + b1(DBH)	b0 = 1.2083 (0.2136)	5.66 (<0.0001)	1.2153	1.2214	0.55	<0.0001
		b1 = 0.1474 (0.0090)	16.30 (<0.0001)				
13	CW = b0 + b1(HT) + b2(DBH)	b0 = 2.4393 (0.1753)	13.91 (<0.0001)	0.8721	0.8790	0.77	<0.0001
		b1 = -0.2130 (0.0147)	-14.46 (<0.0001)				
		b2 = 0.2892 (0.0118)	24.60 (<0.0001)				
14	CW = b0 + b1(log(CL)) + b2(HT) + b3(DBH)	b0 = 0.3932 (0.3731)	1.05 (=0.2931)	0.8083	0.8167	0.8	<0.0001
		b1 = 1.4695 (0.2412)	6.09 (<0.0001)				
		b2 = -0.2285 (0.0139)	-16.46 (<0.0001)				
		b3 = 0.2450 (0.0131)	18.71 (<0.0001)				

Table 3. 4 Model form, parameters, coefficient of determination (R2) and associated p-value for model equations 15-17.

Eq.	Model Form	Parameters	Model RMSE	R^2	P-value
15	SawtimberBPop = b0 + b1(RCP) + b2(RCP-0.53611)^2 + (RCP-0.53611)^3	b0 = 0.1952	0.2053	0.81	<0.0001
		b1 = 2.0195			
		b2 = -2.8628			
		b3 = -6.3006			
16	PoleBPop = b0 + b1(RCP) + b2(RCP-0.53611)^2 + (RCP-0.53611)^3	b0 = 2.3126	0.4024	0.82	<0.0001
		b1 = 0.3416			
		b2 = -10.2270			
		b3 = -6.6580			
17	SaplingBPop = b0 + b1(RCP) + b2(RCP-0.53611)^2 + (RCP-0.53611)^3	b0 = 1.6835	0.3721	0.66	0.0013
		b1 = -0.2429			
		b2 = -3.6102			
		b3 = -6.8858			

Table 3. 5 Model evaluation statistics for equations 1-17.

Eq.	e	MAD	MSEP	R_p^2
Branch Length				
1	0.140	0.803	1.391	0.63
2	-0.186	0.730	1.099	0.71
3	-0.472	1.371	3.343	0.10
Maximum Branch Length				
4	0.162	0.957	1.882	0.68
Branch Diameter				
5	-0.119	3.579	29.849	0.92
6	-0.171	3.598	30.296	0.92
Crown Length				
7	-0.268	2.182	8.103	0.59
8	-0.482	2.195	7.990	0.59
9	-0.026	1.590	4.907	0.75
10	-0.609	2.217	8.690	0.56
Crown Diameter				
11	0.729	1.225	2.655	0.12
12	-0.220	0.934	1.230	0.59
13	-0.183	0.711	0.842	0.72
14	-0.131	0.635	0.706	0.77
Branch Population				
15	0.075	0.200	0.090	0.560
16	0.085	0.358	0.221	0.662
17	0.041	0.255	0.114	0.639

e = prediction error, MAD = mean absolute difference, MSEP = mean square error of prediction, Rp2 = prediction coefficient of determination

Figure 4. 1. Conceptual diagram depicting the clear wood and knotty core portions of a tree bole.

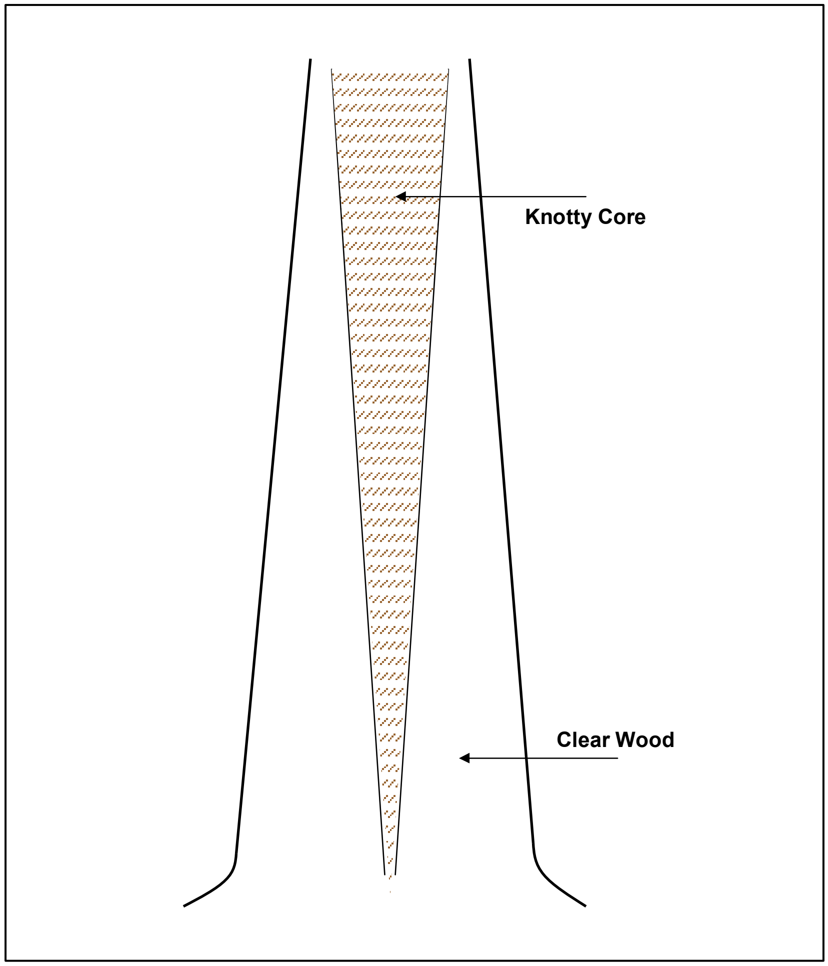


Figure 4. 2. Diagram depicting the procedure used to calculate knotty core volume within the Knotty Core calculator of the CherrybarkSQ simulation system.

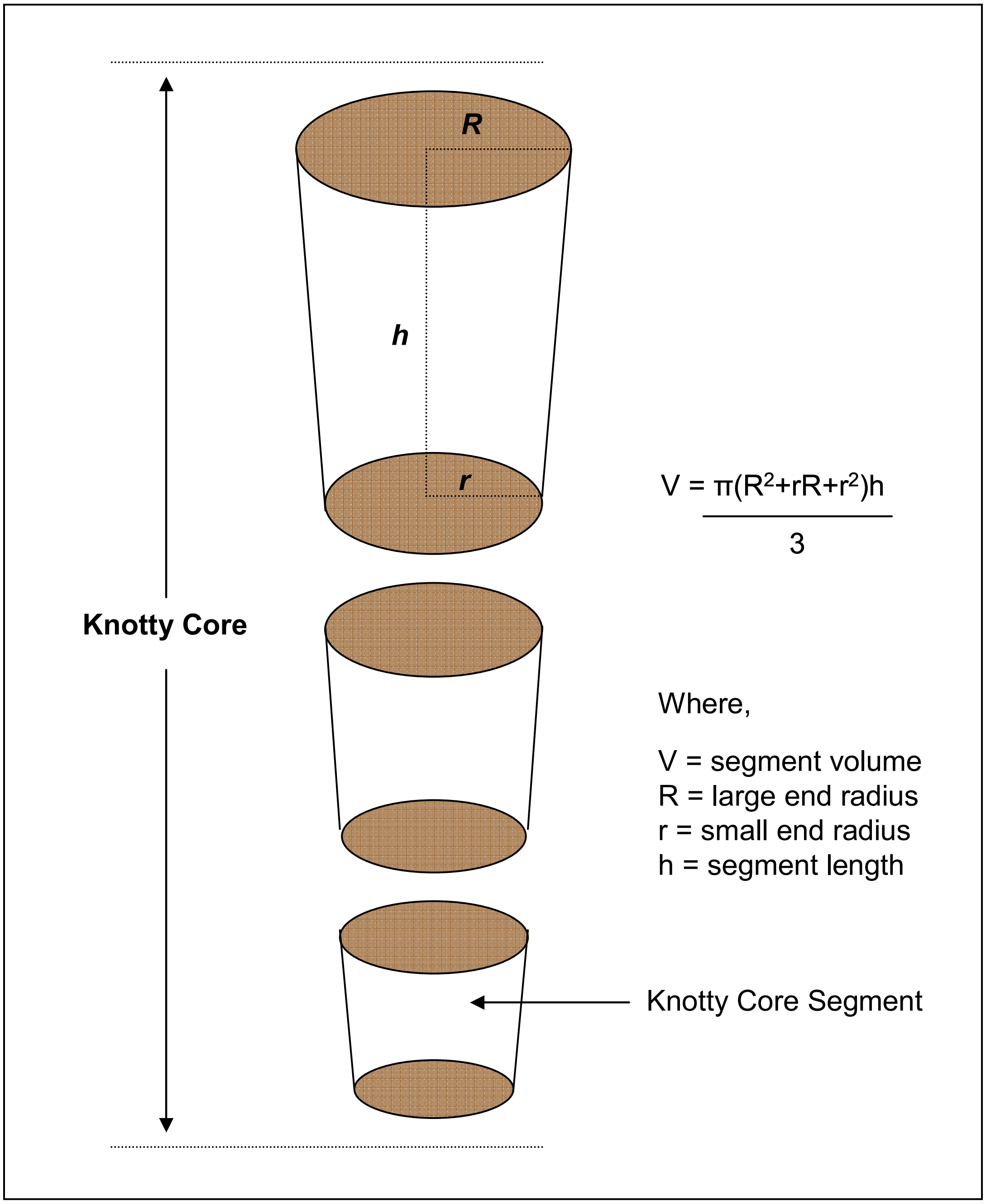


Figure 4. 3. Diagrams of each of four plantation designs used in the CherrybarkSQ simulation system.

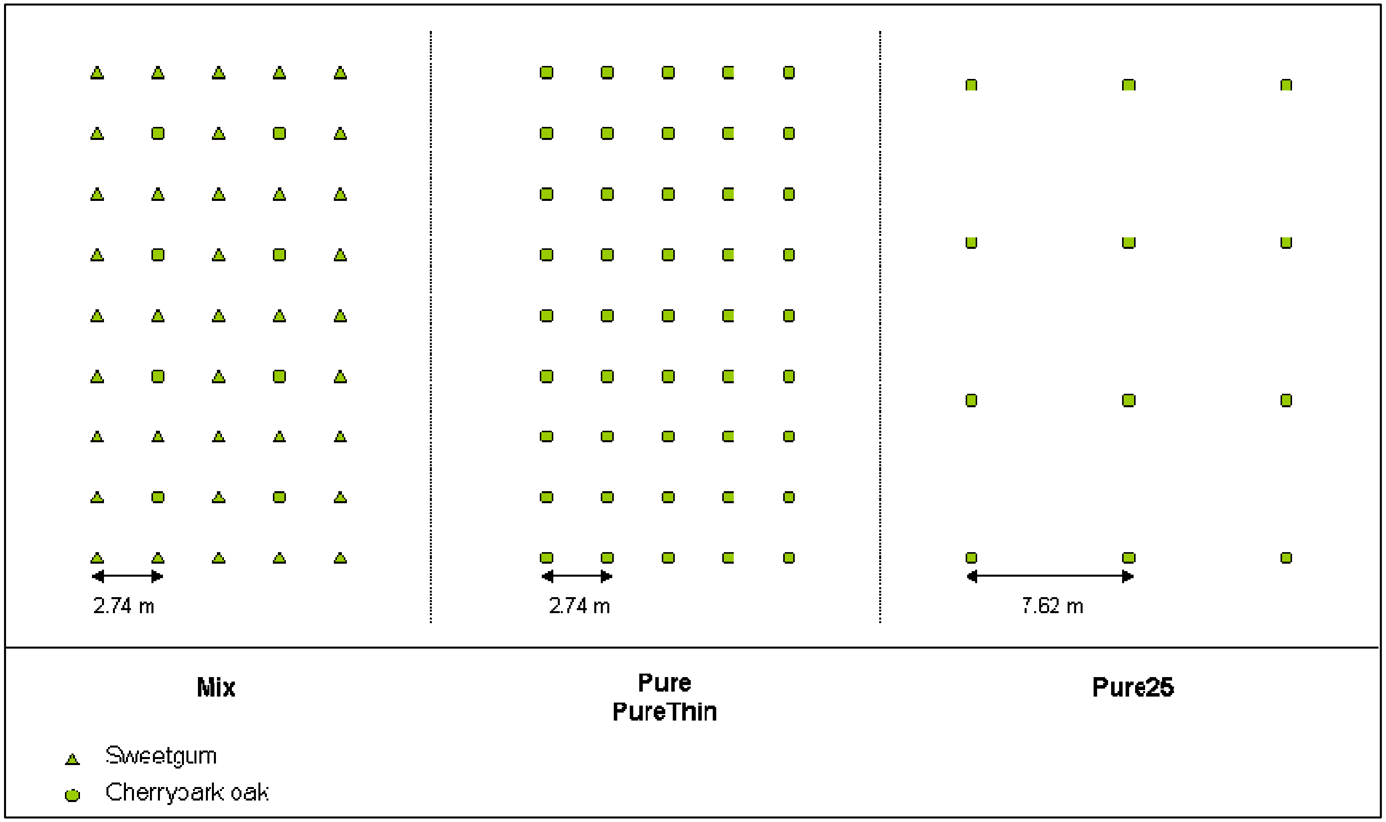


Table 4. 1. Initial characteristics of simulated cherrybark oak plantations.

Metric	Pure	PureThin	Pure25	Mix
Initial spacing	9 x 9 ft.	9 x 9 ft	25 x 25 ft	9 x 9 ft
Stems per acre	538	538	70	60
Sweetgum	-	-	-	478
Crown Width (m)	1.57	1.57	1.64	1.58
Crown Length (m)	1.97	1.99	2.05	1.93
Diameter Breast Height (cm)	5.34	5.33	5.34	5.35

Table 4. 2. Mean characteristics of simulated cherrybark oak plantations at the end of the simulation period for each of four plantation designs.

Metric	Pure	PureThin	Pure25	Mix
Thinning (no. stems)	0	240	0	0
Mortality (no. stems)	427	142	2	22
Sweetgum	-	-	-	291
Crown Width (m)	7.35	6.98	10.24	9.02
Crown Length (m)	9.19	10.19	14.78	11.28
Diameter Breast Height (cm)	37.7	42.8	73.2	52.8
Branch Diameter (mm)	56	61	79	65
Stem Volume (m^3 $stem^{-1}$)	1.83	2.28	6.77	3.53
Stand Volume (m^3)	10,658	15,645	18,644	15,193
Stem Knotty Core Volume (m^3 $stem^{-1}$)	0.77	0.81	0.8	0.81
Stand Knotty Core Volume (m^3)	4,500	5,565	2,204	3,478
Clear Wood Index	0.58	0.47	0.22	0.36

Figure 4. 4. Mean stem density for simulations of cherrybark oak and sweetgum grown with the Mix plantation design within the CherrybarkSQ simulation system.

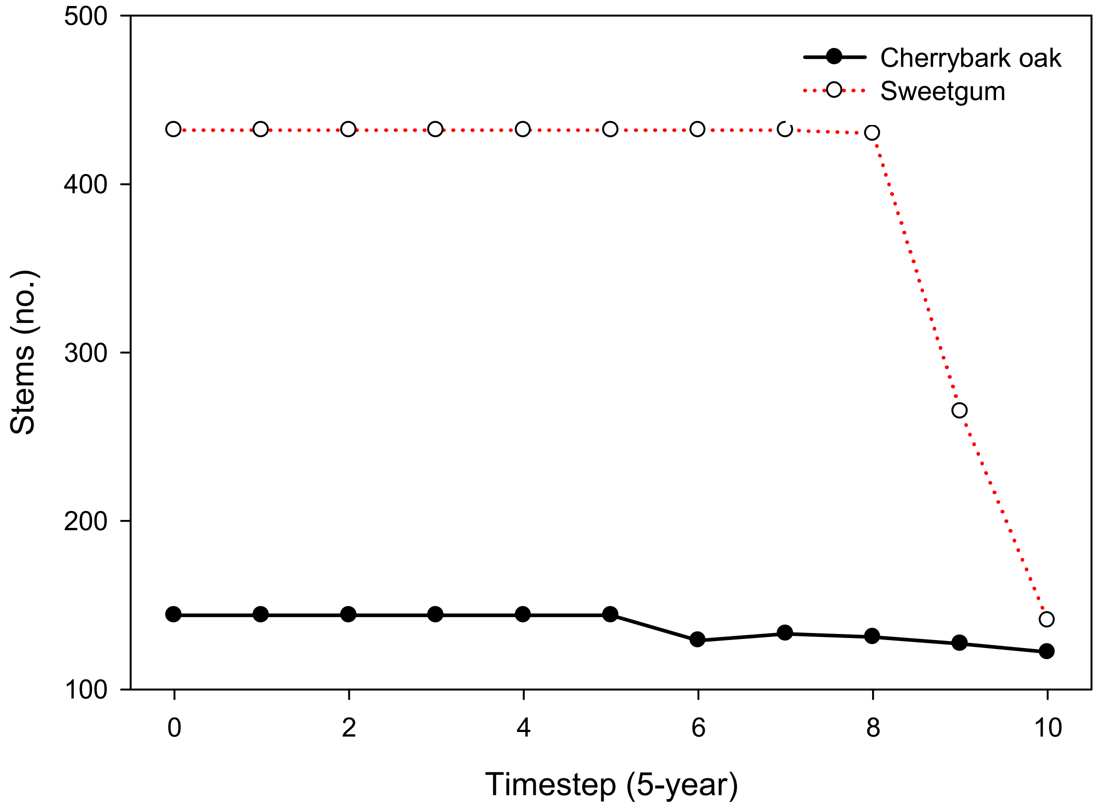


Figure 4. 5. Mean diameter breast height (a), crown width (b) and height (c) for all simulations of cherrybark oak and sweetgum grown with the Mix plantation design within the CherrybarkSQ simulation system. Error bars represent one standard error of the mean across all simulations.

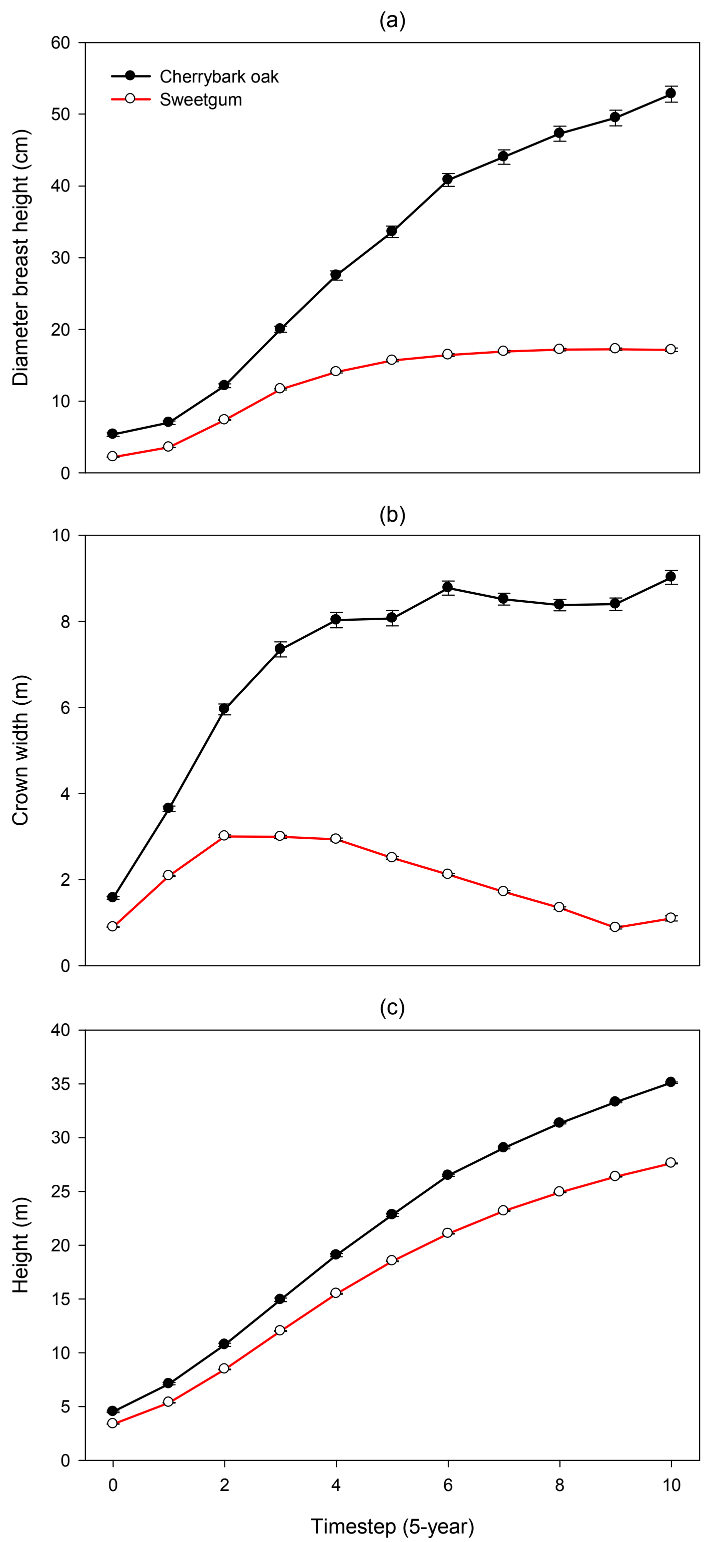


Figure 4. 6. Mean stem density for cherrybark oak from 10 simulations for each of four plantation designs over time simulated with the CherrybarkSQ simulation system.

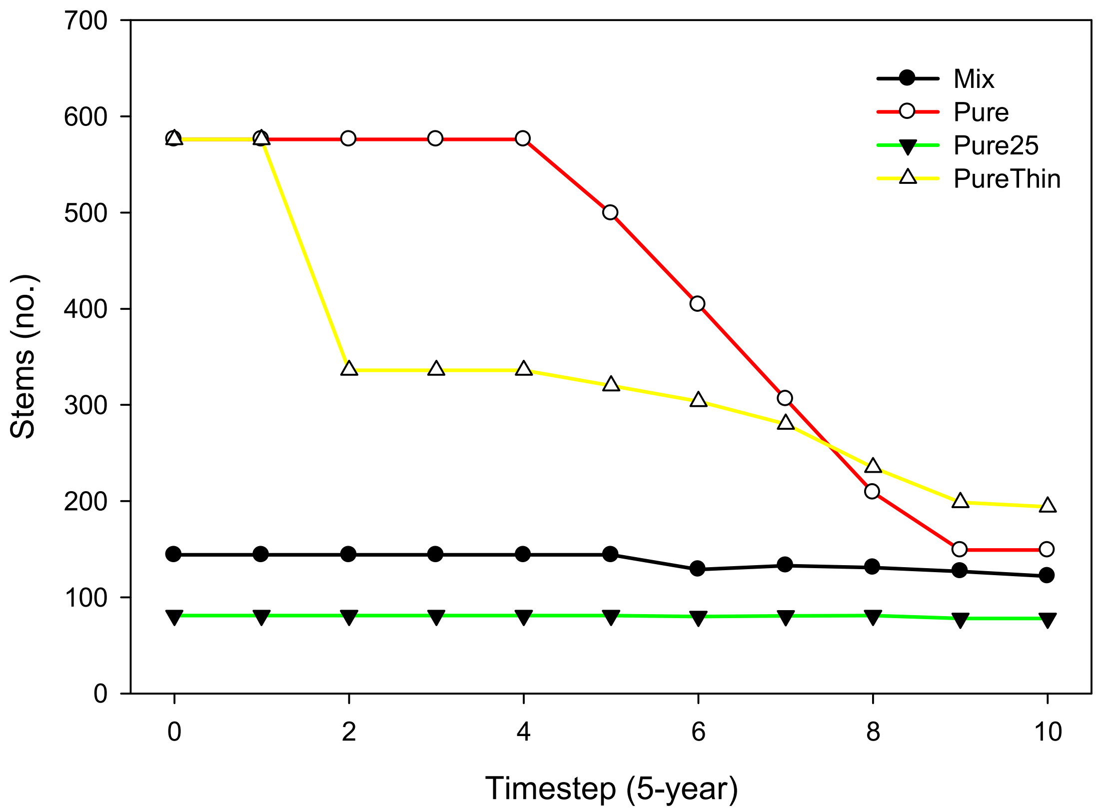


Figure 4. 7. Mean mortality for cherrybark oak from 10 simulations for each of four plantation designs simulated with the CherrybarkSQ simulation system. Error bars represent one standard error of the mean. Different letters indicate significant differences among plantation designs at the α = 0.05 level.

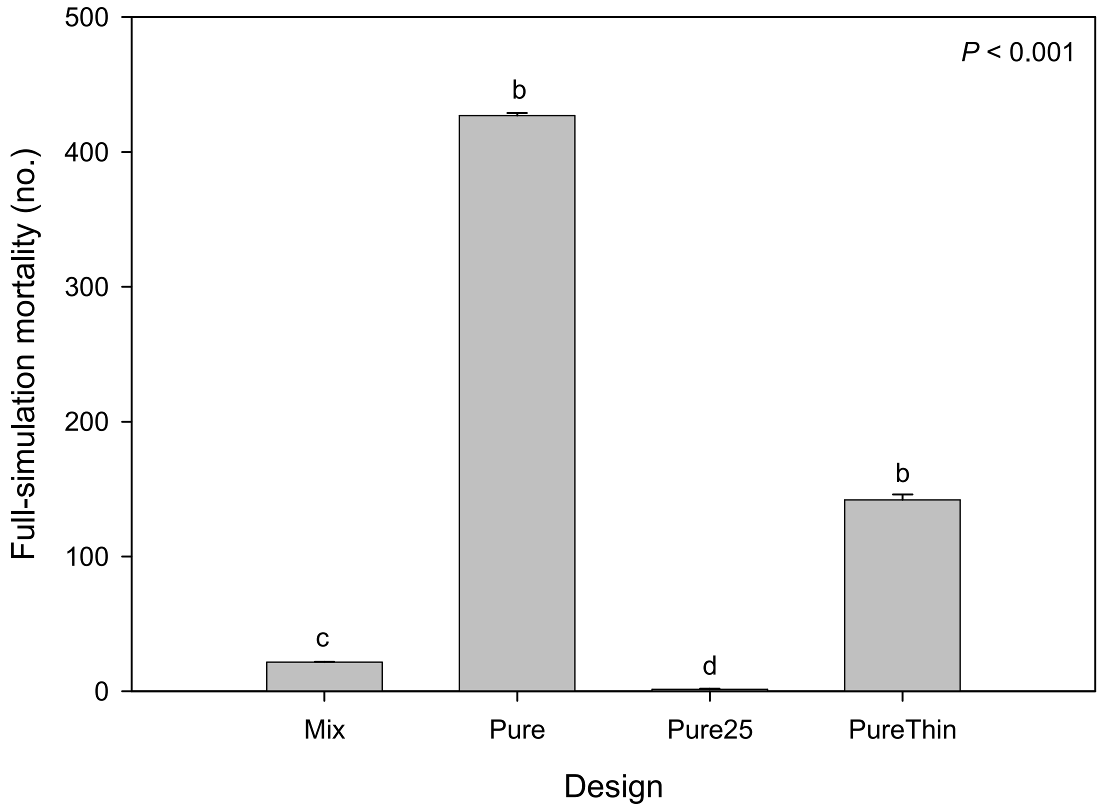


Figure 4. 8. Final (end of simulation) mean diameter breast height (dbh) for cherrybark oak from 10 simulations for each of four plantation designs simulated with the CherrybarkSQ simulation system. Error bars represent one standard error of the mean. Different letters indicate significant differences among plantation designs at the α = 0.05 level.

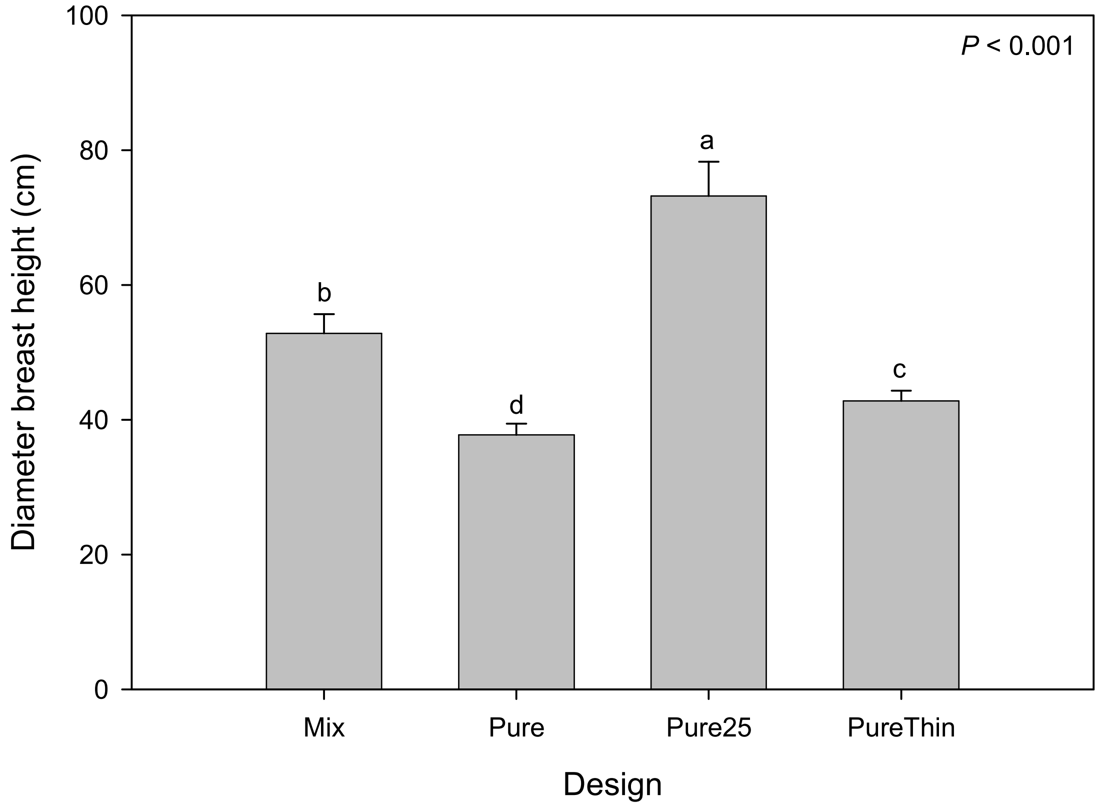


Figure 4. 9. Mean diameter breast height (dbh) for cherrybark oak from 10 simulations for each of four plantation designs over time simulated with the CherrybarkSQ simulation system. Error bars represent one standard error of the mean.

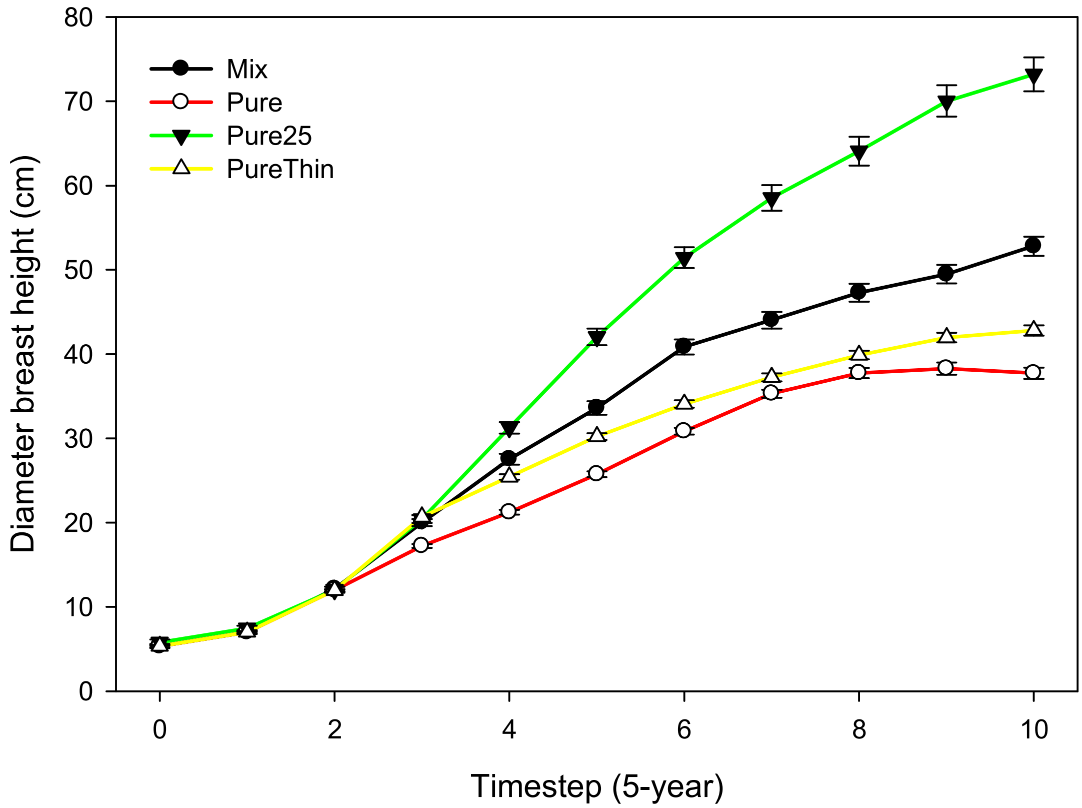


Figure 4. 10. Final (end of simulation) mean crown length (a) and crown width (b) for cherrybark oak from 10 simulations for each of four plantation designs simulated with the CherrybarkSQ simulation system. Error bars represent one standard error of the mean. Different letters indicate significant differences among plantation designs at the α = 0.05 level.

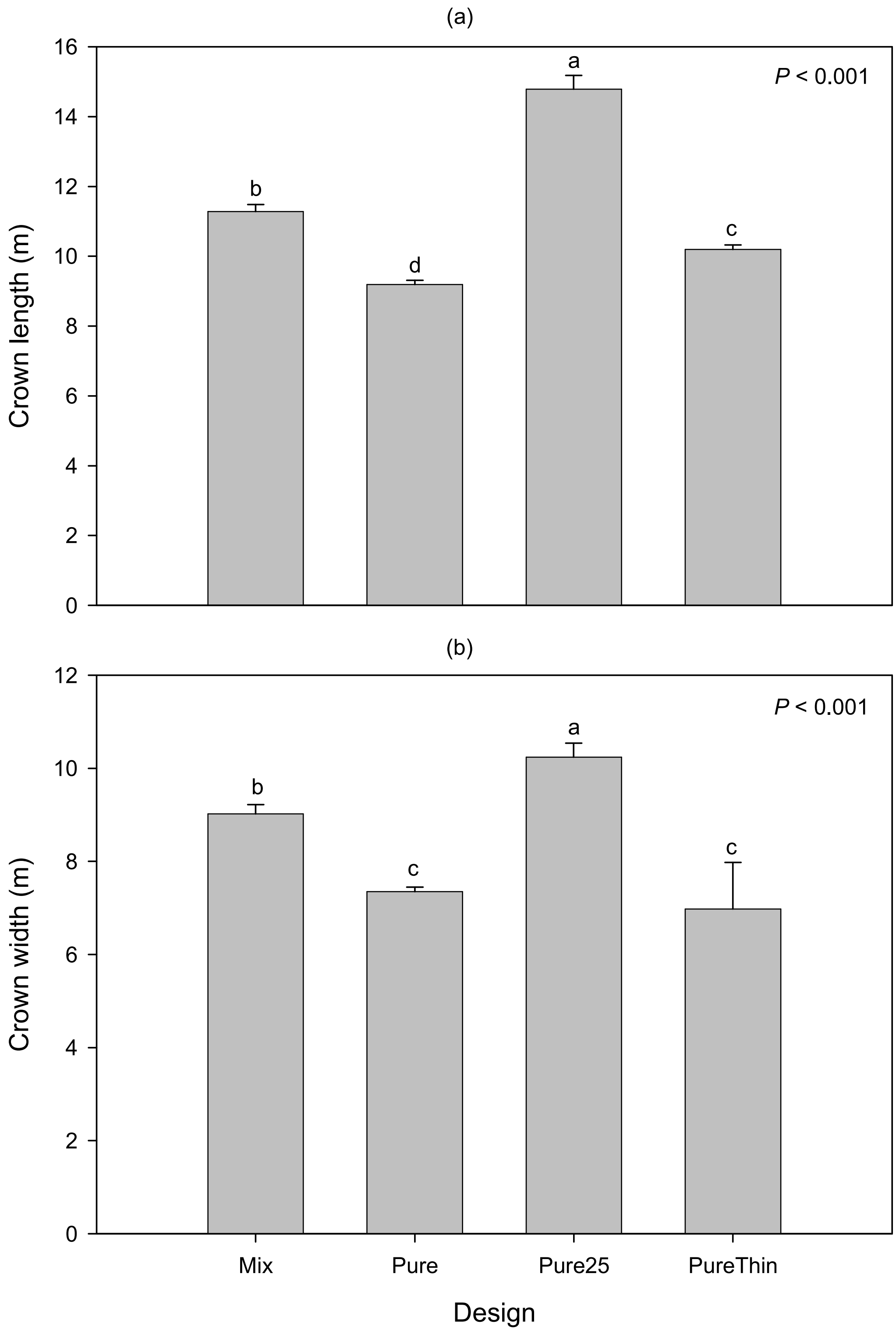


Figure 4. 11. Mean crown length (a) and crown width (b) for cherrybark oak from 10 simulations for each of four plantation designs over time simulated with the CherrybarkSQ simulation system. Error bars represent one standard error of the mean.

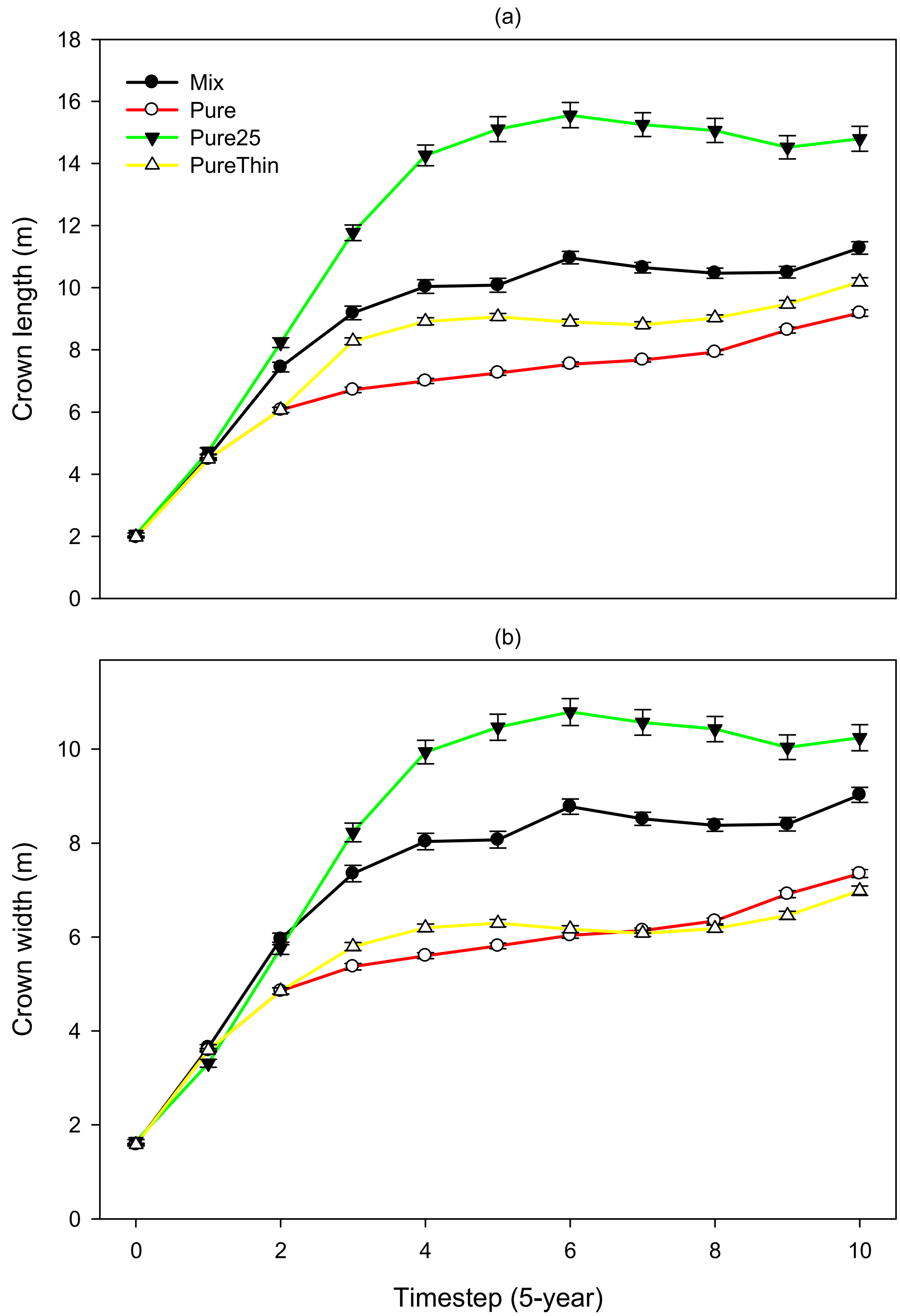


Figure 4. 12. Mean crown base branch basal diameter for cherrybark oak from 10 simulations for each of four plantation designs over time simulated with the CherrybarkSQ simulation system. Error bars represent one standard error of the mean.

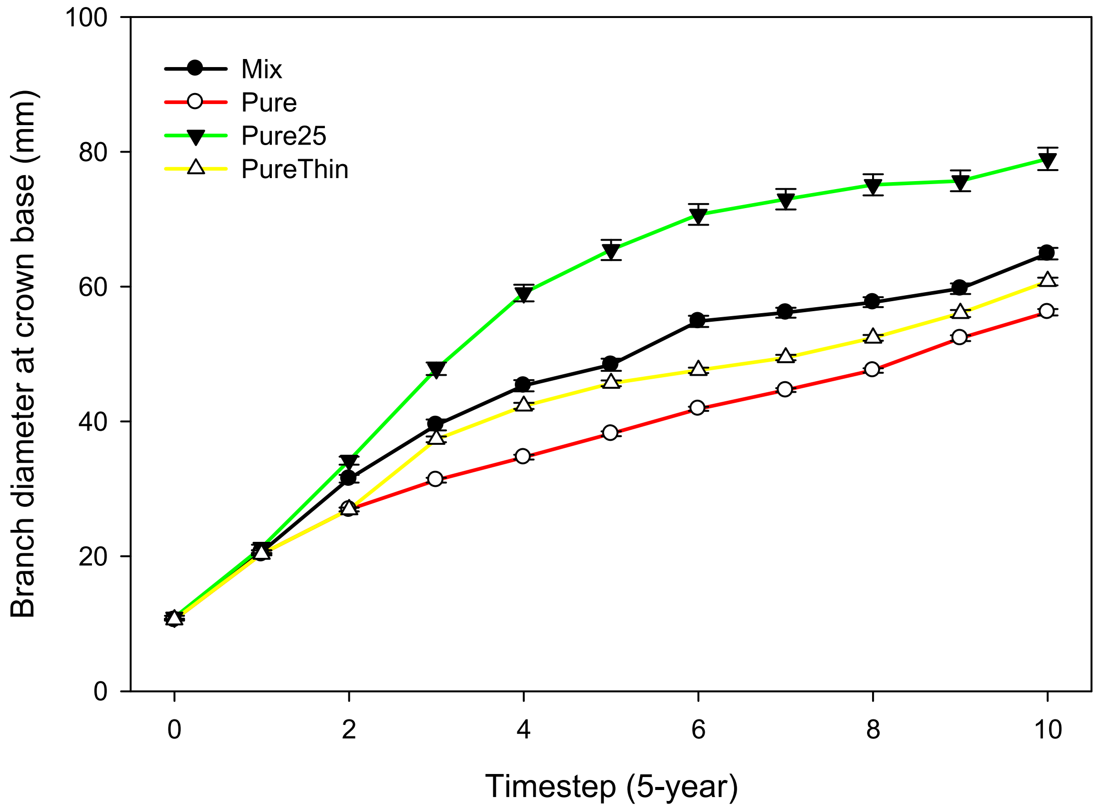


Figure 4. 13. Final (end of simulation) mean crown base branch basal diameter for cherrybark oak from 10 simulations for each of four plantation designs simulated with the CherrybarkSQ simulation system. Error bars represent one standard error of the mean. Different letters indicate significant differences among plantation designs at the α = 0.05 level.

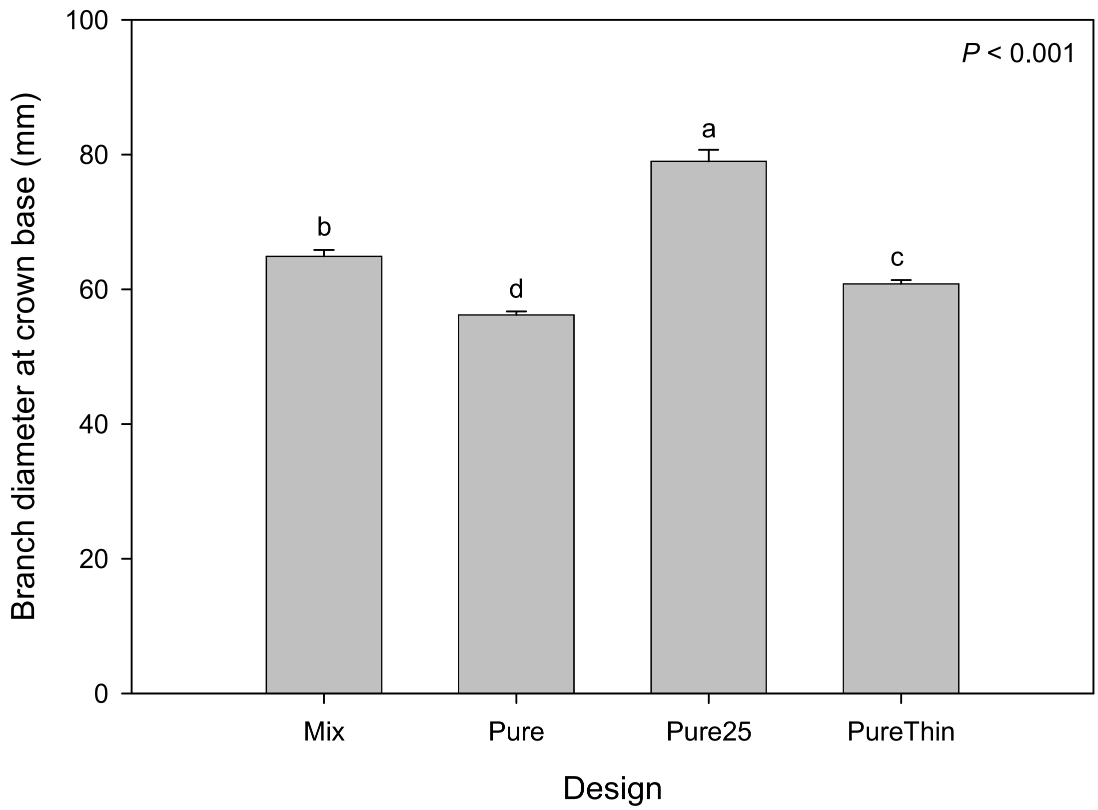


Figure 4. 14. Mean individual tree volume (a) and mean stand volume (b) for cherrybark oak from 10 simulations for each of four plantation designs over time simulated with the CherrybarkSQ simulation system. Error bars represent one standard error of the mean.

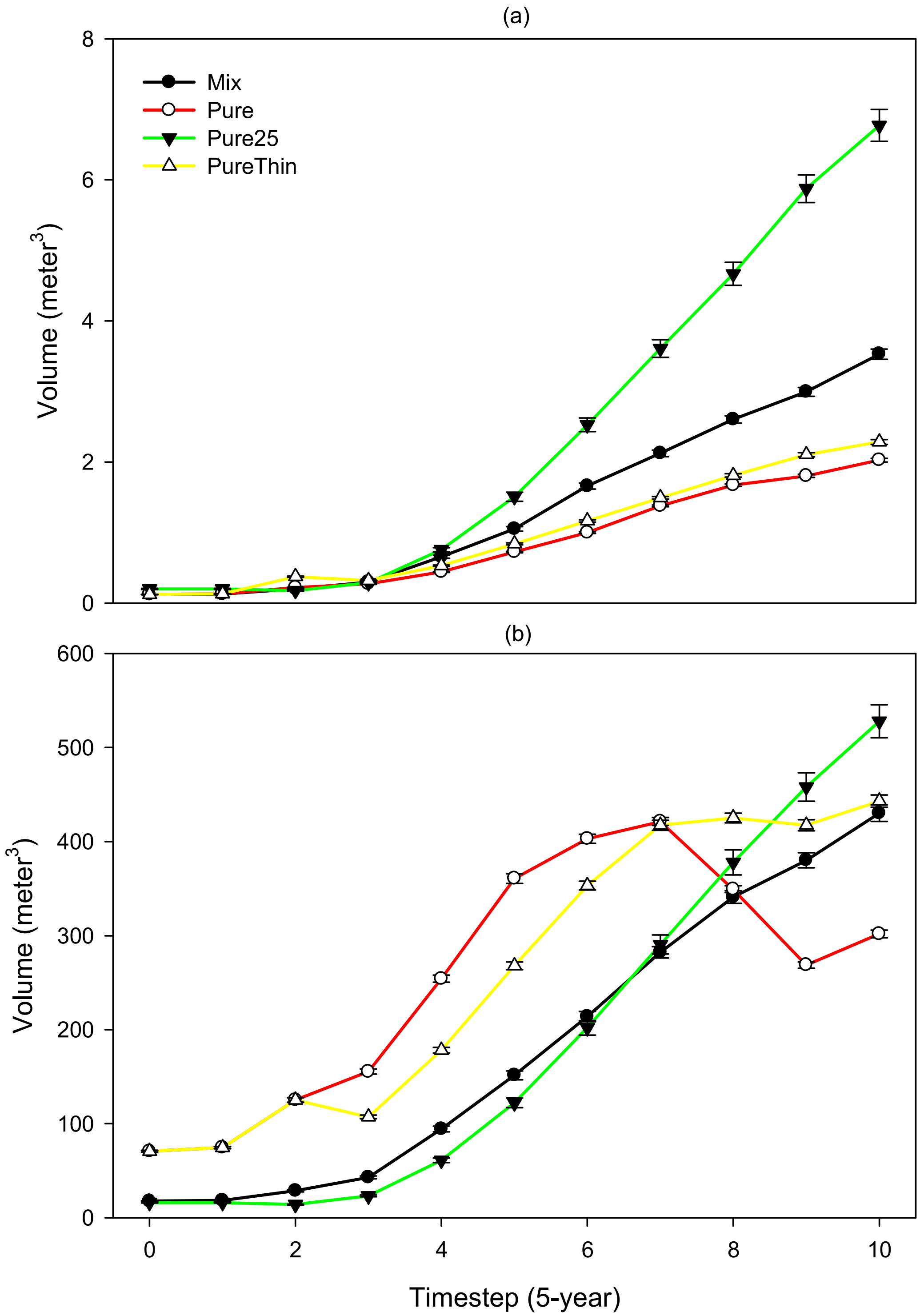


Figure 4. 15. Final (end of simulation) mean Clear Wood Index (CWI) for cherrybark oak from 10 simulations for each of four plantation designs simulated with the CherrybarkSQ simulation system. Note: Lower CWI values indicate a higher proportion of total volume in clear wood. Error bars represent one standard error of the mean. Different letters indicate significant differences among plantation designs at the α = 0.05 level.

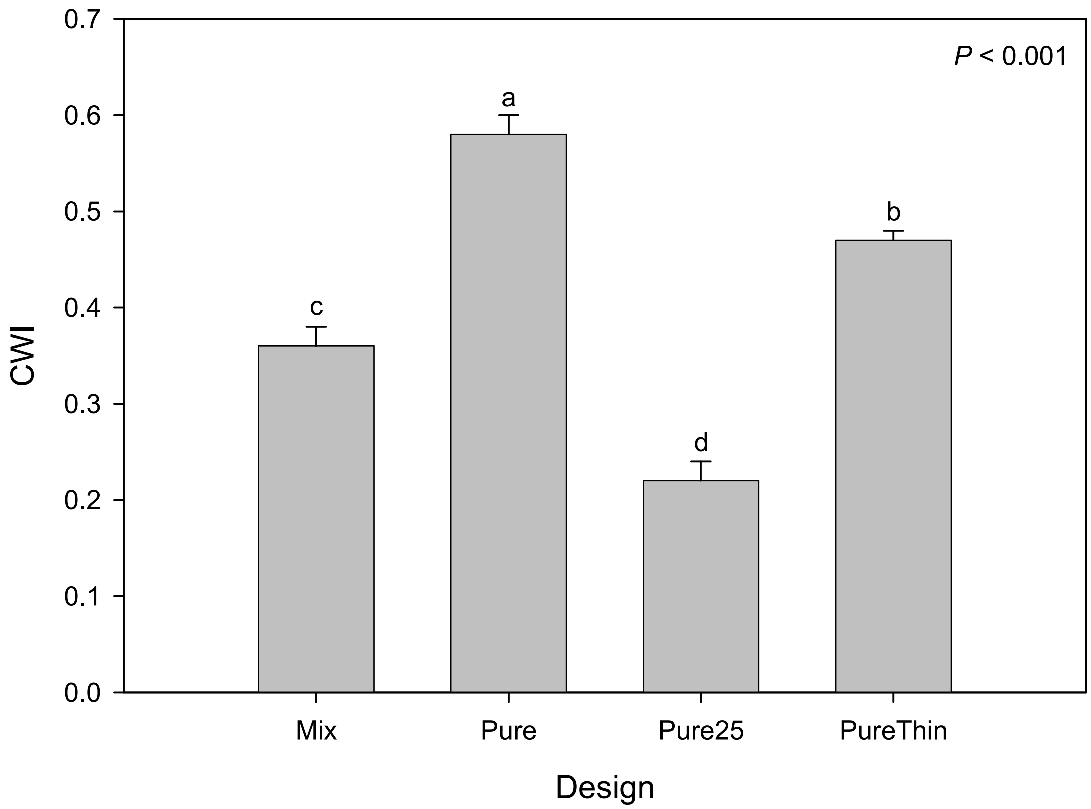


Figure 4. 16. Mean Clear Wood Index (CWI) for cherrybark oak from 10 simulations for each of four plantation designs over time simulated with the CherrybarkSQ simulation system. Note: Lower CWI values indicate a higher proportion of total volume in clear wood. Error bars represent one standard error of the mean.

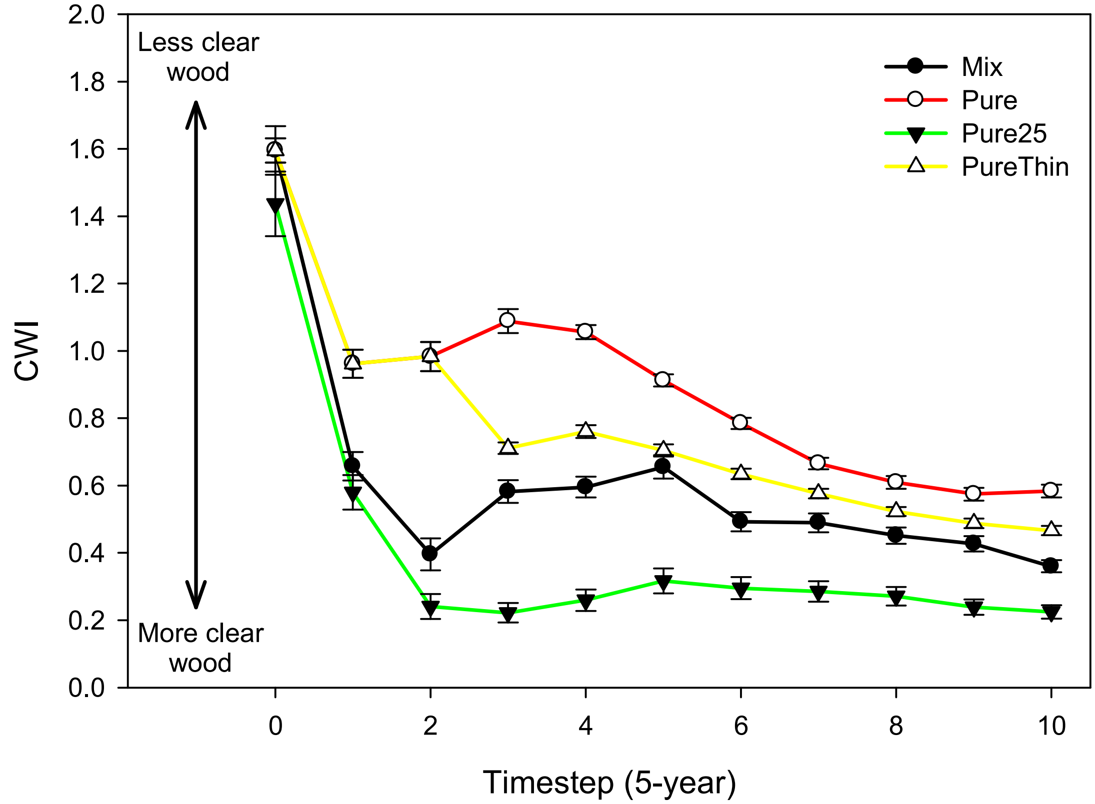


Figure 4. 17. Sensitivity of mean Clear Wood Index (CWI) to changes in the knotty core diameter equation for cherrybark oak from 10 simulations for each of four plantation designs over time simulated with the CherrybarkSQ simulation system. Asymmetric error bars represent the change in CWI as a result of altering the scaling exponent of the knotty core diameter equation by plus (positive error bars) or minus (negative error bars) one standard error.

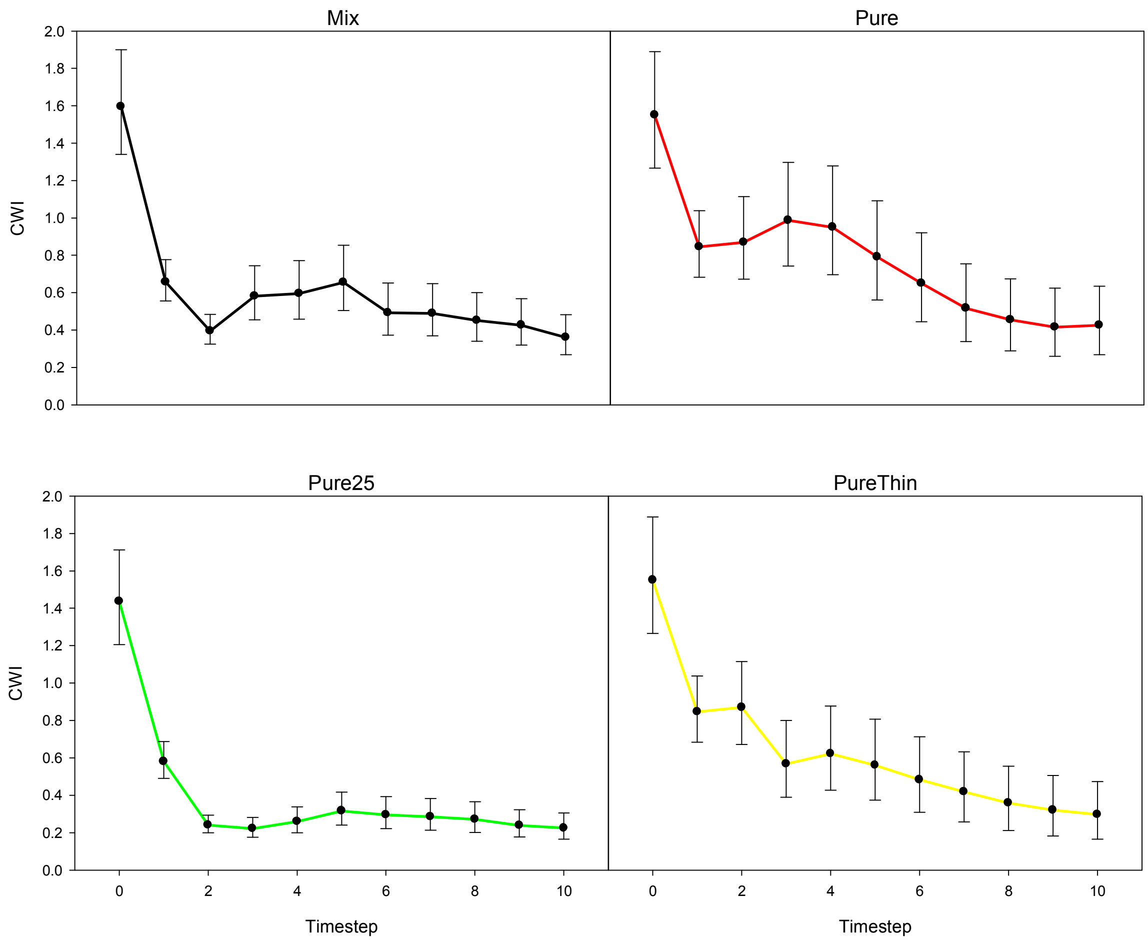
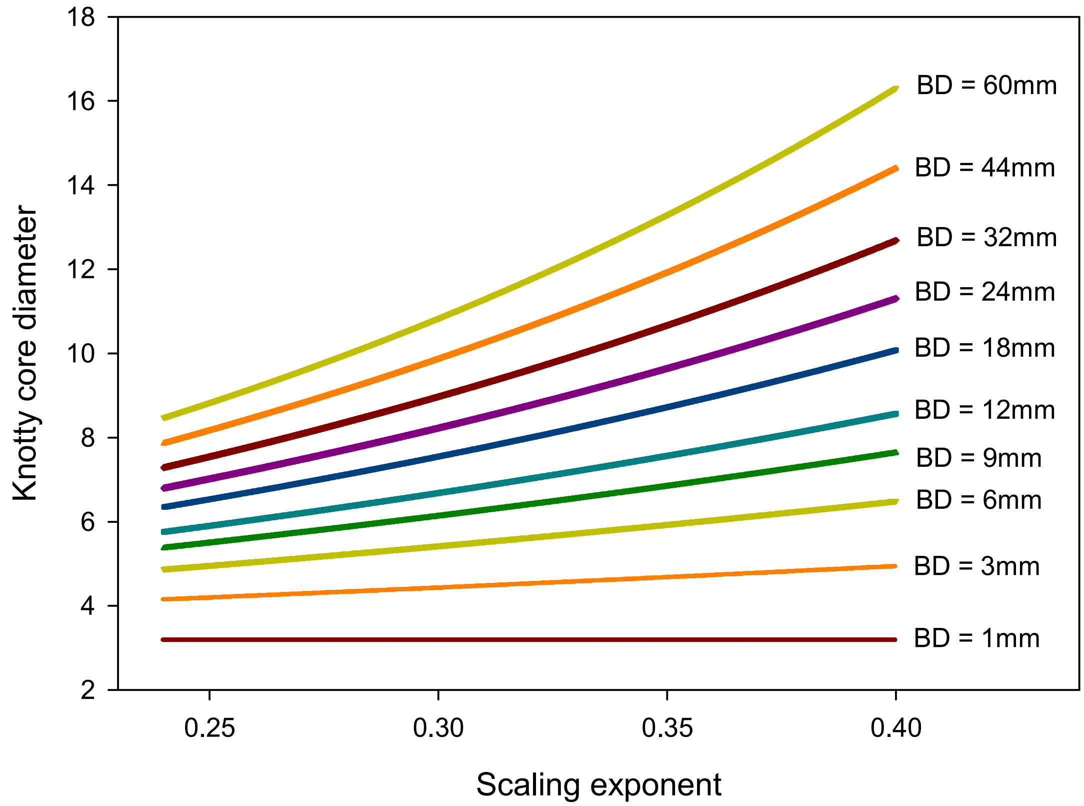


Figure 4. 18. Sensitivity of the knotty core diameter equation to changes in the scaling exponent for a range of observed branch diameters.



APPENDIX B - Procedures for CherrybarkSQ Simulations

A set of procedures for running CherrybarkSQ simulations are outlined for organizing the data into the correct format, running Sylvan simulations, exporting data from Sylvan, importing data into the other components of CherrybarkSQ and executing the equations described in Chapters 2 and 3.

1) **Sylvan parameterization –** The primary requirement for the parameterization of the Sylvan Stand Structure Model is the development of a local height-age curve. For this investigation two separate stands were used: a ___ year old pure cherrybark oak plantation on the Natchez Trace State Forest in west Tennessee and a ___ year old mixed cherrybark oak / sweetgum plantation on the Noxubee Wildlife Refuge outside Starkville, Mississippi. Data were obtained from either repeated measures of the Noxubee stand or stem analysis of the Natchez Trace stand (see Chapter 3 for complete description). An iterative procedure was used to visually fit sampled stems to a Weibull function using the R statistical package and a simple curve fitting program developed by David R. Larsen. The parameters from the Weibull fit are used in the height growth function in Sylvan. This is analogous to using a site index as an index of site potential. Figure A.1. is an example of the Weibull fit for cherrybark oak.

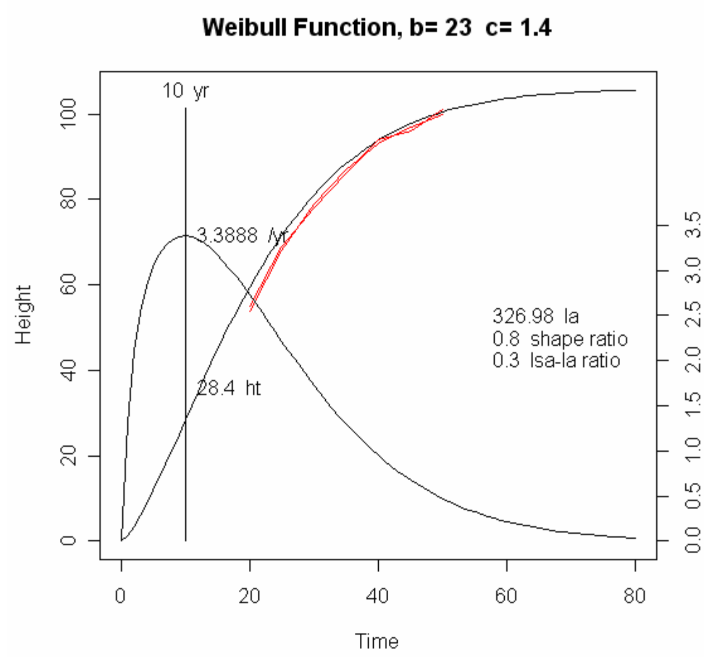


Figure A. 1. Example of a Weibull fit for a series of cherrybark oak samples (red lines) using the R statistical package for determining height growth parameters for the Sylvan Stand Structure Model.

Separate parameter sets were developed for cherrybark oak and sweetgum for the Noxubee stand. Figure A.2. is an example of the Weibull fit for sweetgum. The fit is used to identify the point at which the maximum height growth rate occurs. Maximum height growth rate occurs at the inflection point of the height-age curve and is the maximum of the first derivative of the height-age curve. A stem map is also necessary for proper Sylvan parameterization. Both the Noxubee and Natchez Trace stands were stem-mapped for Sylvan to replicate the spatial properties. Figure A.3. is an example of a stem map for a portion of the Natchez Trace stand planted on a 9 x 9 ft. spacing with limited mortality.

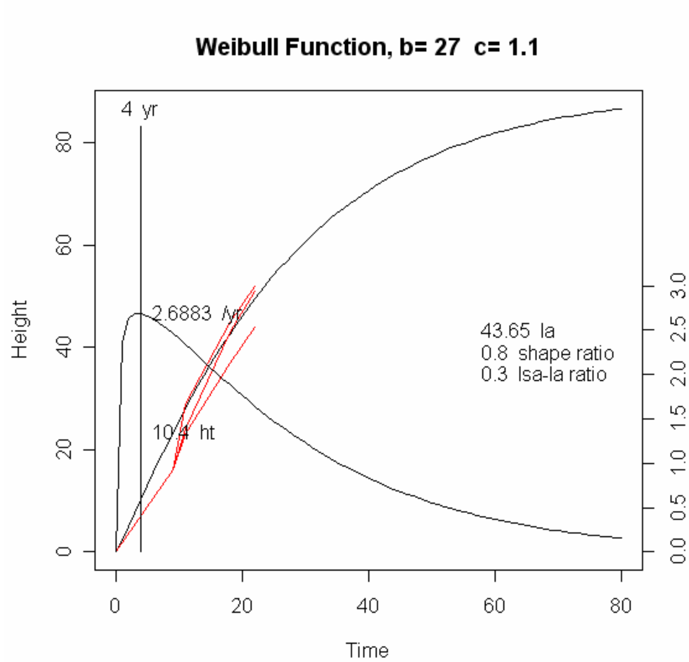


Figure A. 2. Example of a Weibull fit for a series of cherrybark oak samples (red lines) using the R statistical package for determining height growth parameters for the Sylvan Stand Structure Model.

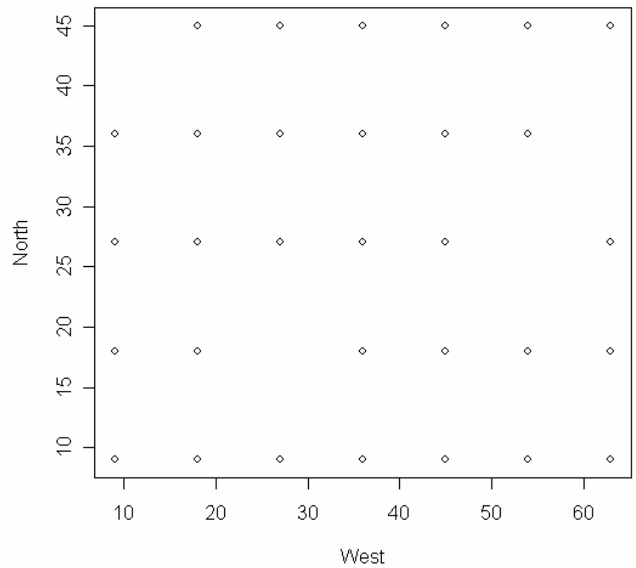


Figure A. 3. An example of a stem map for a portion of the Natchez Trace stand planted on a 9 x 9 ft. spacing with limited mortality. Each circle represents one stem.

2) **Development of simulated plantations –** Currently Sylvan calculates species specific proportions for an input stand and applies the calculated proportions randomly during the process that generates a full treelist. The full treelist represents one unit of area (e.g. an acre or hectare) and is needed because a full unit is rarely sampled completely. The Generate function in Sylvan reads the sampled treelist that contains species information along with the spatial information supplied by the stemmap and generates a full treelist with spatial characteristics similar to that of the sampled stand. The age of the generated treelists is approximately 10 years. Refer to Larsen (1994) for a complete description of the Generate function in Sylvan.

   Because the species proportions of the sampled stand are applied randomly to the generated stand, the generated stand does not resemble any particular plantation design. However, specific designs were of interest for simulating with the CherrybarkSQ sytstem. As a result, the treelists output by the Generate function were manually altered in order to transform the plantation from a random design (Figure A.4.) to a design of interest (Figure A.5.). This was achieved by manually adjusting the x and y coordinates of trees in the generated treelist until the treelist matched the spatial arrangement of interest for both the mixed species and monospecific designs. It was necessary to alter both the mixed species design and monospecific designs because of the random assignment of spatial coordinates.

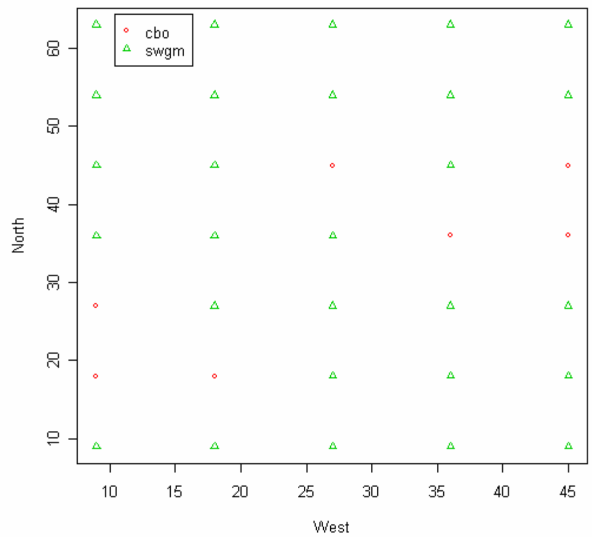


Figure A. 4. Conceptualization of randomized spatial coordinates output from the Generate function of the Sylvan Stand Structure Model.

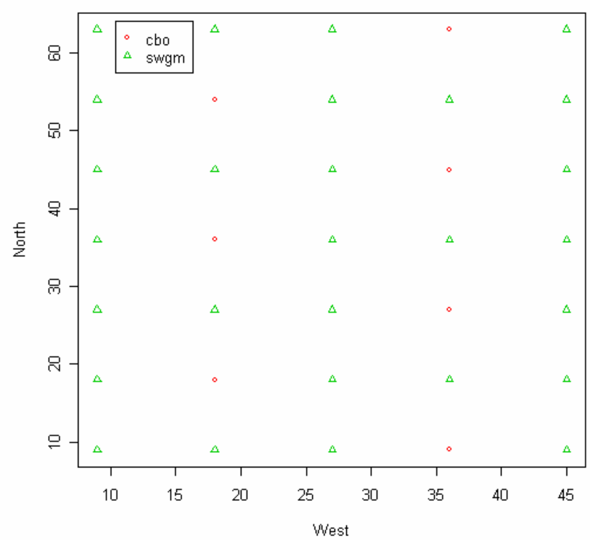


Figure A. 5. Conceptualization of the spatial coordinates after manually adjusting the output from the Generate function of the Sylvan Stand Structure Model in order to achieve specific plantation designs. In this example cherrybark oak stems (red circles) are surrounded by a sweetgum stem (green triangles) on all sides.

3) **Sylvan simulations -** The altered treelists are read by the Sylvan model through the use of the graphical user interface Sylview (Figure A.6.). Sylview (Scott 2007) allows for the easy input and output of data and offers multiple ways to view the data in both graphical and tabular format. The Grow function of the Sylvan model is initialized in Sylview. For this analysis, both parameter sets were used and multiple simulations (10 timesteps each) were run. Treelists from each simulation were stored in a comma delimited format.

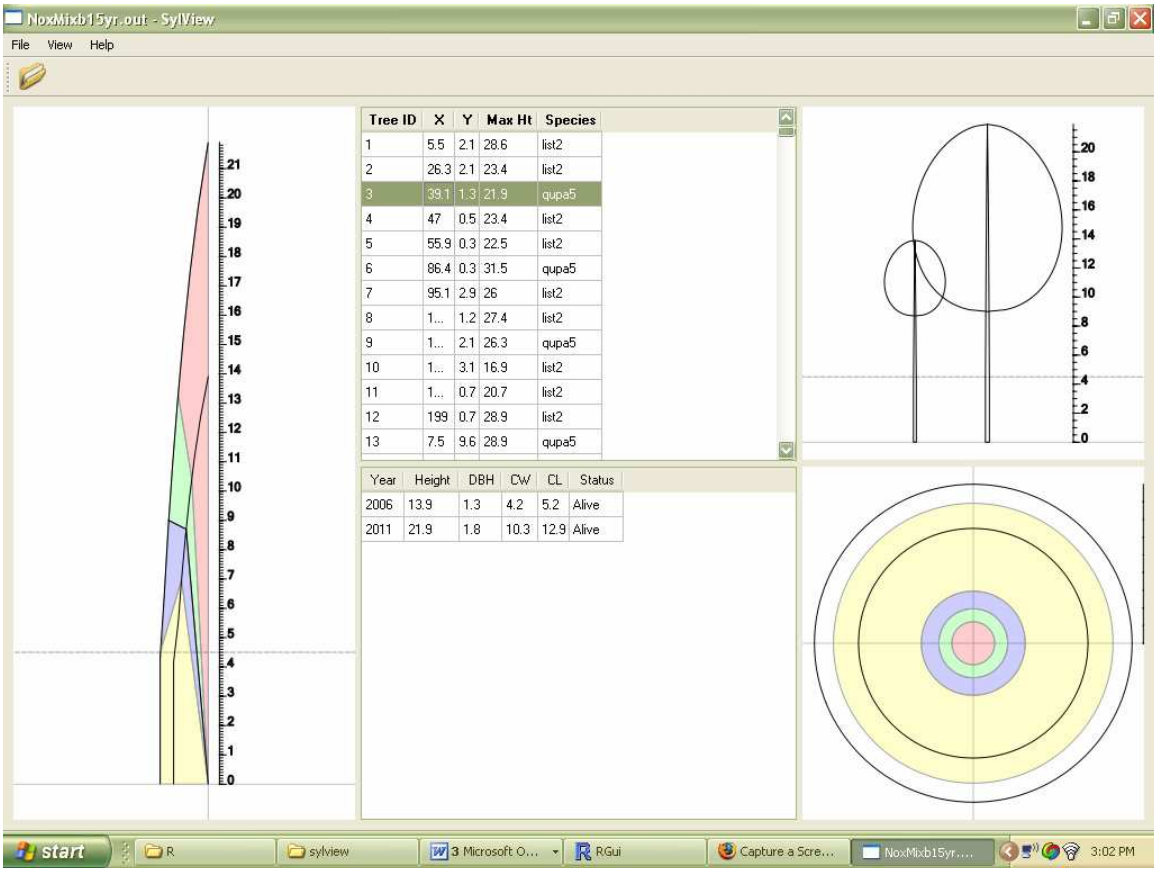


Figure A. 6. Screen-capture of the Sylview graphical user interface accessing modeled data generated with the Sylvan Stand Structure Model.

4) **Calculation of branch characteristics –** The comma delimited treelists output from Sylvan were imported into SAS for calculating the branch characteristics used in the knotty core equations. Because Sylvan outputs the treelist in English units, all variables were converted to metric units for use in the developed equations (Chapters 2 and 3). The height of the base of the live crown (CB) for tree *i* at time *t* was calculated with the following equation for each tree and timestep.:

$$CB_{ti} = H_{ti} - CL_{ti}$$

where Ht is the total height of the tree and CL is the total length of the live portion of the crown. Crown length was logarithmically transformed and renamed to Log Crown Depth (LogCD) because CL is analogous to the depth of the first-order branch that delimits the length of the live crown.

The logarithm of branch diameter (BD) for the branch at the base of the live crown was then calculated for each tree at each timestep with the following equation:

$$LogBD_{ti} = 2.4877 + 0.8258(-0.9071 + 0.8915(LogCD_{ti}) + 0.0209(H_{ti}))$$

LogBD for each tree at each timestep was then back-transformed along with the addition of a correction term (*C*):

$$C = \exp(\frac{SEE^2}{2})$$

$$SEE = \sqrt{\frac{\sum \log y_i - \log \hat{y}_i)^2}{n-2}}$$

The result was the branch diameter at the base of the live crown ($BDcb_{ti}$).

5) **Calculation of knotty-core characteristics –** A knotty-core diameter (KCD) was calculated for CB for each tree and each timestep with the equation:

$$KCDti = 3.17(BDcb_{ti}^{0.32})$$

The knotty-core in each tree is comprised of a collection of knotty-core segments. Each knotty core segment is defined by the KCD at time *t* (KCD_t), KCD at time *t+1* (KCD_{t+1}) and $Ht_{t+1} - Ht_t$. A constant of 1 cm was used for the KCD at the base of the tree. The volume (V) for each knotty-core segment was calculated with the equation for the frustum of a cone, where:

$$V = \frac{\pi(\frac{1}{2}(KCD_{t+1}))^2 + ((\frac{1}{2}(KCD_t))(\frac{1}{2}(KCD_{t+1}))) + (\frac{1}{2}(KCD_t))^2)(Ht_{t+1} - Ht_t)}{3}$$

The tree knotty-core volume (KCV) was calculated as the sum of the volume of all knotty-core segments for each particular tree.

6) **Calculation of clear wood index** – A clear wood index (CWI) was used as an index of clear wood production in each stem. The CWI is calculated with the following equation:

$$CWIi = \frac{KCV_i}{MBV_i}$$

where MBV_i is the merchantable bole volume for tree *i*. The MBV is defined as the volume of wood in the main bole of the tree from a 0.3 meter (1 foot) stump to the base of the live crown. Merchantable bole volume was calculated using equations developed at the USDA Forest Service Forest Inventory and Analysis program in the Southern Research Station. The equations were tested to be appropriate for cherrybark oak by Oswalt and Saunders (In press).

VITA

Christopher Michael Oswalt was born in Memphis, Tennessee on the 24th day of October, 1975 to parents J. Elmer and Deborah T. Oswalt. Raised throughout the south, Chris developed a deep respect and enduring wonder for the Creation in which he lived and played. His formalized education of the ecological world began with the teachings of his Grandfather as he trailed him on his daily chores on his farm in the foothills of the Ouachita Mountains.

Chris's fascination with the forests of the south that began as a child never left him as he continued his education. He received a Bachelor's degree in Forestry with a concentration in Forest Resource Management from the University of Tennessee in 1999. Chris then went on to work for the Bureau of Land Management in Glennallen, Alaska, for the United States Forest Service on the White River National Forest in Rifle, Colorado and a private timber company in Jackson, Tennessee. Chris returned to the University of Tennessee to complete a Masters of Science in Forest Ecology in 2003 under the direction of Dr. Wayne K. Clatterbuck. Chris continued his research in forest stand dynamics under Dr. Clatterbuck in order to obtain a Ph.D in Natural Resources with a focus on Forest Ecology and Silviculture. His doctoral work was completed in 2007. Chris currently works as a scientist for the United States Forests Service Forest Inventory and Analysis program.