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Branch characteristics of widely spaced Douglas-fir in south-western Germany: Comparisons of modelling approaches and geographic regions

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ABSTRACT

Models of Douglas-fir branch and whorl characteristics were developed from contrasting spacing experiments in southwest Germany. The dataset was based on 100 young (20–30 years old), unpruned and partially pruned trees from a 100, 200, and 1200 stems ha^{-1} spacing experiment on Douglas-fir that was replicated 3 times across the region. The material was used to predict (1) the number of branches $whorl^{-1}$, (2) branch angle, (3) status (living/dead) of the branches within the living crown, (4) maximum branch diameter $whorl^{-1}$, and (5) relative diameter of branches within a whorl. For each of these models (except branch status), both a linear and nonlinear, generalised hierarchical mixed effects equation was developed. The comparison of the linear and nonlinear approaches showed that both had a relatively similar level of bias, but the nonlinear equations generally performed better (reduction in mean absolute error of 1.1–69.5%). Overall, individual branch and tree properties were sufficient to give logical and precise predictions of the branch characteristics for the models across the range of sampled stand densities. In addition, the models showed a similar behaviour compared to models on Douglas-fir crown structure from the Pacific Northwest, USA. This suggests that the allometric relationship between tree size and branch characteristics for a given species may be relatively consistent across regions, even ones with highly contrasting growing conditions like in this study. The models performed well across a range of stand conditions and now will be further integrated into an individual tree growth and yield simulations system.

1. Introduction

Attributes of individual branches define crown structure and have important implications at multiple-levels in a forest stand. For example, crown development and structure has been related to stem growth, wood quality attributes, wildlife habitat, and key physiological processes such as interception of radiation and precipitation. Crown structure is quite sensitive to stand conditions imposed by silviculture, but these changes have generally been predictable from site, tree, or branch-level factors (e.g. Kantola and Mäkelä, 2004; Achim et al., 2006; Weiskittel et al., 2007a).

Models of individual branch attributes exist for several commercially important species including: silver birch [*Betula pendula* Roth.] (Mäkinen et al., 2003), Scots pine [*Pinus sylvestris* L] (Mäkinen and Colin, 1999), Norway spruce [*Picea abies* (L.) Karst.] (Hein et al., 2007), radiata pine [*Pinus radiata* D. Don.] (Grace et al., 1999), Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] (Maguire et al., 1994), and Sitka spruce [*Picea sitchensis* (Bong.) Carr.] (Achim et al., 2006). These models have been combined with individual tree growth and yield simulators and have been found useful for understanding the effects of silviculture on wood quality as well as improving growth predictions across a wide range of stand conditions (e.g. Weiskittel et al., 2007b). Despite the wide array of research that has been done on individual branches, little work has been done on comparing different modelling approaches, observed variation between geographic regions, or even inherent species differences.

An important distinction between branch modelling done in Europe and the United States is model form. Hierarchical linear models have been generally used in Europe, while nonlinear forms

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have been preferred in the Pacific Northwest region of the United States. In addition, overall modelling approaches have also been different. For example, Hein et al. (2007) used a generalised, mixed effects Poisson distribution probability approach to predict the number of branches per annual whorl and Maguire et al. (1994) simply used a nonlinear model based on the normal distribution. Further, the degree and impact of autocorrelation on branch-level models has also not been assessed. Weiskittel et al. (2007a) found a significant degree of autocorrelation in several branch-level models, but Garber and Maguire (2005) detected no significant autocorrelation between maximum branch diameters throughout an individual crown. Several statistical approaches to modelling branchiness attributes were evaluated in this study and will help guide future efforts.

Most studies on branch-level properties have been concentrated in uniform areas of a particular region so geographic influences have been minor. A striking example of differences between geographic areas because of local climate conditions is illustrated in the work of Watt et al. (2005). In this study, radiata pine branches were assessed on trees with varying distance from the coast and hence, mean windspeeds. It was found that the maximum branch diameter were significantly higher on highly exposed trees when compared to trees with less exposure, even accounting for tree size differences. The data presented in this study provides a unique opportunity to make comparisons between Douglas-fir grown in the Pacific Northwest (PNW) and Germany, which have distinctly different growing conditions.

Douglas-fir is an important species in Western Europe and south-western Germany in particular. The development of these branch-level prediction models will help to understand growth response at the tree-level and allow assessment of potential wood product quality in this region, which should promote more effective and efficient silvicultural practices. The overall goal of this research project was to develop branch-level models that can be integrated into an individual tree growth and yield simulation system. Specific objectives were to develop models for: (1) the number of branches per annual whorl; (2) branch angle; (3) the probability of a branch being alive or dead; (4) branch diameter profiles for the thickest branch per whorl and (5) the relative diameter of the smaller branches within a whorl. In addition, comparisons were made between modelling approaches and two distinct geographic regions.

2. Material and methods

2.1. Experiments and measurements

The material was collected from three spacing experiments within the program "Solitary Trees" ["Solitärprogramm"] in south-western Germany (Abetz, 1987; Abetz and Lässig, 1989). The principal and original aim of the experiments was to study the effects of weather conditions, air pollution and biotic damage on tree growth without confounding effects of inter-tree competition.

The spacing experiments were established in seven approximately 10–25-year-old single-species stands of Douglas-fir all located in south-western Germany between 1989 and 1991. At each location where the experiment was installed, 1–3 plots were established: (1) a plot with an initial density of 100 stems ha^{-1} (4 plots); (2) a plot with an initial density of 200 stems ha^{-1} (8 plots); and (3) a plot with initially 1200 stems ha^{-1} (5 plots). The latter representing the common number of stems at sapling phase (height of 20–50 cm) in Germany, but also close to recommendations for planting Douglas-fir in neighbouring countries.

For each plot, tree height, stem diameter at breast height, height of the crown base (the height of the lowest living primary branch), and tree age were measured. Regarding the trees, the sampling was targeted at dominant trees that were randomly selected under the condition of having no visible signs of damage. The trees used in this study were harvested 15–17 years after the beginning of the experiments. No thinnings have been carried out after the establishment of the experiments. After felling the sample trees, the distance of whorls from the stem apex, branch status (living or dead), the branch angle (in 5° increments) and diameter (on branch base after base swell) both in the horizontal and vertical directions of all branches above 1.3 m height were measured. The branch angle was defined as the vertical angle between the stem and the branch. The average branch diameter was calculated as an arithmetic mean of the horizontal and vertical diameters. Stem cross-sections were taken at 0.3 and 1.3 m heights, then every 5.0 m thereafter beginning from 5.0 m height upwards. The number of annual rings was counted, and then compared with the number of whorls above the cross-section in order to assure the correct numbering of the whorls. All symbols for plot, tree, whorl and branch attributes used in the analysis are explained in Table 1.

In total, data from 17 plots on 7 different locations were available. The site index (dominant height at 100 years) ranged between 49.9 and 56.5 m with no large differences between the three treatments. One hundred trees were sampled from the 17 plots, with 23 trees from the lowest density, 40 from the intermediate, and 37 trees from the highest density. Summary statistics of tree attributes are listed in Table 2. The whole dataset covers a range of tree diameter between 24.1 and 54.2 cm and a height of 18.0–30.0 m measured at the time of felling.

On seven trees, branches in the lower part of the crown were cut during the first years of the experiment (up to a height of 2.5 m as the highest value) in order to allow an easy access to all parts of the plot for measurements. For the analysis, these trees together with 43 trees where no branches have been removed at all were assigned the pruning category $\leq$2.5 m (in total 50 trees). A second category contained 30 trees pruned up to a height of $\leq$4.5 m, while twenty trees had been high pruned up to $\leq$7.5 m. In total, 12,855 branches

Table 1
Explanation of symbols used in the text

Variable	Definition
brd	Branch diameter (cm)
brd max	Maximum branch diameter in a whorl (cm)
brdrel	Relative branch diameter of the smaller branches (brd/brd max)
brs	Branch status [living = 1, dead = 0]
cl	Crown length (h − hcb) (m)
cr	Crown ratio (h − hcb)/h
dbh	Diameter at breast height (cm)
dist	Distance between the whorl and stem apex (m)
dist1	dist/(h − hcb)
dist2	ln(1.1 − dist/(h − hcb))
dist3	ln(dist1 + 0.1)
wh	Whorl height above ground (m)
h	Tree height (m)
hcb	Height of the crown base (lowest living branch), measured from stem base (m)
hd	h (m)/dbh (cm) × 100
hcm	Height to crown midpoint (hcb + cl/2) (m)
ih	Annual height increment (m)
r	Rank of the branch, ordered from largest to smallest diameter
nbrt	Total number of branches in a whorl (living and dead combined)
α, β, γ, δ, ε	Variance components of the models 4–8, respectively
E, $\lvert E \rvert$, E^2	Mean error, mean absolute error, mean squared error, respectively
l, p, t, w, b, D, i	Subscripts for experiment/location, plot, tree, whorl, branch, treatment (i.e. initial density) and an individual observation, respectively