Models of Knot Characteristics in Young Coastal US Douglas-Fir: Are the Effects of Tree and Site Data Visibly Rendered in the Annual Ring Width Pattern at Breast Height?

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Abstract

The large variation in knot characteristics within and between trees and stands makes proper interpretation of wood properties in the different steps along the forest–to–forest product conversion chain difficult and makes production and use of wood a challenge. Finding good methods and models to interpret the knot characteristics along the different steps of this chain is therefore important. In all, 28 young Douglas-fir (*Pseudotsuga menziesii*) trees were sampled from four stands with different site indices and tree densities. This gave working material consisting of 189 whorls of knots total. Models predicting knot diameter and sound knot length were developed. Important variables reducing the residual variance were mean annual ring width at breast height, mean annual ring width for different annual ring intervals at breast height, site index, and number of trees per hectare. The study shows that models estimating knot diameter and sound knot length with mean annual ring width for certain annual ring intervals (intervals 6 to 10 and 11 to 15) reduced the residual variance somewhat more than variables describing site index and tree density, respectively.

Different knot characteristics, such as diameter, frequency, and type, are important determinants of quality in major solid wood products. The huge variation in knot characteristics within and between trees and stands makes it challenging to properly interpret wood properties in the different steps along the forest–to–forest product conversion chain, leading to less than optimal production and use of wood. Finding good methods to quantify the knot characteristics throughout the chain is therefore of great importance.

For sawn timber, knots lead to cut and discontinuous fibers, which leads to stress concentrations and fracture initiation (Wolfe 2000). Owing to its relationship with different mechanical properties, knot diameter is included in grading rules for structural wood. For appearance wood, knot attributes are also important. These knot attributes are reflected in grading rules for such wood all over the world; grading rules for appearance wood include distinctions between dry and sound knots.

A general pattern found for vertical knot diameter profiles is an increase in knot diameter with increasing distance from ground into the live crown, followed by a decrease further up in the crown (Mäkinen and Colin 1998, Moberg 2000, Vestøl and Høibø 2001).

When estimating branch diameter profiles for whole trees of Norway spruce (*Picea abies* (L.) Karst), Colin and Houllier (1991) based their equations on segmented polynomials. Maguire et al. (1994) compared segmented polynomials with other model forms for young Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) sampled before crown closure. Maguire et al. (1999) did a more comprehensive study on Douglas-fir across the size range of the species. They used mixed nonlinear models, estimating maximum branch diameter with depth into the live crown.

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Kershaw et al. (2009) compared fixed and mixed nonlinear approaches and found that the differences in adjusted coefficient of determination, root mean square error, and Akaike information criterion depended on the model variant and that the mixed nonlinear approaches were superior only for the naive and simple model.

Models based on relationships between branch diameter and growing conditions or different variables describing attained tree size have been developed for several species. Mäkinen and Colin (1998) found that branch diameter increased with diameter at breast height and crown length. Maguire et al. (1999) got similar results for Douglas-fir. Important fixed effects in the final model were diameter at breast height, tree height, and live crown length (Maguire et al. 1999). Björklund and Petersson (1999) found considerable differences between tree classes, with dominant trees having the thickest knots. Their results indicated that knot diameter also increased with increasing site index, which follows logically from the well-known fact that increasing site index increases diameter growth of the stem. Høibø (1991) and Vestøl and Høibø (2001) also found a positive correlation between knot diameter and diameter growth of the stem for Norway spruce. This corresponded with the Scots pine (*Pinus sylvestris* L.) studies of Moberg (2000).

Mäkinen and Colin (1998) concluded that branch characteristics might be predicted from the measurement of only a few tree-level variables without detailed knowledge of the stand history. In a study of mixed stands of *Pinus ponderosa* and *Pinus contorta* and stands of *Abies grandis* and *P. ponderosa,* Garber and Maguire (2005) also found that different tree variables were able to account for most stand conditions, but the models with explicit treatment variables were superior. Vestøl et al. (1999) found in a spacing study on Norway spruce only a slight, but still significant, effect of stand density in addition to the effect of diameter at breast height. Duchateau et al. (2015) developed models that linked knot ontogeny to stem growth based on data from X-ray tomography. They found that the ratio between increment of the total knot area and the increment of stem basal area for a certain year varied with age and the stem height–to–diameter ratio of the tree. The results from the studies described above show that knot diameter profiles in trees may be predicted not only from individual tree attributes, but also from site quality, initial spacing, and thinning regime. It also is plausible that these relationships are somehow visibly rendered in the annual ring width pattern at breast height.

Vertical trends in sound knot length, or sound knot length profiles in general, follow the same pattern as the knot diameter profiles. For Norway spruce, Øyen (1999) found an increase in sound knot length with increasing distance from the ground into the base of the live crown, with subsequent decreasing sound knot length, following the stem radius farther up in the tree. Høibø et al. (1999) found a similar pattern for Scots pine. Øyen (1999) also found a positive correlation between diameter growth and sound knot length.

Depending on the study objective, some research (e.g., Maguire et al. 1999) on Douglas-fir has been done on branches in the upper part of the tree, where the branches are alive, while other research (e.g., Maguire 1994; Briggs et al. 2007, 2008) has been done on branches in the lower part of the tree. Høibø (1991) found, in a spacing study of Norway spruce, that breast height diameter measured early in the tree's life was a better predictor for quality in the lower part of the bole, while the breast height diameter measured late in the tree's life told more about the properties farther up the stem. Variables studied were knot diameter, modulus of rupture, modulus of elasticity, and wood quality according to Norwegian structural and appearance grading rules. Høibø (1991) did not analyze annual ring width patterns, but his results indicate likely relationships between annual ring width patterns at breast height and vertical knot diameter profiles. Such relationships are plausible for the reason that given a particular stand condition, the proportionality between stem diameter growth and branch diameter growth is maintained, because they both mirror the production from photosynthesis, which to a great extent depends on the size of the crown.

From the relationships described above, it is likely that certain annual rings might be suited to somehow describe the knot/branch characteristics in certain parts of the tree, especially those branches functional within the same period. It is also plausible that the effect of site index on different knot characteristics might be described by the width of certain rings, preferably annual rings that are less influenced by the competition between trees.

Diameter growth has always been an important output from growth and yield models. Therefore, models that are able to predict the relationship between annual ring width patterns and knot characteristics within trees and/or other important wood quality attributes could be used together with growth and yield models to predict quality from information about growing conditions, like site index, spacing, and silvicultural regime.

The aim of this study was to develop models describing vertical profiles of knot diameter and sound knot length in young Douglas-fir trees with information from ring width profiles. We also wanted to study how different stand and tree characteristics worked as explanatory variables compared with information from the ring width profiles.

Materials and Methods

In total, 28 trees from four plots were available for this study. Two plots, one representing a low density and the other a high density, came from a fairly high site index. The other two plots came from a low site index stand, one representing a low density and the other high. The two stands (high and low site) are part of a larger spacing study overseen by the Stand Management Cooperative, School of Environmental and Forest Sciences, University of Washington. Each spacing treatment was applied to a square 0.4047-hectare treatment plot, with tree measurements taken on the trees in a centrally located square 0.20235-hectare measurement plot, leaving a 9.3-m-wide buffer on every side. The buffer on one side of each treatment plot was set up originally to be doubly wide, i.e., 18.6 m, to allow periodic destructive sampling events to occur in the future without compromising the central measurement plot. Study site attributes are listed in Table 1, and plot and tree characteristics are listed in Table 2. Symbols and variable definitions are listed in Table 3.

For each plot, diameters at breast height (DBHs) were measured for all trees in the double-buffer area, 45×9.3 m $= 0.0418$ hectare. The measured trees were sorted according to DBH and divided into seven groups, an equal number in each group (septile). From each septile, one tree was sampled randomly, i.e., seven trees total from each plot.

Table 1.—Characteristics of the study sites.

Installation no.	705	706
County	King	Grays Harbor
State, USA	Washington	Washington
Latitude	47°10′36″N	46°45′43″N
Longitude	121°43′4″W	123°44′49″W
Elevation (m)	823	91
Slope (%)	30	25
Aspect	180	270
SI_{50} (m)[a]	27	38
Planting date	Jan 1976	Jan 1978
Stock type	1 − 1	2 + 1
No. of trees/ha, plot established[b]	1,729	1,598
Year plots established	1987	1987
Age, plant to precommercial thinning established	11	13
Age, plant to harvest of study trees	24	26

[a] Site index, based on age 50 years at breast height (King 1966).

[b] Mean of the four initial stems per hectare (stems per hectare present at establishment age before precommercial thinning) plots on each installation.

Two of the original 28 trees were taken out of the material before modeling because they were abnormal. One tree had a serious breakage some years back, causing abnormal branch growth at the part of the stem actually measured. The other tree had bark damage at breast height and below, causing a reduction in diameter in this part of the stem.

On each sampled tree, the north direction was marked. The DBH was measured with a tape in the forest. In addition, DBH was measured in two directions perpendicular to each other on the sampled disks in a wood shop. Tree height (H), height to where three-quarters of the branches were alive (CrH_{270}), height to where half of the branches were alive (CrH_{180}), and height to the first living branch were measured with a tape just after felling. Height to each sampled whorl was also measured with a tape just after felling. All heights were measured from ground level.

Each third whorl was sampled (whorl number: 3 [from top], 6, 9, 12, 15, 18, and 21, and for some trees also whorl number 24). Only the knots in the main whorl were included in the disks sampled, except in cases where the main whorl included fewer than five knots. When this happened, a sufficient number of knots below the main whorl were included such that the sampled disk included five knots total. In addition, clear wood stem disks at breast height were sampled. A mark that showed the north direction was put on the top of all the disks.

Measurements on disks with knots

The azimuth for each knot was measured clockwise from the north mark. Measurements were done on the upper crosscut of the stem disks. The distances from pith to the stem disk surface (radius) for each knot were also measured on the upper crosscut. Diameter for each branch was measured outside and inside bark at a distance approximately equal to the knot diameter (KD) from the stem surface to avoid swelling due to the branch collar.

For disks where some of the knots were dry (corresponding to dead branches), each knot was cut through its center, radially through the stem. The distance from the stem disk surface to the border between the dry and sound knot was measured on the radial knot surface perpendicular to the pith in order to find the individual sound knot length (SKL_{indiv}; Fig. 1). The border was defined according to Maguire and Hann (1987), where the connection between branch wood and stem wood was broken over half of the circumference of the knot.

Maximum KD for each knot was measured on the radial surface perpendicular to the knot at the border between sound and dead knot. For sound knot disks the KD measurements were based on the branch stump at a distance from the stem surface approximately equal to the KD (branch measurement). These disks were not cut through.

Measurements on clear wood stem disks

DBHs were measured in two directions perpendicular to each other. First, the maximum diameter was found. Thereafter, if the disk had not been cut perpendicular to the stem length, the angle or opposite leg was measured to calculate a correct diameter. The second diameter was measured perpendicular to the first one.

Each annual ring width (ARW) was measured on the breast height stem disks for all the trees sampled. The annual rings were measured along the mean radius. The mean radius was calculated from the mean value of the largest and the smallest diameter found on the stem disk. If

Table 2.—Plot and tree characteristic.[a]

Site	Plot	SI_{50}	Stems/ha	Mean age at BH	Mean (SD) DBH (mm)	Mean (SD) ARW_{BH} (mm)	Mean H (m)	Mean CrH_{270} (m)
705	6	27.4	861	20	189 (25)	4.8 (0.7)	18.0	4.7
705	12	27.4	1387	21	168 (41)	3.9 (0.9)	18.6	9.4
706	3	38.1	1291	21	181 (40)	4.3 (0.9)	20.2	12.7
706	7	38.1	669	21	228 (43)	5.4 (1.0)	21.2	11.2

[a] See Table 3 for definitions of abbreviations.

Table 3.—List of symbols and variable definitions.

ARW_{mean}	Mean annual ring width at breast height (mm)
DBH	Diameter at breast height (mm)
CrH_{270}	Full crown height (m), distance from ground to full crown (three-quarters or more of the branches are alive)
CrH_{180}	Half crown height (m), distance from ground to where 180 degrees of the crown was alive
H	Tree height (m), distance from ground to the top of the tree
KD	Knot diameter (mm)
KD_{indiv}	Diameter for individual knots
KD_{mean}	Mean knot diameter in each whorl (normally a mean value of five knots)
KD_{max}	Maximum knot diameter in each whorl
SI_{50}	Site index (m), height of the trees width largest DBH at 50 yr breast height age (King 1966)
Trees/ha	Plot variable, no. of trees per hectare
SKL_{indiv}	Sound knot length (mm) for individual knots
SKL_{mean}	Mean sound knot length (mm) in each whorl
WH	Whorl height (m)

the disk was not cut perpendicular to the stem axis, the annual rings were adjusted to the calculated mean diameter.

Models

The dependent variables to be modeled were KD and sound knot length (SKL). The analyses of KD were performed in two steps:

1. Models were developed and tested describing the vertical variation in KD.
2. Parameters in the models from the first step were modeled by tree-level and stand-level variables.

Under Step 1, a second-degree polynomial function (Model 1) was used to describe KD vertical profiles for single trees from butt end to top. A symmetric model form was used because this material was young and the profiles were relatively symmetric. Residuals from predicting KD for each tree individually with a second-degree polynomial showed a stable variance from small to large knots. When the residuals were plotted against whorl height, no obvious change in variance was observed, nor were there any increasing or decreasing linear trends with increasing whorl height (WH), just a very small wavy pattern about one-quarter to one-half the magnitude of the root mean square error (RMSE) on average. Models based on several functions describing the different parts of the tree have been used earlier (Colin and Houllier 1991, Moberg 1999), but such models have more variables and are more difficult to explain. Moberg's models are based on older trees, and more of his trees had more pronounced nonsymmetric profiles than the trees in this study. Random coefficient models were used in which the parameters contained one fixed component common to all trees and a random component varying from tree to tree (Littell et al. 1996). Model 1 is shown in the equation below, where a normal distribution was assumed for the random error components.

$$Y = \alpha + a_i + (\beta + b_i) \times \mathrm{WH} + (\gamma + c_i) \times \mathrm{WH}^2 + e_i \quad (1)$$

where Y is one of the three response variables, KD_{indiv}, KD_{mean}, or KD_{max}; α, β, and γ are fixed components of the model coefficients; a_i, b_i, and c_i are random deviations of the ith subject from the fixed component of the model coefficients; WH is whorl height; and e_i is a residual, i.e., an error unexplained by predictor variables and random tree effects.

Because the trees were not fully mature and the upper part of the trees had not yet fully developed into the final product, models describing only the lower part of the trees were also explored. These models described KD vertical profiles from the butt end to the whorl with the largest knots and profiles from butt end to the center of the crown (one-third up in the crown from the CrH_{180}), where the largest knots normally are located. Because logarithmic functions are nonsymmetric, simple, and relatively flexible, they were chosen for Model 2 and are shown in Equation 2:

$$Y = \alpha + a_i + (\beta + b_i) \times \mathrm{WH} + (\gamma + c_i) \times \ln \mathrm{WH} + e_i \quad (2)$$

where ln is the natural logarithm and all other variables and coefficients are defined as in Model 1 (Eq. 1).

For SKL, only a single parameter could be determined for Model 3, representing a mean level for all WHs, because the material was too young and data were too few to identify vertical SKL profiles for all the trees.

$$Y = \alpha + a_i + e_i \quad (3)$$

where Y is either of the two response variables, SKL_{indiv} or SKL_{mean}, and all other coefficients are as defined previously.

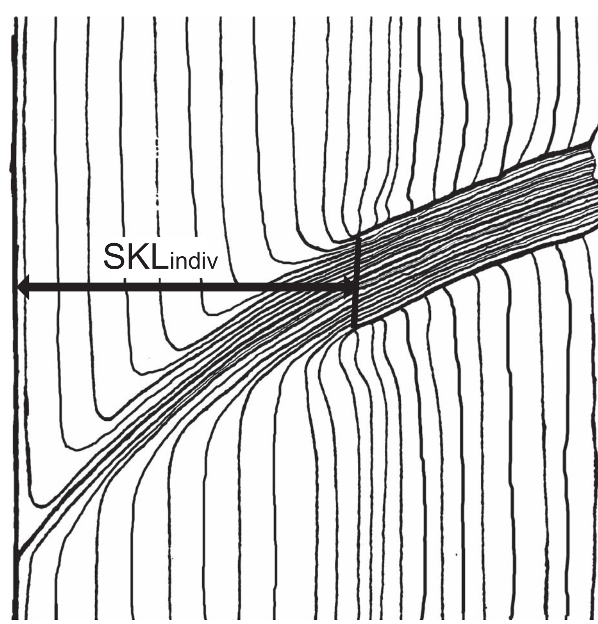

Figure 1.—Annual ring pattern for cut through knots, after Øyen (1999). SKL_{indiv} = individual sound knot length.

The SKL models were based on knots from the butt end up to CrH_{180}. In older stands, varying SKLs following particular patterns that depend on the growing environment for the individual tree (local stand density, social position, treatment-induced changes in crown recession rate, etc.) will be expected (Høibø et al. 1999).

Models were fit in SAS, Software 9.2 (random coefficient models) following Littell et al. (1996).

Null hypotheses that the fitted parameter values equaled zero were rejected if the probability of Type I error was smaller than 0.05. The RMSE and R^2 values (not adjusted) from analysis Step 2 (Tables 4 and 5) were derived using the residuals from linear regressions between the fitted and the measured values. In these linear regressions, the lines were forced through zero with an inclination of one to include the bias. Both fixed and random effects were included when calculating RMSE and R^2 values for model Step 1. This is equal to individual profile fits for each tree. For model Step 2, only the reduction in variance resulting from fixed effects was included when calculating RMSE and R^2 values. This was done with JMP 9.0 (SAS Institute Inc.).

Results

KD models

The second-degree polynomial was found to be a relatively good model to describe vertical profiles of knot diameters (KD_{indiv}, KD_{mean}, and KD_{max}) for the whole tree (Model 1). Statistics obtained by fitting each tree individually with second-degree polynomials are given in Table 4.

While fitting KD profiles over less than the whole tree, the model form was changed from a second-order polynomial to a transformed-variable model with ln(WH) as the sole predictor. Thus a reduced model was used when the vertical KD profiles from butt end to the whorl with the largest knots were modeled (Model 4), as well as when vertical KD profiles from butt end to the crown center (one-third up in the crown from the CrH_{180}) were modeled (Model 5). Equation 4 shows Models 4 and 5:

$$Y = \alpha + a_i + (\gamma + c_i) \times \ln \mathrm{WH} + e_i \qquad (4)$$

Statistics for the two logarithmic models, fitting each tree individually from butt end to the whorl with the largest knots (Model 4) and to the center of the crown (Model 5), respectively, are given in Table 4. The variance components from this first analysis step state the total variation between trees before introducing tree- and stand-level variables. An increase in R^2 value between 9 and 19 percent age point can be seen when going from fitting individual knots to fitting the mean knot diameter (KD_{mean}) for each whorl (analysis Step 1; Table 4). Even higher R^2 values were achieved when fitting maximum knot diameter (KD_{max}). The largest variance components were found for the intercept (σ^2_a) and for the residuals (σ^2_e, variation around the individually modeled profiles).

In Model 1.2.a, additional fixed effects were added to Model 1. Site index based on age 50 years at breast height (SI_{50}) gave a positive contribution to the intercept but negative contribution in the interaction with WH (Table 4).

Table 4.—KD models from model Step 2 and variance components and summary statistics from model Steps 1 and 2.[a]

Analysis step	Model no.	Y	n	Variance components (mm^2) σ^2_a	σ^2_b	σ^2_c	σ^2_e	Summary statistics RMSE (mm)	R^2
1	1	KD_{indiv}	901	9.95	0.611	0.0026	12.2	3.5	0.72
1	4	KD_{indiv}	623	13.38	—	1.95	11.46	3.38	0.74
1	5	KD_{indiv}	648	13.66	—	1.92	11.34	3.37	0.74
1	1	KD_{mean}	189	4.80	0.39	0.0019	7.55	2.96	0.81
1	4	KD_{mean}	127	12.58	—	1.85	3.85	1.97	0.93
1	5	KD_{mean}	134	12.45	—	1.58	4.64	2.15	0.91
1	1	KD_{max}	189	8.65	0.52	0.0019	6.63	2.78	0.87
1	4	KD_{max}	127	15.37	—	2.20	3.10	1.77	0.95
1	5	KD_{max}	134	15.36	—	1.77	4.63	2.16	0.92
2	$1.2.a_{mean}$	KD_{mean}	189	—	0.49	0.0022	7.59	3.8	0.59
2	$1.2.b_{mean}$	KD_{mean}	189	—	0.24	0.0014	7.09	3.6	0.63
2	4.2_{mean}	KD_{mean}	127	—	—	0.95	4.82	2.7	0.79
2	5.2_{mean}	KD_{mean}	134	—	—	0.55	5.20	2.6	0.81
2	$1.2.a_{max}$	KD_{max}	189	—	0.38	0.0019	7.58	4.1	0.61
2	$1.2.b_{max}$	KD_{max}	189	—	0.33	0.0018	6.70	4.0	0.63
2	4.2_{max}	KD_{max}	127	2.56	—	0.54	3.14	2.6	0.83
2	5.2_{max}	KD_{max}	134	2.36	—	—	4.85	2.6	0.83

Models

$1.2.a_{mean}$: $KD_{mean} = 0.35 \times SI_{50} + (0.64 \times ARW_{mean} - 0.020 \times SI_{50}) \times WH - 0.028 \times ARW_{mean} \times WH^2$

$1.2.b_{mean}$: $KD_{mean} = 1.91 \times ARW_{6\text{–}10} + 0.47 \times ARW_{11\text{–}15} \times WH - 0.027 \times ARW_{11\text{–}15} \times WH^2$

4.2_{mean}: $KD_{mean} = 2.28 \times ARW_{6\text{–}10} + 0.70 \times ARW_{11\text{–}15} \times \ln WH$

5.2_{mean}: $KD_{mean} = 2.74 + 1.87 \times ARW_{6\text{–}10} + 0.65 \times ARW_{11\text{–}15} \times \ln WH$

$1.2.a_{max}$: $KD_{max} = 0.43 \times SI_{50} + (0.74 \times ARW_{mean} - 0.025 \times SI_{50}) \times WH - 0.033 \times ARW_{mean} \times WH^2$

$1.2.b_{max}$: $KD_{max} = 2.32 \times ARW_{6\text{–}10} + 0.53 \times ARW_{11\text{–}15} \times WH - 0.032 \times ARW_{11\text{–}15} \times WH^2$

4.2_{max}: $KD_{max} = 4.67 + 2.05 \times ARW_{6\text{–}10} + 0.74 \times ARW_{11\text{–}15} \times \ln WH$

5.2_{max}: $KD_{max} = 5.01 + 2.01 \times ARW_{6\text{–}10} + 0.68 \times ARW_{11\text{–}15} \times \ln WH$

[a] Both fixed and random effects were included when calculating the summary statistics for model Step 1. This is equal to individual profile fits for each tree. For model Step 2, only the reduction in residual variance due to fixed effects were included when calculating the summary statistics. See Table 3 for definitions of abbreviations.

Table 5.—SKL models from model Step 2 and variance components and summary statistics from model Steps 1 and 2.[a]

Analysis step	Model no.	Y	n	Variance components (mm^2) σ^2_a	σ^2_e	Other statistics RMSE (mm)	R^2
1	3	SKL_{indiv}	307	544	136	11.7	0.81
1	3	SKL_{mean}	66	516	65	8.0	0.93
2	3.2	SKL_{indiv}	307	109	136	15.1	0.66
2	3.3	SKL_{indiv}	307	75	136	14.1	0.70
2	3.2	SKL_{mean}	66	85	65	11.8	0.75
2	3.3	SKL_{mean}	66	59	65	10.9	0.79

Models

3.2_{mean}: $SKL_{mean} = -34.9 + 1.14 \times SI_{50} + 17.5 \times ARW_{mean}$

$3.3_{mean:}$ $SKL_{mean} = 4.75 + 9.67 \times ARW_{6\text{–}10} + 4.30 \times ARW_{11\text{–}15}$

[a] Both fixed and random effects were included when calculating the summary statistics for model Step 1. This is equal to individual profile fits for each tree. For model Step 2, only the reduction in residual variance due to fixed effects were included when calculating the summary statistics. See Table 3 for definitions of abbreviations.

The interaction leads to less effect of WH on KD with increasing site index given the same ARW. When the interaction between mean annual ring width at breast height (ARW_{mean}) and WH was removed from the model, the parameter estimate for the interaction effect between SI_{50} and WH became positive (model not presented).

In Model 1.2.b, the parameters are modeled by the width of different ring intervals. SI_{50} was supplanted with mean annual ring width for the interval from annual rings six to ten ($ARW_{6\text{–}10}$). The interaction variables with WH and WH^2 were supplanted with $ARW_{11\text{–}15}$ (Table 4). This model ($1.2.b_{mean}$) reduced the residual variance more than the first model ($1.2.a_{mean}$). From Figure 2 it can be seen how Model $1.2.b_{mean}$ fits the data compared with Model $1.2.a_{mean}$ for 12 of the studied trees. In Figure 2, all knots in each whorl are plotted in order to illustrate the variation in KD within the whorl.

The different parameters estimated in Models $1.2.a_{max}$ and $1.2.b_{max}$ are somewhat larger compared with their corresponding parameter estimates in Models $1.2.a_{mean}$ and $1.2.b_{mean}$, respectively (Table 4).

In Table 4, the variance components (remaining tree effects) are also stated for the models with fixed effects added (analysis Step 2, Models 1.2.a and 1.2.b). When comparing the different variance components from analysis Steps 1 and 2 (Table 4), a reduction can be seen for all models after tree and stand variables were introduced. Several variance components were almost eliminated. Random effects that were not significant were excluded in analysis Step 2 (Table 4). The difference between perfect one-to-one fits and the model fit is exhibited in Table 4; see RMSE and R^2 values for analysis Steps 1 and 2.

The parameters in Models 4 and 5 were predicted by the width of different ring intervals (Models 4.2 and 5.2). Most parameters in Models 4.2_{max} and 5.2_{max} were somewhat larger when compared with the corresponding parameter estimates in Models 4.2_{mean} and 5.2_{mean}, respectively (Table 4). In Figure 3, modeled vertical KD profiles (excluding random tree effects) for some of the trees are plotted.

More models with different combinations of the variables SI_{50}, trees per hectare, $ARW_{6\text{–}10}$, $ARW_{11\text{–}15}$, $ARW_{11\text{–}15} \times \ln$ WH, and the width of other ring intervals were tested too. These analyses showed that $ARW_{6\text{–}10}$ was a good variable describing the effect of SI_{50} on KD, while $ARW_{11\text{–}15}$ described the effect of trees per hectare (stand density) rather well. Both SI_{50} and trees per hectare reduced the residual variance for the KD profiles significantly, but when $ARW_{6\text{–}10}$ and $ARW_{11\text{–}15} \times \ln$ WH were introduced they did not, or their effects were substantially reduced.

When comparing the tree effects before and after tree and stand characteristics were included (Models 4.2 and 5.2), a tree effect reduction (lower variance components) can be seen (Table 4). Several variance components were eliminated also for these models (Table 4). However, also after including the tree and stand characteristics, there still were some significant random tree effects left.

All the variables included in Models 1.2.a, 1.2.b, 4.2, and 5.2 reduced the residual variance significantly ($P < 0.05$). The variables reducing the residual variance most were mean diameter increments for the different ring number intervals at breast height.

SKL models

In Table 5, statistics for Model 3, including variance components (a_i), are exhibited. Variation with WH within each tree was not included when modeling sound knot lengths (SKL_{indiv} and SKL_{mean}), because the material was too young and data were too few to make vertical profiles for all the trees.

To produce Model 3.2 in Step 2, tree-level and stand-level fixed effects were introduced into Model 3 (see Table 5). In Model 3.3, the single fixed-effect parameter in Model 3 is predicted by the width of different ring intervals only (Table 5). In Table 5, statistics are given for the mixed models with fixed stand effects and fixed tree effects included (Models 3.2 and 3.3).

All the parameters in Model 3.2 reduced the residual variance significantly. When comparing the tree effect (variance components) for SKL_{indiv} before and after tree and stand characteristics were included, a reduction of the variance components (σ^2_a) from 544 to 109 and 75 for Models 3.2 and 3.3, respectively, can be seen (Table 5). Still, there were significant random tree effects left that apparently could not be replaced by any fixed-effect tree-level covariates tested. Also for SKL, different models with different combinations of the variables SI_{50}, trees per hectare, $ARW_{6\text{–}10}$, $ARW_{11\text{–}15}$, and ARW_{mean} were tested. These analyses showed that $ARW_{6\text{–}10}$ was a useful variable describing the effect of SI_{50} on SKL, while $ARW_{11\text{–}15}$ or ARW_{mean} described the effect of trees per hectare (stand

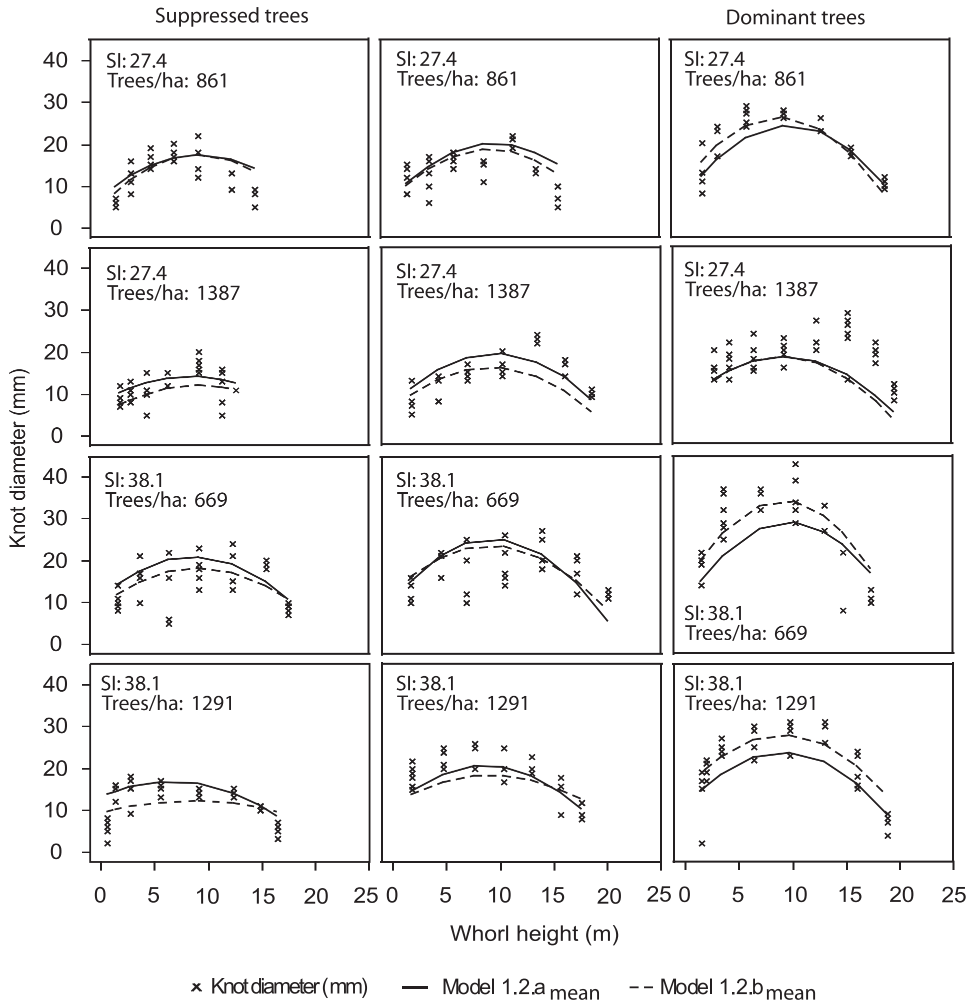

Figure 2.—Vertical profiles for individual knots and modeled vertical knot diameter profiles for Models 1.2.a and 1.2.b for some of the trees. Only fixed effects were included when calculating the predicted values. SI = site index.

density) well. Without other predictors, both SI_{50} and trees per hectare reduced the residual variance for SKL significantly, but when $ARW_{6–10}$ and $ARW_{11–15}$ or ARW_{mean} were introduced, they did not.

Discussion

ARW_{mean} at breast height and mean ring width for certain annual ring intervals at breast height were the best variables found to describe the knot structure within the stems studied. This is in accordance with Vestøl and Høibø (2001) and Øyen (1999), who found that a variable describing diameter growth is the best variable to describe the knot characteristics. If the stand is close to being even aged it is possible to use mean breast height age for the stand together with breast height diameter to describe the diameter growth for the individual tree. These two variables are easier to use in practice, for instance when using the models to optimize crosscutting of stems in a harvester (Øyen 1999). In addition to variables describing diameter growth, it is important to include a site index–describing variable to adjust the model for the stand growth potential.

SI_{50} was used in Model 1.2.a, but in Model 1.2.b, SI_{50} was supplanted with $ARW_{6–10}$. The better result achieved for Model 1.2.b may be because $ARW_{6–10}$ is an individual tree variable, describing the single tree production potential better compared with site index, which only gives a mean value for all trees within the stand. Interval 6 to 10 was more effective than other intervals, most probably because the trees had limited competition from other trees in this period, leading to a good relationship with the site production potential. The ring widths started to decrease approximately after annual ring 10, the dense and high site index stand somewhat earlier compared with the others that started somewhat later, revealing that the competition between trees started at approximately 10 years of age. Probably therefore ring intervals before year 11, but after the plants were well established, was the best interval describing the growth potential or site index for this material.

Curtis and Reukema (1970) found markedly less stem diameter and crown development in dense stands compared with wider-spaced stands. Today it is well known that the stand density regime is one of the more decisive factors for branch diameter growth (Høibø 1991, Maguire et al. 1999, Lowell et al. 2014). A negative parameter estimate for SI_{50} might therefore be expected when modeling KD with ARW and site index, because equal ARWs in trees from two different site qualities normally is a result of a more narrow spacing on the richer site, leading to smaller branch diameter growth. Still, in this study the SI_{50} parameter

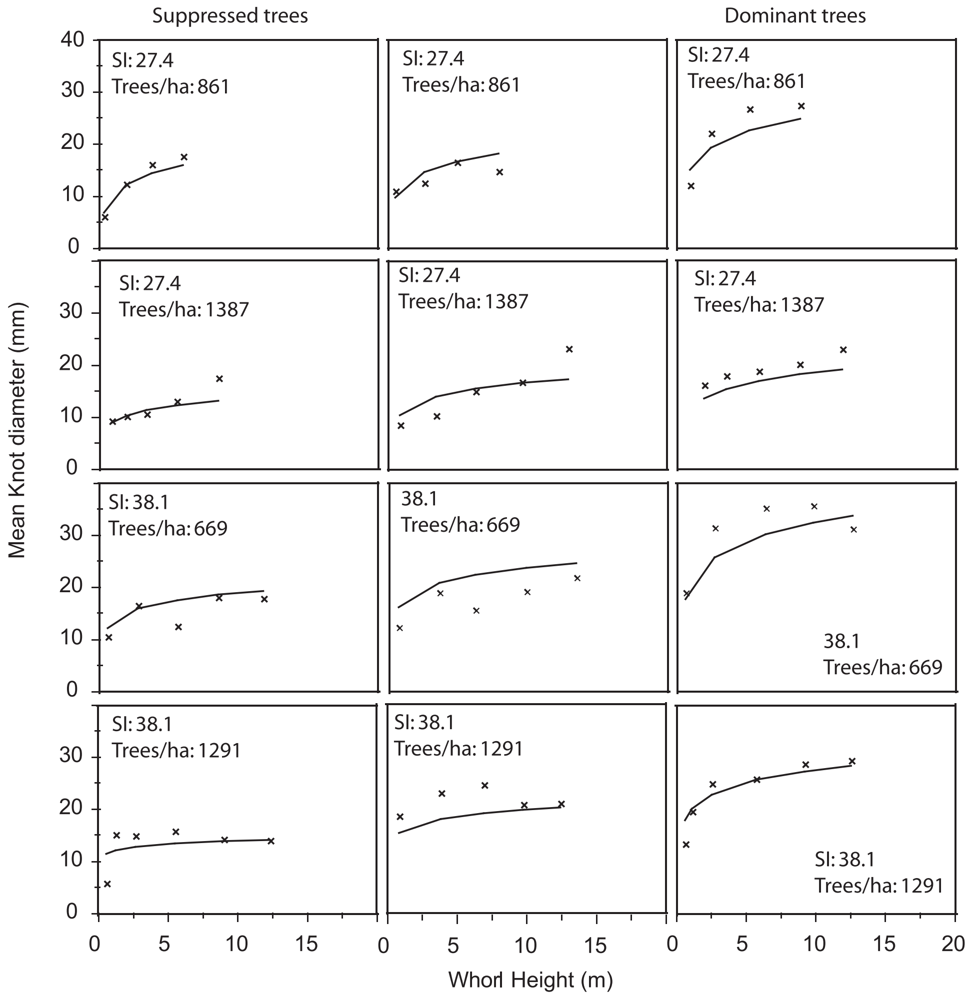

Figure 3.—Mean knot diameter in each whorl and modeled vertical knot diameter profiles for Model 5.2$_{mean}$ for some of the trees. Only fixed effects were included when calculating the predicted values. SI = site index.

estimate was positive when modeling KD (Models 1.2.a$_{mean}$ and 1.2.a$_{max}$; Table 4). This result might be due to the young age and few years with competition between the trees studied, leading to a limited effect of competition but a larger positive effect of site quality on KD. The negative parameter estimate for the interaction between WH and site index (SI_{50}; Models 1.2.a$_{mean}$ and 1.2.a$_{max}$; Table 4) pulls the result in the opposite and more expected direction. The negative parameter estimate decreases the effect of WH with increasing site index, when ARW_{mean} at breast height is held constant. Further, this exhibits less effect of WH on KD for denser stands and more suppressed trees. The last point can be seen in Figure 3. It must be said that the effect of site index on KD was rather weak (small parameter estimate) compared with the effect of ARW_{mean} and WH.

To account for the effect of competition between trees, $ARW_{11–15}$ was found to be a good explanatory variable. For older trees, probably a longer interval would be better (Høibø et al. 1999, Øyen 1999, Vestøl and Høibø 2001).

From Figure 2 we can see that the vertical KD profiles are not symmetric for all trees. This might be owing to different growth for these trees in certain periods, caused by different competition from other trees. How the vertical KD profiles develop for older trees will depend on the thinning regime and other impacts leading to changes in the stand structure (Maguire et al. 1999). For older stands, where asymmetric vertical KD profiles are expected, segmented polynomials continuous at their join points probably is a good or necessary choice when modeling the whole tree.

Model 4.2 is based on knot data from the butt end to the whorl with the largest branches in the crown. Model 5.2 is based on the knot data from the butt end to the center of the crown (one-third up in the crown from the CrH_{180}) where the largest knots often are located. Models 4.2 and 5.2 (Table 4) gave approximately the same parameter estimates. Model 5.2 is recommended before Model 4.2 because it is easier to find and measure the height to the center of the crown (one-third up in the crown from the CrH_{180}) than the height to the largest branches.

Also when modeling SKL, the models with the two different ring width intervals reduced the residual variance most. The independent variables found to be among the best in the KD models were the best for SKL, as well; for instance, ARW_{mean} and SI_{50} (Model 3.2; Table 5), which were similarly replaced with $ARW_{6–10}$ and $ARW_{11–15}$, respectively (Model 3.3). The parameter estimates for SI_{50} were positive also when SKL was modeled. Using the same or similar explanatory variables when modeling SKL and KD is plausible, because KD and SKL normally are well correlated (Høibø et al. 1996).

Mäkinen and Colin (1998) found that branch characteristics might be predicted from measurement of only a few tree-level variables, without detailed knowledge of the stand history. Garber and Maguire (2005) found that different tree variables also were able to account for most stand conditions, but models with explicit treatment variables were superior. Vestøl et al. (1999) found in a spacing study on Norway spruce only a slight but still significant effect of stand density on KD in addition to the effect of DBH. For this study, site index and stand density significantly reduced the residual variance when modeling KD and SKL. However, when introducing $ARW_{6–10}$ and $ARW_{11–15}$, site index and stand density did not reduce the residual variance significantly, neither for KD (Models 4.2 and 5.2) nor for SKL (Model 3.3). This reveals that ARW patterns at breast height may be used to predict the knot structure within single trees without knowing the stand history, that is, without explicitly including treatment variables.

The studied trees are young and the models are static because they only describe the current status of the branches. Therefore, the models developed cannot be used directly on old stands because the crown recession and branch growth will further develop for a long period. Still, the knot characteristics in the lower part of the stem for this material was set because the crowns had receded up to approximately 9 m for most trees.

Stands often exhibit wider diameter distributions as they develop; therefore, depending on thinning regime and other impacts, the difference in knot properties between trees probably will be larger than what has been found in this work. Well-thinned stands with more even diameter distributions normally display relatively smaller tree effects and relatively larger stand effects (differences between stands) on knot properties than unthinned stands. This can be seen both for Norway spruce and Scots pine, when comparing research done on well-treated research stands with fairly narrow diameter distributions (Moberg 1999) with research done on ordinary forest stands with wider diameter distributions (Vestøl 1998, Høibø et al. 1999). Still, variables describing single tree diameter growth probably will be the most important variables describing the knot properties in stems of many tree species because fast growing trees have larger crowns and therefore larger branches and KDs.

The range in site index, spacing, and tree status was relatively large, realistically covering the range of growing conditions common to intensively managed coastal Douglas-fir plantations of western North America. However, the material is still limited in terms of the number of trees and stands and stand ages investigated. For older stands, more flexible and nonsymmetric model forms are required when profiles for the whole tree are to be modeled because the position of the largest branches for older stands to a greater extent depends on stand density. In dense old stands, the largest knots will be found relatively close to the top of the tree, while in open stands with long crowns, the largest knots will be found much closer to ground because the largest knots usually are found relatively close to the base of the living crown. Therefore, it is important not to go outside the range of the data used, and it would be fruitful to go further with both a larger and more widely ranging material in order to go deeper into the relationships discussed.

One application for such models could be to predict KD and SKL in the context of inventory and sorting during harvesting. However, today ARW patterns are more difficult to measure compared with stem diameter profiles from harvester equipment or data from common forest inventories. Other applications could be in the context of simulating knot attributes as in response to silvicultural regime in dynamic growth models, where annual diameter growth is starting to be among the common outputs from the models. Sound KD and length and loose KD and length could be outputs from the simulation of individual tree growth and development if models describing relationships between ARW patterns and knot structure are established.

Conclusions

The study shows that it is possible to model knot characteristics in Douglas-fir with only a few tree and stand variables.

The best variables found to describe the knot structure within the stems studied were mean annual ring width at breast height and mean ring width for certain annual ring intervals at breast height.

Site index and stand density significantly reduced the residual variance when modeling knot diameter and sound knot length. However, when introducing mean annual ring width for years 6 to 10 and mean annual ring width for years 11 to 15, site index and stand density did not reduce the residual variance significantly, or their effects were substantially reduced, neither for knot diameter nor for sound knot length. This reveals that annual ring width patterns at breast height may be used as effective surrogates for stand history to predict the knot structure within single trees, because they reflect the mechanistic interrelationships between site quality, stand density, crown dynamics, and diameter growth rate.

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