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Modeling Knot Properties for Mongolian Pine in Northeast China

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Abstract : This study was performed in 14 unthinned Mongolian pine (*Pinus sylvestris* L. var. mongolica Litvin) plantations in northeast China. Data were collected on 70 sample trees of different canopy position with diameter at breast height (DBH) ranging from 6.9 cm to 34.5 cm. Diameter and length of knots per whorl below the living crown were studied by different vertical levels divided by relative knot height (RHK) in this paper. Models taking DBH and height to the crown base (HCB) as independent variables were developed to predict knot diameter (KD) in a sample whorl. According to the vertical distribution tendency and range of sound knot length (KLsound), KLsound was modeled as multiple linear function of DBH, KD and relative knot height (RHK). The loose knot length (KLloose) was described as a function of DBH, KD and height above the ground for knots (HK) in a mixed log-linear model. Results from this study can provide abundant knot information so as to describe the knot size and vertical distribution tendency of Mongolian pine plantation.

***Key words* :** Pinus sylvestris *L. var. mongolica, knot diameter, sound knot length, loose knot length*

Introduction

To establish the basic theory of silvicultural techniques, it is necessary to obtain information about the dynamics of the growth for a tree. Knots in a stem give an abundance of information on the dynamics of the crown structure throughout the life of a tree (Maguire and Hann, 1987).

For Mongolian pine, as with most other species, the optimal utilization of a stem is to have a great extent determined by the knot structure within the stem. A knot is defined as the portion of a branch contained within the tree stem. In terms of lumber quality, a knot is thought of as a void or hole that decreases the overall product strength. The size and location of knots in lumber is directly related to strength and visual grade. The requirements concerning knots in lumber depend on the use of the lumber. These requirements are described in different grading rules for lumber. The location, size of each knot and whether it is sound or dead are determining factors in the visual grade assigned to a given piece of lumber. Previous studies have shown that improvements in lumber value can be achieved if the location of knots is considered during primary breakdown (Wagner and Taylor, 1975; Samson, 1993; Lemieux *et al.*, 2002).

Consequently, both foresters and sawmillers are interested in the knot structure of trees, in particular the position and number of knots, knot diameter and knot length. Unfortunately, these parameters are very difficult to measure. Traditional methods are destructive, i.e. individual knots can be achieved by creating longitudinal sections of whorl knots using a bandsaw (Maguire and Hann, 1987), by producing veneer strips and recording the position of knot features in the radial, longitudinal and tangential planes (Lemieux *et al.*, 1997). An alternative to destructive analysis for knot characterization is to use computer tomography (CT) and two different destructive methods. The result shows that the accuracy of the detection of small knots and the measuring of dead knot and knot length using CT-method had to be improved (Oja, 1997).

The objective of this study was to describe the vertical variation in knot diameter and knot length within trees. The best models of predicting and describing knot diameter, sound knot length and loose knot length were developed in this paper using the software of STATISTICA 6.0 and SAS 8.0. The models were developed based on site level and tree level attributes. These results can be applied to provide abundant branch and knot information so as to describe current and past tree growth dynamic of Mongolian pine plantation.

Materials and Methods

1. Data collection

Sample trees were collected in 14 unthinned Mongo-

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lian pine plantations of different age and density from Mengjiagang forest farm, western part of Wanda Mountain, which is located in Jiamusi city of Heilongiang province, northeastern China, ranging across 130°33' ~130°53'E and 46°20'~ 46°31'N. One plot was chosen in each plantation with areas of 0.04~0.20 ha. Stem diameter at breast height (DBH), total height (HT), height to crown base (HCB), crown width (CW), and the coordinate of x and y were recorded for each tree in the plots. The crown base was defined to be the location where the lowest living branch is. The stand variables were summarized in Table 1.

The cumulative basal area distribution of the trees on each plot was divided into five equal size strata and the average diameter at breast height and total height of each stratum were calculated. In each stratum, one sample tree was chosen randomly according to DBH and HT outside the plot in the stand, 70 different sizes of trees were selected as sample trees for stem analysis and knots analysis.

The sample trees were felled and the height to the ground of each living and dead whorl was recorded. The dead whorls below the lowest dead branch may only have knots and the location and size of knots was deduced on the basis of branch scars. The discs were taken from the stem at height of 1.3 m, stump, and then at 1 m interval above stump following Smalian's method of stem analysis. Every branch within each whorls of sample tree was numbered and descriptive variables of crown structure defined by Li and Yun (1996) were measured. Age of branch was determined based on the whorl order of the tree, the measured number of annual rings in the branch, and on the number of annual rings in the adjacent stem discs and branches.

Near each dead whorl, stem was divided into sections of 20-30 cm lengths containing the whorl in the center without destructing dead branches or knots. The number, azimuths, height of knots in each section were recorded. One or two knots were chosen in each section. The sample knots are the largest knots of the whorl according to the scar on the stem surface. Longitudinal sections through each sample knots were made by sawing the stem along a line between the center of the knot scar and the pith of the stem. Four period of a branch were distinguished according to the years when the branch: (1) emerged from the shoot apex (it can be obtained from the number of annual rings on the stem at height of the knot); (2) ceased to form annual rings at its base, i.e. the annual rings of the stem did not curve inside the branch; (3) died, i.e. branch and stemwood became anatomically separated; and (4) was occluded, i.e. stem growth rings grew over the knot (Makinen, 2002). A knot can be divided into two parts: (1) from the birth of a branch to its death, which is called sound knot; (2) from death to occlusion, which is called loose knot.

The following knot properties were studied: knot diameter, which was determined as the widest part of the knot section (KD); knot length, which includes the sound knot length (KL_{sound}), i.e. the distance between the pith and the sound knot border, and the loose knot length (KL_{loose}), i.e. the distance between the sound knot border and the occluded knot end. The knot variables are illustrated in the transverse plane in Figure 1.

In this study, knot analysis data were collected on 2308 knots from 70 trees. All the knots have sound knot and only 484 knots can be used to predict loose knot length. All the data were divided into two parts: 480 knots of 15 sample trees were selected randomly as validation data and the other 1828 knots of 55 trees were fitting data. All the symbols and variables used in this paper is listed and explained in Table 2. The attributes of

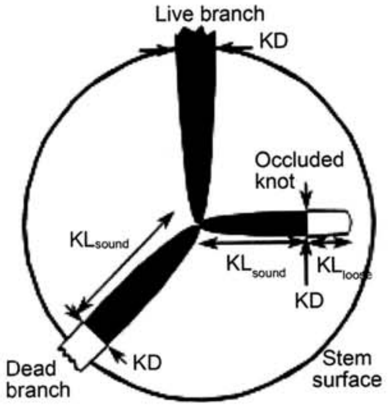

Figure 1. Illustration of knot parameters in the transverse plane of a stem.

Table 1. Descriptive statistics of stand variables.

	Minimum	Mean (s.d.)	Maximum
Area(ha)	0.03	0.07 (0.04)	0.20
Age	18	35.71 (9.27)	47
Mean DBH(cm)	8.9	18.29 (6.62)	30.2
Mean HT(m)	5.7	14.53 (4.96)	21.4
Site index	9.47	12.15 (1.56)	15.33
Stand density (trees/ha)	385	1654.36 (1154.65)	3840

Table 2. Tree and knot variables measured in the field.

Variable	Definition
Stand variables	
SI	Site index
SD	Stand density (trees/ha)
Tree variables	
DBH	Diameter outside bark at breast height (1.3 m above ground level) (cm)
HT	Total tree height (m)
HCB	Height above the crown base (m)
CL	Crown length (=HT-HCB) (m)
CW	Crown width (m)
CR	Crown ratio (=CL/HT) (%)
Knot variables	
HK	Height above the ground for knots (m)
RHK	Relative knots height (=HK/HT)
KD	Diameter of the knot (cm)
KL_{sound}	Sound knot length(cm)
KL_{loose}	Loose knot length(cm)

sample trees and knots studied were summarized in Table 3.

2. Model development

The knot diameter (KD) and knot length were considered as dependent variables in the study. They were chosen in flavor of the biggest knot in each whorl of a tree. The vertical variation of knot diameter (KD) and sound knot length (KLsound) were analyzed based on the preliminary examination and scatter plot of the data. The vertical position is represented as knot height above the ground (HK) and the relative knot height (RHK=HK/HT). The stem was divided into different vertical levels according to RHK. At each level, the mean value and the range of the sound knot length (KLsound) within each sample whorl were analyzed and described.

1) Knot diameter

According to the vertical variations of knot diameter (KD), predictor variables were then determined and tested using linear and non-linear models from the following set of stand and tree variables (see Table 2): SD, DBH, HT, CL, CW, HCB, HK, RHK as well as different combinations and transformations of these variables. Alternative models that added various combinations of independent variables and their transformations were tested and compared. The following equation was found to be the best model for estimating knot diameter of Mongolian pine trees.

$$KD = (a_0 + a_1 DBH) + \exp(a_2 + a_3 DBH + a_4 HCB)\ln(RHK) \tag{1}$$

Where KD is the knot diameter; DBH is the tree diameter at breast height; HCB is the height to the crown base and RHK is the relative knot height; a_0~a_4 are parameters to be estimated from the data.

The final global model for the whole data set was fitted as a non-linear model with the STATISTICA procedure "NLIN" using the Gauss-Newton method. Root mean square error (RMSE) and coefficient of determination (R^2) were used to evaluate model fit.

2) Sound knot length

The sound knot length (KLsound) also varied with vertical levels (RHK). From the knots data for Mongolian pine, it was found that KLsound was closely related to DBH and HK. The simple correlation coefficient of KLsound with DBH and HK were 0.57 and 0.73, respectively. Based on the preliminary examination and scatter plot of the data, multiple regression method was performed to develop the sound knot length model. After testing many combinations of potential independent variables as well as their transformation, the following model was selected:

$$KLSound = b_0 + b_1 kD + b_2 \ln(DBH) + \ln(BHK) \tag{2}$$

Where KLsound is the sound knot length, DBH is the tree diameter at breast height; KD is the knot diameter

Table 3. Summary of sample trees and knots attributes for the Mongolian pine plantation.

Attribute	Minimum	Mean (s.d.)	Maximum	Minimum	Mean (s.d.)	Maximum
Tree (*n*=70)		Fitting data (*n*=55)			Validation data (*n*=15)	
AGE	18	35.86(9.01)	47	18	35.67(8.96)	47
DBH (cm)	6.9	18.78(6.93)	34.5	9.2	18.47(6.40)	30.50
Total tree height (HT) (m)	7.2	15.17(4.64)	22.5	8.1	14.95(4.31)	21.8
Crown length (CL) (m)	3.00	6.55(2.19)	16.45	3.63	6.40(2.21)	11.55
Crown width (CW) (m)	0.35	2.60(1.52)	6.65	0.68	2.43(1.23)	5.20
knots (*n*=2308)		Fitting data (*n*=1828)			Validation data (*n*=480)	
Knots diameter (KD) (cm)	0.18	2.13(0.86)	7.94	0.22	2.03(0.74)	6.77
Sound knot length (KLsound) (cm)	0.18	7.74(2.91)	17.79	1.14	7.76(2.82)	15.79
Loose knot length (KLloose) (cm)	0.20	3.05(1.76)	8.17	0.66	3.43(2.00)	10.64

and RHK is the relative knot height; b_0~b_3 are parameters to be estimated from the data.

3) Loose knot length

Loose knot length (KLloose) was first fitted to data on tree-level means to identify predictor variables from the set of stand and tree variables described above. It was difficult to find significant explanatory variables for the within-tree variation of loose knot length (KLloose). The simple correlation coefficient between KLloose and all the independent variables is less than 0.30. Using a mixed-modeling approach, different knot variables (HK, KD, KDmean, RHK) were then tested on the whole data set. In addition, KLsound was tested as a predictor of KLloose. The final model for the whole data set was obtained using a mixed model with the REML method through the SAS procedure "MIXED" (Littell *et al.*, 1996).

The following log-linear mixed model was chosen:

$$KLloose = \exp(c_0 DBH^{c_1} KD^{c_2} HK^{c_3}) \qquad (3)$$

Where KLloose is the loose knot length, DBH is the tree diameter at breast height; KD is knot diameter and HK is the knot height above ground; c_0~c_3 are parameters to be estimated from the data.

The natural log transformation was applied on KL_{loose} when fitting the model in order to stabilize the variance and to avoid the possibility of negative estimates of the dependent variable.

The models involved an explorative, tree-level and model-screening phase using ordinary least squares. This allowed the use of diagnostic tools such as the variance inflation factor, residual standard deviation, correlation index to check for the appropriate number of independent variables and possible difficulties with correlated variables. Variance homogeneity and normality of errors were evaluated through residual plots.

3. Validation

The validation date set includes 480 knots of 15 sample trees (Table 3). The independent validation procedures for each model of knot properties in the validation data were performed using the following statistical measures (Li *et al*, 2001):

1) Mean Error (ME): $\sum_{i=1}^{n}\left(\frac{y_i-\hat{y}_i}{n}\right)$

2) Absolute Mean Error (AME): $AME = \sum_{i=1}^{n}\left|\frac{y_i-\hat{y}_i}{y_i}\right|$

3) Relative Mean Error (RME):

$$RME = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{y_i-\hat{y}_i}{y_i}\right)\times 100$$

4) Absolute Relative Mean Error (ARME):

$$ARME = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i-\hat{y}_i}{\bar{yi}}\right|\times 100$$

5) Precision Estimation: $P = \left(1-\frac{t_{0.05}S_{\bar{y}}}{\hat{\bar{y}}}\right)$ where

$$S_{\bar{y}} = \sqrt{\frac{\sum(y_i-\hat{y}_i)^2}{n(n-p)}}$$

Where y_i is observed value, $\hat{y}_i$ is predicted value, and p is number of parameters.

Results and Discussion

1. Average vertical trend of KD

The vertical variation of KD is presented in Figure 2 (some abnormal data was eliminated). The vertical trend of KD described by each vertical position increased from stump height up to 40% of the tree height and then decreased upwards when regarding all 70 trees as one group (See Figure 2).

The vertical trend shows that the large knots are located in the middle section of the trees. The knots in the lower part of the trees were generally small. This indicated that the presence of large knots is not a major defect in the butt log. Even if the knots are small, there is a large vertical variation within the lower part of tree. Therefore, knowledge about this vertical variation is important for improving the crosscutting of tree into logs.

2. Vertical variation in sound knot length

The vertical trend of KLsound is similar with that of

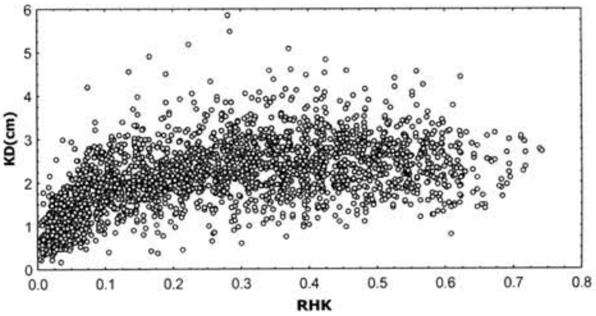

Figure 2. Vertical trend in KD for all 70 trees.

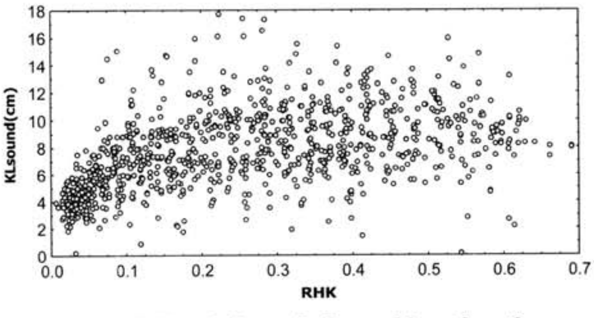

Figure 3. Vertical trend of sound knot length.

knot diameter, which was increasing upwards in the lower 40% of the tree followed by a decreasing trend upwards (Figure 3). For the big knots with bigger KD usually have a longer KLsound.

The vertical trend described by an upward increase in the lower part of the stem followed by a decrease towards the base of the living crown was found in 64 of the 70 trees. For 62 trees the maximum of mean sound knot length is located near the 40% of total tree height (RHK=0.4); for 2 trees the maximum value is at the 55% and 25% of total tree height, respectively; For 4 trees it was increasing all the way up to the living crown, the data shows that the HCB of the 4 trees is lower than the 40% of total tree height; while in 2 trees it decreased directly from the bottom and all the way up to the base of the living crown (the data of these two trees were not included in the scatter plot).

The maximum, minimum, mean and range of sound knot length in different vertical levels were summarized (by calculating the mean value of KLsound in each vertical level for all the sample trees) in Table 4.

The vertical variation in mean sound knot was found to be relatively small compared to the variation among trees. The largest vertical change was found between 0 and 30% of the tree height where the mean value changed from 12.99 cm to 15.10 cm.

The mean value of KLsound was increasing from 5.20 cm at 0% of total height up to 9.18 cm at 40% of total height from where it reaches its peak value. From 40% of total height and upwards, it was decreasing. The range of KLsound was increasing from 12.99 cm at the stump up to 15.10 cm at 30% of total height. From 30% of total height and upwards, it was decreasing. The range of KLsound within a tree was not symmetrical with more values smaller than the mean presented and few large values away from the mean.

One might expect the vertical profile of the mean sound knot length to depend on the position of the crown base. All the trees had crown heights above 20% of the total tree height, 65 above 30%, 44 above 40%, 17 above 50% and 4 above 60%. The vertical trend in mean sound knot length was recalculated for each of these groups. The largest mean value was found at 40% of the total height for all the groups.

The vertical variation of sound knot length may be caused by two different factors. On one hand, it may be caused by the upwardly increasing taper, while on the other hand, it may be caused by increased crown recession and decreased radial growth at crown base. It may also be a combination of these two factors. The results indicate that there is an average upwardly increasing trend in mean sound knot length at the crown base height when this height is less than 40% of tree height, and an upwardly decreasing trend when this height is larger than 40%. To analyze the relationship between crown height and vertical change in mean sound knot length for each tree, the crown base height would have to be measured several times throughout the life time of the tree. Such data was not available for this study. Therefore, only the present situation was analyzed.

3. Knot diameter model

Parameter estimates and fit statistics for knot diameter model (equation 1) were obtained using nonlinear regression (Table 5). The residuals were plotted against the predicted KD and the residual plot shows no trends with respect to knot diameter. Parameter estimates, fit statistics and residuals all suggested biologically reasonable behavior and an adequate fit to the data.

The model of predicting knot diameter with DBH and HCB as independent variables described different effects which influence the knot diameter. DBH is the most

Table 4. Range of sound knot length for different vertical level.

Vertical level(RHK)	0.1	0.2	0.3	0.4	0.5	0.6
maximum (cm)	15.07	15.58	17.79	15.98	14.69	15.96
minimum (cm)	2.08	1.98	2.69	0.92	1.49	2.81
mean (cm)	5.20	7.75	8.74	9.18	9.14	9.02
range (cm)	12.99	13.60	15.10	15.06	13.20	13.15

Table 5. Parameter estimates and fit statistics of equation (1).

Parameter	Estimate	Standard Error	t-value	p-value	Fit statistics		
					n	RMSE	R^2
a_0	2.6303	0.0769	34.2053	0.0000	1828	0.2514	0.9150
a_1	0.1445	0.0038	38.2598	0.0000			
a_2	0.1889	0.0252	7.5031	0.0000			
a_3	0.0353	0.0010	34.8917	0.0000			
a_4	-0.0261	0.0007	-37.4708	0.0000			

Table 6. Parameter estimates and fit statistics of equation (2).

Parameter	Estimate	Standard Error	t-value	p-value	Fit statistics		
					n	RMSE	R^2
b_0	-3.2849	0.5135	-6.3967	0.0000	1828	1.6774	0.6687
b_1	1.4408	0.0855	16.8595	0.0000			
b_2	3.2018	0.1862	17.1939	0.0000			
b_3	0.8954	0.0691	12.9510	0.0000			

Table 7. Parameter estimates and fit statistics of equation (3).

Parameter	Estimate	Standard Error	t-value	p-value	Fit statistics		
					n	RMSE	R^2
d_0	1.8310	0.7803	2.3466	0.0204	364	0.8953	0.5423
d_1	0.0908	0.0324	2.8024	0.0058			
d_2	-0.8798	0.2630	-3.3456	0.0011			
d_3	0.4385	0.1729	2.5364	0.0124			

Table 8. Validation results of prediction equation for independent data set (n=480).

Model	ME	MAE	M%E (%)	MA%E (%)	Precision (%)
KD(cm)	-0.6549	1.2193	-3.3769	15.6259	94.5773
KLsound (cm)	0.2534	1.2255	-2.9677	17.9375	97.4887
KLloose (cm)	0.9587	2.0213	10.1564	22.5483	89.2850

important variable describing the knot diameter for single trees. Since DBH probably has a large variation within a stand, single tree models are required. Height to the crown base (HCB) has been shown to be a good stand level description. In the forest with large density, the tree often has higher HCB and the branch is suppressive, which causes small knots in the stem.

4. Sound knot length model

Parameter estimates and fit statistics for sound knot length model (equation 2) were present in Table 6. All of the results did not indicate any problematic behavior. The model indicates that a large tree often has knots with large size and knots with large diameter usually have longer sound knot length.

5. Loose knot length model

Parameter estimates and fit statistics of the loose knot length model (equation 3) for Mongolian pine plantation were presented in Table 7.

The model reflects the loose knot length increased with tree size (DBH), and knot height (HK). The loose knot length (KL_{loose}) of bigger knots with large knot diameter (KD) is shorter than that of smaller knots.

6. Model validation

For the validation procedure, the performance evaluation criteria were computed with the models of knot attributes developed above for the validation data set (Table 3). The result of statistical validation test was summarized in Table 8

The results indicated that deviance measures were all fairly low. The model for predicting sound knot length performed better with less bias than other two models. The estimated precisions of all models for the validation data sets were greater than 89%.

Conclusions

The vertical trend of the knot diameter in a sample whorl increased from stump height up to 40% of the tree height and then decreased from there and upwards when regarding all 70 trees as one group. It shows that larges knots are located in the middle section of the trees. The knots in the lower part of the trees were generally small.

Tree diameter at breast height (DBH) and height to the crown base (HCB) were the best predictors for knot diameter model. DBH is the most important variable describing the knot diameter for single trees and HCB has been shown to be a good stand level description. The knot diameter model reflected that the size of knots increasing with the size of tree.

Sound knot length (KLsound) was increasing upwards in the lower 40% of the tree followed by a decreasing trend upwards, which is similar with that of knot diameter. KLsound of the knots in above 90% of the sample trees have the same vertical distribution tendency. It may be caused by the upwardly increasing taper, increased crown recession and decreased radial growth at crown base. The range of KLsound was increasing from 14.9 cm at the stump up to 28.55 cm at 30% of total height. The sound knot length was best modeled as multiple linear function of tree diameter at breast height (DBH), knot diameter (KD) and relative knot height (RHK) .The loose knot length was described as a function of DBH, KD and height above the ground for knots (HK) in a mixed log-linear model.

The deviance measures were all fairly low and estimated precisions of all the models established in this study for the independent data sets were close to or greater than 90% according to the model validation. The result of this study can provide abundant knot information, such as knot size and vertical distribution tendency along the stem, so as to describe tree growth dynamic of Mongolian pine plantation.

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