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Distribution, Size and Development Phases of Knots for *Pinus sylvestris* L. var. *mongolica* Litvin in Northeast China

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Abstract : This study was performed in a 38-year-old Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litvin) plantation in northeast China. Data were collected from 5 sample trees with different canopy position ranging in DBH from 14.6 cm to 23.8 cm. Sawn speciments that included the biggest knot were taken from the stem below the living crown. Number and distribution of knots per whorl below the living crown were studied by relative height below living crown (RHBC). A linear model expressed as function of whorl age (AGE), whorl height (H_k) and the stem diameter at which the whorl was located (D_k) was developed to predict the knot diameter and angle. The number of annual rings in four periods and the width of respective zone alone stem were used as dependant variables to analyze the knot develop phases. In average, the number of years from branch birth to ceased forming rings was 7.8, the branches remained alive for 4.2 years without forming annual rings, and branches were occluded 14.4 years after their death. These results can provide abundance branch and knot information so as to describe current and past tree growth dynamic of Mongolian pine plantation.

***Key words* :** Pinus sylvestris var. mongolica, *knot distribution, knot diameter, knot angel*

Introduction

To establish the basic theory of silvicultural techniques, it is necessary to obtain information about the dynamics of the growth for a tree. For the treatment of a tree or a stand, such as by thinning or pruning, the dynamics of the crown structure and stem-growth development is especially important. The dynamics of stem growth can be estimated by a common stem analysis, but obtaining the past history of the dynamics of the development of the crown structure might seem to be impossible. However, 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; 1990).

In terms of lumber quality, a knot is thought of as a void or hole that decreases the overall product strength. The requirements concerning knots in lumber depend on the use of the lumber. These requirements are described in different grading rules for lumber. The knots are evaluated on the surface of the board. The location (centerline or edge), size of each knot and whether it is sound or dead is a determining actor in the visual grade assigned to a given piece of lumber. For purposes, where the visual appearance is of main importance, like panels, furniture etc., the quality of the knot is the most important. For constructional use, the size and the position of the knots in the cross section are more important. In production of lumber it is, therefore, of importance to separate the wood with sound knots from the wood with dead knots. It has been shown that lumber grade can be predicted using simple geometric equations to describe knot characteristics based on external measurements (Lemieux *et al.*, 2000). 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.*, 2001; 2002).

The problem in characterizing the size and shape of knots is that the features to be measured in internal. Traditional methods are destructive. Analysis of 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), or by cutting each knot into thin slices and assuming straight conical sections (Lemieux *et al.*, 2001). An alternative to destructive analysis for knot characterization is to employ the

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use of computer tomography (CT) scanning technology (Taylor *et al.* 1984; Funt and Bryant, 1987). Oja (1997) compared CT-method 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.

The objective of this study is to study the number of knots per whorls and the knot distribution below the living crown in Mongolian pine plantation, and develop equations to predict the knot diameter and angle in a whorl. Specific objective of this paper is to discuss and study the different phases of knot development, such as birth, growth ceasing, dead and occluded. These results can be applied to provide abundance branch and knot information so as to describe current and past tree growth dynamic of Mongolian pine plantation.

Materials and Method

1. Data collection

Sample trees were collected in a 38-year-old unthinned Mongolian pine plantation from Hengtoushan forest farm, western part of Wanda Mountain, which is located in Jiamusi city of Heilongiang province, northeastern China, ranging across 130°28'~130°40'E and 40°34'~46°34'N. One plot with area of 0.08 ha was chosen in this stand. 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 plot. The crown base was defined to be the lowest living branch that is separated from other living branches above it by 1 m at most. A branch was classified as living if it had green leaves. Mean DBH, mean height and number of trees per hectare of the plot were 15.42 cm, 16.9 m, and 1025 stems, respectively. The basal area of the plot was divided into five equal size strata and the average DBH and total height of each stratum was calculated. In each stratum, one sample tree was chosen randomly according to DBH and HT outside the plot in the stand, i.e., 5 different sizes of trees were selected as sample trees for stem analysis and knot analysis.

The sample trees were felled, and the height of each living and dead whorls to the ground were 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 a 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 and azimuth 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. The number and distance of stem annual rings from the stem surface were measured for the years when the branch: (1) emerged from the shoot apex (B) (it can be obtained from the number of annual rings on the stem and height of the knot); (2) ceased to form annual rings at its base (C), i.e. the annual rings of the stem did not curve inside the branch; (3) died (D), i.e. branch and stemwood became anatomically separated (loose knot); and (4) was occluded (O), i.e. stem growth rings grew over the knot (Figure 1). The knot diameter, which was determined as the widest part of the knot section, and the knot angle between knot chord and bole were also measured for each knot.

Four different time periods in branch development from branch initiation to occlusion were distinguished: (1) from the birth of a branch to its growth cessation (BC), (2) from growth cessation to death (CD), (3) from death to occlusion (DO), and (4) the entire period from birth to occlusion (BO). The numbers of annual rings in these periods, as well as the width of the respective zone, were used as dependent variables in the following analysis.

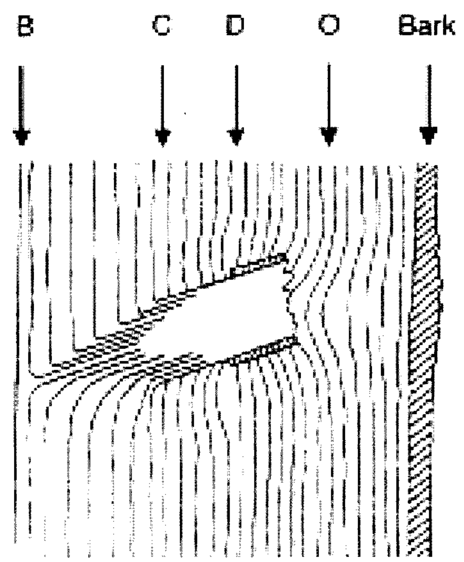


Figure 1. Stem-dissection method through a knot.

Table 1. Explanation of the tree and knot variables measured in the field.

Variable	Definition
DBH	Tree diameter at breast height (1.3 m from ground level) (cm)
HT	Total tree height (m)
HBC	Height below living crown (m)
CL	Crown length (m)
NUMK	Number of knots on each whorls below the living crown
H_k	Height above the ground for *k*th whorl (m)
D_k	Stem diameter at which *k*th whorl is located (cm)
RHBC	Relative whorl height below crown (=H_k/HBC)
θ	Angle between the bole and the knot chord (°)
KD	Diameter of the knot (cm)
R_{XY}	Number of rings in the zone from X to Y
W_{XY}	Width of the zone from X to Y
Subscripts B, C, D,O	Birth, growth cessation, death, and occlusion of knot, respectively

Table 2. Summary of sample trees and branch attributes for the Mongolian pine plantation.

Attribute	Minimum	Mean (s.d.)	Maximum
Tree (n=5)			
DBH (cm)	14.6	19.52(3.42)	23.8
Total tree height (HT) (m)	16.2	16.74(0.31)	17.0
Crown length (CL) (m)	6.3	7.14(0.67)	8.0
Crown ratio (%)	0.38	0.43(0.04)	0.47
Crown width (CW) (m)	1.48	3.21(1.26)	4.90
Total number of knots per tree	104	108(6.82)	120
knots (n=196)			
Number of knots on each whorl (NUMK)	2	5.5(1.29)	8
Stem diameter located kth whorl (D_k)(cm)	7.91	14.32(3.06)	20.94
Height above the ground for whorl k (H_k)	0.1	4.42(3.07)	10.25
Azimuth angle (ϕ) (°)	0	183.3 (101.8)	350
Knot angle (θ) (°)	5.00	35.6 (12.5)	63.0
Knot diameter (KD) (cm)	0.38	1.88 (0.75)	4.16

All the symbols and variables used in this paper is listed and explained in Table 1. The attributes of 5 sample trees and all knots were summarized in Table 2.

2. Number and distribution of knots below the living crown

Numbers of knots on each whorl below the crown base was recorded based on the branch scars outside the bark. The numbers of new branches per whorl is affected, for example, by site fertility, stand density and genetic factors. The number of knots on a whorl is a count of events, i.e., it is a discrete and positive variable.

The model for predicting the vertical location of knots below living crown for Mongolian pine must be constrained by the number of knots. It has two components: (*i*) whorl location on the stem and (*ii*) allocating knots among whorls. To explore the pattern in relative frequency of knots below crown, all of the knots from total sample trees were divided into 10 intervals of equal RHCB (relative height below crown). The relative frequencies of whorls and knots in each RHCB class were then computed for all knots of sample trees combined. Rectangular (uniform) distribution was fitted to describe the whorls and knots distribution below the crown base for Mongolian pine. The probability density function (pdf) of uniform distribution can be expressed as

$$f(x_i) = \frac{1}{n} \quad (1)$$

where x_i represents *i*th RHCB class, *n* is number of the RHCB class.

The uniform distribution was test for all data using the Chi-square (X^2) statistics.

3. Knot diameter

A regression model was sought to predict the knot diameter below the crown of Mongolian pine. Alternative models that added various combinations of tree and knot variables and their transformations were also tested combined with graphic analysis of primary knot characteristics. It showed that the knot diameter of a whorl k below living crown was related mainly to its height above the ground (H_k), stem diameter at which whorl k is located (D_k) and whorl age for Mongolian pine. Knot diameter increased continuously with increasing H_k and approached to an asymptotic size at living crown base. It obviously decreased with increasing whorl age.

4. Knot angle

Branches angle (θ) is often directly related to amount of light (Hashimoto, 1990). Knot angle became progressively larger (knots more horizontal) with increasing RHBC probably because of the weight of the branch when it was living, light attenuation by mutual shading, or mechanical constraint (Deleuze *et al.* 1996).

From the observations of knots for Mongolian pine, it was found that the knots angle was closely related to AGE, D_k and H_k. The simple relative coefficient between knot angle with AGE, D_k and H_k. were -0.65, -0.54, and 0.60, respectively. Therefore, multiple regression method was performed to develop the knots angle model. Independent variables considered in regression were AGE, D_k and H_k.

5. Different knot development phases

The years when the branch birth (B), ceased forming rings(C), dead (D), occluded (O) are determined and recorded. The number of annual rings for the four periods (BC, CD, DO, BO), as well as the width of respective zones from the stem surface, were measured and used as dependent variables in the analysis.

The transition years between the different phases of branch development were not the same on different sides of a branch. A difference of one to several years was found. To avoid systematic bias, the measurements were made on the upper side of branches. The border between stemwood and branchwood was clearer on the upper side of the branch because the angle of the annual rings in the stemwood and branchwood was large. On the lower side of the branches, annual rings of the stemwood bent gradually toward the branch, and the boundary between the stem and branchwood was not clear.

Results and discussion

1. Number and distribution of knots below the crown

Based on the preliminary examination of the data, the number of knots on a whorl had no clear trend along the stem (Figure 2). It varied from 2 to 8, with an average of 5.5 (Table 2). In this study, the knots of the whorls near the ground are hard to distinguish according to the outer branch scars. Thus, there is a little bias in analyzing the number of knots for the lowest whorls and the observation numbers is fewer than the actual numbers in the whorl. The percentage of whorls containing a given number of knots can be found in Table 3. Most of whorls have 5-7 knots, and it accounts 78.6% of all whorls.

To illustrate frequency distribution of knots by relative height below crown class below living crown for Mongolian pine, all the knots for entire sample tree were

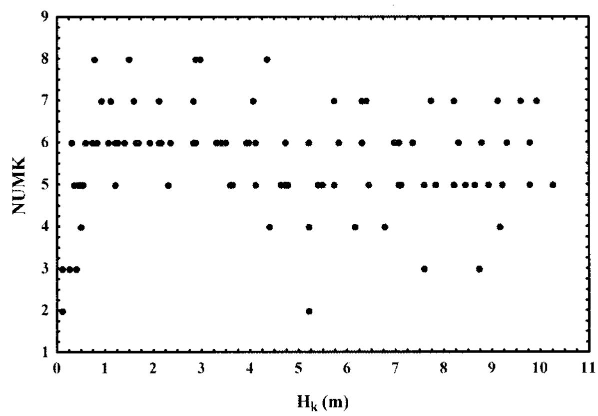


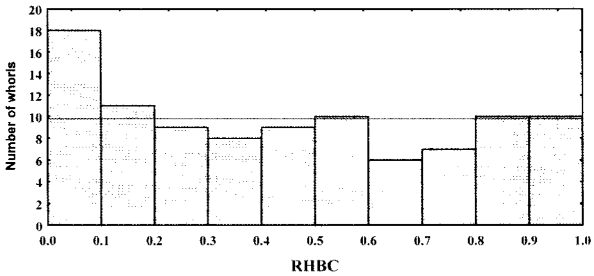
Figure 2. Relationship between whorl height (H_k) and number of knots per whorl (NUMK).

Table 3. Percentage of whorls constraining specified number of knots below living crown.

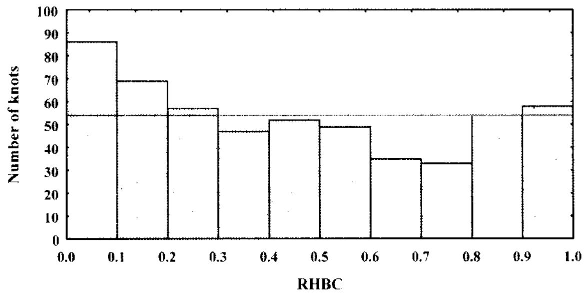
Number of knots in whorl	Number of whorls	Percentage of whorls (%)
2	2	2.04
3	7	7.14
4	7	7.14
5	29	29.59
6	34	34.69
7	14	14.29
8	5	5.10
Total	98	100

Table 4. Observed frequencies and percentages of knots in different RHBC classes.

RHBC	Observed	Cumulative	%	Cumul. %
0~0.1	86	86	15.93	15.93
0.1~0.2	69	155	12.78	28.70
0.2~0.3	57	212	10.56	39.26
0.3~0.4	47	259	8.70	47.96
0.4~0.5	52	311	9.63	57.59
0.5~0.6	49	360	9.07	66.67
0.6~0.7	35	395	6.48	73.15
0.7~0.8	33	428	6.11	79.26
0.8~0.9	54	482	10.00	89.26
0.9~1.0	58	540	10.74	100.00



(a) Whorl



(b) Knots

Figure 3. Observed frequencies of whorls and knots with relative whorl height below crown.

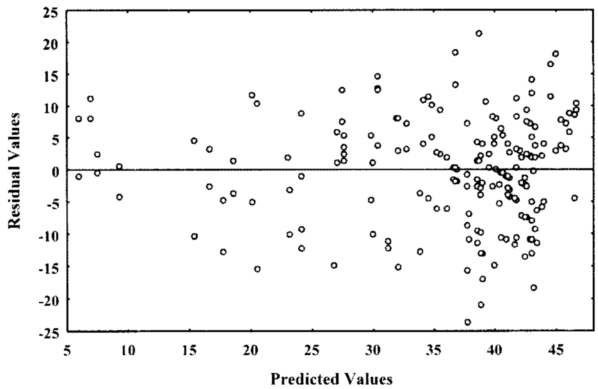


Figure 4. Residuals for model estimating knot diameter of Mongolian pine (Eq. (2)).

pooled and showed in Table 4.

The frequencies of knots have no obvious difference in different RHBC classes. It decreases with RHBC with a peak at the lowest RHBC class, where RHBC=0.1, and then gradually decreases with increasing RHBC. There is a slightly increasing trend at the middle of stem and the crown base, where RHBC ranging from 0.4 to 0.6 and 0.8 to 1 (Figure 3).

The results of the uniform distribution fitted to the vertical distribution of whorls and knots by RHBC classes for sample trees were presented in Figure 3.

The Chi-square test result showed that the numbers of whorls accepted the null hypothesis of rectangle distribution (X^2=9.755<$X^2_{0.05}$(10-2)=15.507, p=0.20), but the fitting of knots numbers was not so ideally (X^2= 39.889 > $X^2_{0.05}$(10-2) = 15.507, p=0.00). The numbers of whorls and knots at the lowest RHBC class (RHBC<=0.1) was a little overestimated (Figure 3). It can be explained that the growth of whorl in lowest part of stem is slowly for few light conditions. Thus the distance between whorls is shorter and this RHBC class has more whorls compared with the upper part of stem. The ground vegetations near them also affect the growth of whorls near the ground.

2. Knot diameter

The knot diameter in whorl k was largely a function of its height above the ground (H_k), stem diameter at which it is located (D_k) and whorl age (AGE). As the results, the following model was selected for predicting the knot diameter.

$$KD = a_0 + a_1 AGE + a_2 D_k + a_3 \ln(H_k) \quad (2)$$

Where KD is the knot diameter; AGE is whorl age; H_k is height of whorl k above the ground; D_k stem diameter at which whorl k is located; a_0, a_1 ,a_2 ,a_3 are parameters to be estimated from the data.

The model is linear, reflecting the monotonic increase of knot diameter with increasing Hk and Dk, and deceasing whorl AGE. Parameter estimates of knot diameter model (2) were present in Table 5 and residual plot in Figure 4. All of the results did not indicate any problematic behavior.

3. Knot angle

The knot angle (θ) model of knots was developed using multiple regression method and the following model

Table 5. Parameter estimates and fit statistics of equation (2).

Parameter	Estimate	Standard Error	t-value	p-level	Fit statistics		
					n	SSE	r
a_0	1.449582	0.436478	3.3211	0.0011	196	33.8902	0.8302
a_1	-0.05211	0.01525	-3.4178	0.0008			
a_2	0.100179	0.014455	6.9302	0.0000			
a_3	0.427414	0.065816	6.4941	0.0000			

Table 6. Parameter estimates and fit statistics of equation (3).

Parameter	Estimate	Standard Error	t-value	p-level	Fit statistics		
					n	SSE	r
b_0	37.3438	10.25417	3.6482	0.0005			
b_1	0.914118	0.308938	2.9589	0.0035	196	13269.32	0.7498
b_2	10.17925	1.31793	7.7237	0.0000			
b_3	-14.3282	3.8995	-3.6744	0.0003			

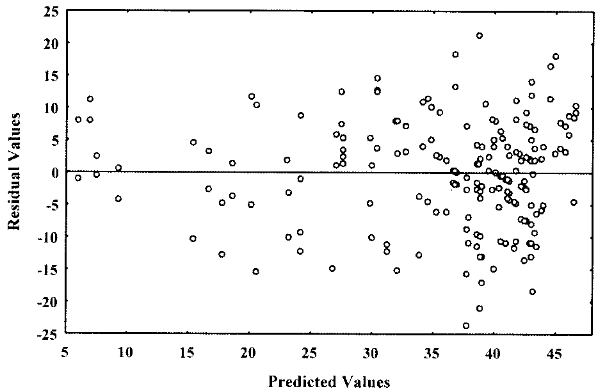


Figure 4. Residuals for model estimating knot angle of Mongolian pine (Eq. (3)).

was selected:

$$\theta = b_0 + b_1 AGE + b_2 \ln(H_k) + b_3 D_K \quad (3)$$

The model form is linear, reflecting the monotonic increase in knot angle with increasing AGE and H_k, decrease slightly with increasing D_k. Parameter estimates and fit statistics of the primary knot angle model (3) for Mongolian pine plantation were presented in Table 6 and residual plot in Figure 5.

4. Different knot development phases

All the sample whorls below the living crown were measured the period BC and CD. Most of the knots had not yet been occluded, and the width of period DO could not be determined for these knots. Thus, only 27 knots used in this study to analyze the period DO and BO. In order to describe knot development phases of trees, the descriptive statistics of knot variables for all trees and for difference tree sizes, such dominant, medial and suppressed trees, were summarized in Table 7 and Table 8, respectively.

Branches formed annual rings was 7.8 years on the average. Radial growth of the branches continued for a longer time in dominant trees compared with suppressed ones. Suppressed trees led to early growth cessation of the branches compared with the dominant trees. R_{BC} of dominant tree and suppressed tree was 8.8 and 7.3, respectively (Table 8).

Table 7. Attributes of knot variables for all trees.

Variable	n	Mean	SD	Minimum	Maximum
R_{BC}	196	7.823	2.507	3.00	15.00
W_{BC}	196	3.516	1.145	0.67	6.21
R_{CD}	196	4.208	1.955	1.00	11.00
W_{CD}	196	1.174	0.530	0.20	3.31
R_{DO}	27	14.407	5.719	5.00	25.00
W_{DO}	27	3.931	1.545	1.91	7.97
R_{BO}	27	22.667	6.133	13.00	35.00
W_{BO}	27	7.509	1.612	5.47	11.39
R_{BD}	196	12.031	3.530	3.53	20.00
W_{BD}	196	4.690	1.308	1.308	7.810

Table 8. Mean value of knot variables for different tree sizes.

Variable	Dominant	Medial	Suppressed
DBH	23.8	19.4	14.6
HT	16.9	16.8	16.2
R_{BC}	8.829	8.308	7.300
W_{BC}	4.202	3.788	2.724
R_{CD}	4.114	4.718	4.175
W_{CD}	1.324	1.220	0.863
R_{BD}	12.943	13.026	11.475
W_{BD}	5.5263	5.009	3.587
R_{DO}	13.500	17.250	18.500
W_{DO}	4.551	4.105	2.460
R_{BO}	22.250	24.750	26.500
W_{BO}	8.047	7.835	5.855

The time period that branches remained alive without visible annual ring production varied from 1 to 11 years, with an average of 4.2 years, which was 34% of the average life time of the branches. The number of years that branches remained alive after growth cessation was not dependent on the variables describing the characteristics of the tree. The number of years without producing visible annual ring in branch of dominant, medial and suppressed tree in the study is 4.1, 4.7, and 4.2, respectively (See Table 8). It seems that they had no obvious variation. Thus, the width of the respective zone in the stem decreased with a decrease in radial growth of the stem, i.e., the CD zone was wider in the fast-growing trees.

The time period from the death of a branch to its occlusion was about 14.4 years in average, which is 63.6% of the period from the birth of the branch to its occlusion. The number of years, as well as the width of respective zone, decreased with increasing stem diameter. R_{DO} of suppressed, medial and dominant tree were 18.5, 17.3 and 13.5, respectively (Table 8). Furthermore, the number of years needed for occlusion increased with increasing branch diameter (Makinen, 1999). The width of the respective zone in the bole increased with increasing radial growth rate and stem diameter. W_{DO} of suppressed, medial and dominant tree were 2.5 cm, 4.1 cm and 4.5 cm, respectively.

The numbers of years form the birth of a branch to its occlusion increased with decreasing stem diameter and radial growth rate of the stem. In contrast, the width of the respective occlusion zone increased by increasing position of tree in same stand. R_{BO} of suppressed, medial and dominant tree were 26.5 years, 24.8 years and 22.3 years, and W_{BO} were 5.85 cm, 7.83 cm and 8.05 cm, respectively.

Conclusion

In this paper, 196 knots below living crown collected from 5 trees of different sizes were used to analyze the number, distribution, size and development phases of knots for a 38-year-old Mongolian pine plantation. The number of knots on a whorl had no clear trend along the stem. It varied from 2 to 8, with an average of 5.5 and the most of whorls have 5-7 knots which accounts for 78.6% of all knots. The frequencies of knots gradually decreased with increasing relative height below crown (RHBC) with a peak at the lowest RHBC class. There is a slightly increasing trend at the middle of stem and the crown base, where RHBC ranging from 0.4 to 0.6 and 0.8 to 1.

The uniform distribution was used to predict the numbers of whorls along the stem, but the fitting of knots numbers is not so ideally. The numbers of whorls and knots at lowest RHBC class (RHBC<=0.1) is a little overestimated. It can be explained that the growth of whorl in lowest part of stem is slowly for few light conditions. Thus, the distance between whorls is shorter and this RHBC class has more whorls compared with the upper part of stem. The ground vegetations near them also affect the growth of whorls near the ground.

The knot diameter and angle below living crown were related mainly to its height above the ground (H_k), stem diameter at where whorl located (D_k) and whorl age (AGE) for Mongolian pine plantation. The knot diameter increased continuously with increasing H_k and obviously decreased with increasing whorl age. But, Knot angles were positively related to whorl age and H_k, and decreased with D_k. The linear models were developed by using AGE, H_k and D_k as independent variables to predict the knot diameter and angle for Mongolian pine plantation.

There are four different time period in knot development: birth to growth cessation (BC); growth cessation to death (CD); death to occlusion (DO); entire period from birth to occlusion (BO). The average ring numbers of four periods were 7.8, 4.2, 14.4, and 22.7, respectively. Suppressed status of a tree, led to early growth cessation of the branches compared with the dominant trees. The number of years that branches remained alive after growth cessation (R_{CD}) was almost independent of the variables describing the characteristics of the tree. The number of years from the death of a branch to its occlusion (R_{DO}), as well as the width of respective zone (W_{DO}), decreased with increasing stem diameter. The time form the birth of a branch to its occlusion (R_{BO}) increased with decreasing stem diameter and radial growth rate of the stem. In contrast, the width of the respective occlusion zone (W_{DO}) increased by increasing position of tree in same stand.

In conclusion, this paper should be considered a case study because of small number of sample trees in single stand with limited site conditions. An additional study with large number of trees from different stands with variable site conditions, stand density and soil fertility is necessary to cover more fully the natural growth conditions of Mongolian pine. The result of this study can provide abundance branch and knot information so as to describe current and past tree growth dynamic of Mongolian pine plantation.

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