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Improvement and Compilation of Density Management Diagram of *Larix principis-rupprechtii* Mayr Forest in Northern Hebei

Jiancheng Liu*, Baoguo Wu*† and Chen Dong**
*School of Information Science and Technology, Beijing Forestry University, Beijing 100083, China
**School of Information Engineering, Zhejiang Agriculture and Forestry University, Hangzhou, 311300, China
†Corresponding author: Baoguo Wu

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ABSTRACT

Stand density management diagram is an average stand model that indicates forest growth at different stages, providing a scientific basis for the mastery of stand density, the prediction of forest growth, the control of water conservation and the measurement of carbon storage. Larch forests in northern China, that is faced with such environmental problems as sand storm and smog, serve the functions of wind break and sand fixation as well as water conservation. This paper makes some improvement to the density management diagram by adding a crown width line to obtain appropriate stand density. In this research: 1. A stand density management diagram is constructed to show growth information in Saihanba Forestry, Hebei province, into which contour lines of constant tree height, degree of closeness, natural thinning, diameter at breast height and crown width are included. 2. The planting density should be set at 3,000 plants.hm^{-2} and 300 m^3 timbers are expected to be obtained from harvest cuttings. Two harvest cuttings should be arranged between 16 and 29 years, with cutting intensities of 28.4% and 36.4%, respectively. The density management diagram is to be constructed to predict the growth of Larch forests in northern China, so as to provide reference for the making of forest management plans and the reasonable arrangement of stand density.

INTRODUCTION

In the face of such current environmental problems as smog, sand storm and land desertification, abundant forest resources are needed. Per capita forest area in China, however, only accounts for one-fourth of the world's level, and per unit forest growing stock accounts for 69% of the world's level. As the biggest terrestrial ecosystem on earth, forests serve the functions of wind break and sand fixation, water conservation, and carbon sink (Clarke et al. 1991, Chen et al. 2012, Xu et al. 2010, Stankova et al. 2007, Wang et al. 2013a). Over the past few years, inappropriate stand density and forest management measures, together with environmental pollution, have made it difficult for those functions to be fully fulfilled (Vacchiano et al. 2013, Pigatto et al. Schneider et al. 2016). Stand density, as one of the most important technical parts of the technological system of man-made forest management, is an important factor that influences the growth of a stand and the quality of timbers, which could play a restricting and determining role in the dynamic change of the amount of water conserved (Chen et al. 2012, Costa et al. 2016). On this account, investigations into stand density control and construction of density management diagrams would be of great significance for the management of forest and the improvement of forest functions.

Till now, a large amount of research has been conducted by scholars both at home and abroad, on the stand density management diagrams of different species of trees (Wang et al. 2011, Retslaff et al. 2016, Wang et al. 2015, Xiang et al. 2014, Tewari et al. 2014, Long et al. 2012), and such diagrams have been widely applied to real-life forest production as well. However, little research has been carried out on the stand density management diagram of Larch forests in northern China (Xiang et al. 2013, Wang et al. 2013a, Wang et al. 2013b, Dong et al. 2016). Given that trees of the same species could grow in different ways in different regions, diagrams should be constructed in accordance with real-life forest production and management. As the major component of forests in northeast China and Inner Mongolia, the extensively-distributed Larch plays an important role in water conservation and ecosystem maintenance. With the man-made Larch forest in Saihanba forestry in northern Hebei province serving as the research subject, this present paper explores the relationship between Larch growing stock and stand density. In this research, crown width line is applied for the first time to the density management diagram of Larch forest in Saihanba forestry. The aim of this paper is to provide necessary reference for the making of reasonable forest management plans, the adjustment of management measures, and the evaluation of ecological benefits of a stand.

MATERIALS AND METHODS

Overview of the research area: This research takes Saihanba Forestry in Hebei province as the research area. Located to the south of Inner Mongolia Plateau (geographical coordinates: 42°48' N, 117°27' E), this area has a temperate continental monsoon climate, with an average temperature of -1.4°C, an annual average precipitation of 438 mm, an annual average evaporation capacity of 1,230 mm and an altitude ranging from 1,500 m to 1,940 m. Hills are the major landscape in this region which is native to such tree species as Larch, Sylvestris, Birch and Spruce. Among these species, Larch is the major species in the man-made forests.

Research data: Based on the 2015 archival information about Saihanba forestry, this research selects some forests with different planting densities, from young forests, half-mature forests, near-mature forests and mature forests, as temporary sample plots. Log scaling is carried out on the Larches in those temporary sample plots. Diameter, tree height, clear height, crown widths in the east and west directions, and crown widths in the south and north directions are recorded, and average tree height, average diameter at breast height, plant number and growing stock in those sample plots are calculated. Five sample Larches without deflected crowns are picked out from each sample plot, whose crown diameters are measured at five different lengths of crown, as shown in Fig. 1.

Data fitting with models and data testing are carried out independently, and the distribution is made according to the principle 8:2 (Liu et al. 2012). Data of sample Larches that are fitted and tested are given in Table 1.

Model selection: Based on previous studies on models related to stand density management diagram (Wang et al. 2013b, Wang et al. 2013c, Wang et al. 2015), mathematical models selected are as follows:

Contour Line of Constant Tree Height:

$$M=a_{11}*H^{b11}*N - a_{12}*H^{b12}*N^2 \quad ...(1)$$

Contour Line of Constant Diameter:

$$M=a*D^b*N^c \quad ...(2)$$

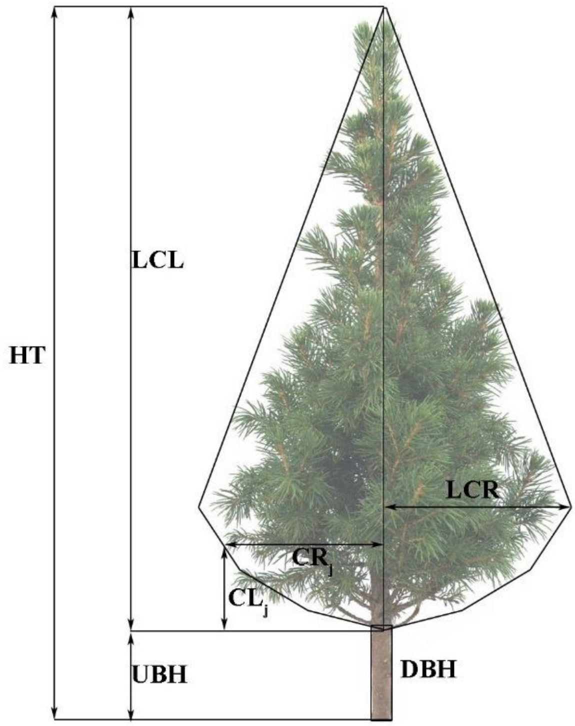
Contour Line of Constant Density:

$$M=K_5*(N_0-N)*N_0^{-k3} \quad ...(3)$$

Contour Line of Constant Degree of Closeness:

$$M=K_p*N_p^{1-k} \quad ...(4)$$

In formulas (1), (2), (3) and (4), M represents growing stock, H represents the height of dominant trees, N represents per hectare plant number, and D represents the average diameter of a stand. Besides, *a11, a12, b11, b12, a, b, c,* K_3, K_5 and K_p are parameters.



HT-Height of tree; LCR-Large Crown Radius; CR_j-Crown Radius; LCL-Large Crown Length; CL_j-Crown Length; *j*=1,2,3,4 indicate the position at 1/4, 1/2, 1/2 and 3/4 of crown length; UBH-under branch height; DBH-diameter at breast height.

Fig. 1: Variables used to characterize individual tree crown.

Variance analysis: One-factor analysis of variance (tree age as the factor) is adopted to analyse the influence of tree age upon such factors as relative crown radius, diameter at breast height, and tree height. Before the analysis, outlier and skewness of data are eliminated, with the help of a box-plot and a histogram; and to the multiple comparisons among different groups, Tukey HSD is applied (significance level: p=0.05). The variance analysis adopted in this research is conducted with the software of SPSS v18.

Model testing: After model fitting, model verification and testing should also be carried out. Coefficient of determination R^2 is used in this research to test the accuracy of models, which is obtained through a calculation based on residual sum of squares and corrected sum of squares, as shown in formula (5).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(x_i - \hat{x}_i\right)^2}{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \quad ...(5)$$

To test whether an assumption about a model is correct or not, residual analysis and χ^2 testing should be performed on the model. If the standardized residual error of an

Table 1: Summary of data from fitting and validating the crown profile model for Chinese fir.

Variables	Fitting data				Inspection data			
	Min	Max	Avg	Std	Min	Max	Avg	Std
DBH	3.8	39.2	8.6	7.2114	2.6	34.8	9.1	6.3854
HT	1.8	25.8	10.7	6.234	2.0	24.5	11.9	4.3797
LCR	1.1	5.7	2.2	1.9061	1.4	5.5	3.5	1.6287
Age	3	45	22	5.2	3	41	19	6.7
Density	426	3189	1570	791.4	395	2 550	1 503	618.5

observed value is smaller than -2 or larger than +2, then the value should be regarded as an outlier, and the standard error should range from -2 to 2 (Guo et al. 2015). In addition χ^2 testing is adopted as a hypothesis testing of models. If $P(\chi^2 < \chi^2_{1-\alpha/2}) = P(\chi^2 > \chi^2_{1-\alpha/2}) > 0.05$, then a model is highly applicable, and vice versa.

CONSTRUCTION OF STAND STOCK DENSITY MANAGEMENT DIAGRAMS

Contour line of constant tree height: When there are no other trees around competing with a Larch, then the forest can be made full use of, and the growth of the Larch can be best realized. When a Larch is competing with other trees, its growth rate would be smaller than that of a Larch that is not influenced by any competition. On this account, the timer volume of each Larch would decrease with the increase in density. The relationship between density and per Larch timber volume can be presented in simple formula (6).

$$V = A - BN \qquad ...(6)$$

In formula (6), V represents the timber volume of each Larch, its unit being m^3; N represents the Larch number of a stand, its unit being Larch/hm^2; A and B are parameters. From the timber volume of each Larch and the Larch number per hectare, it can be deduced that per hectare growing stock M is related to the number of Larch per hectare N, as shown in formula (7)

$$M = AN - BN^2 \qquad ...(7)$$

As indicated in formula (7), per unit forest growing stock would grow with the increase of stand density, and that when use is made to the fullest extent of a growing environment, competition among trees would begin to exert restricting influence upon tree growth and forest growing stock would decrease with any further increase in stand density. Into formula (7) is included the average dominant height of a stand. A= $a_{11}HT^{b_{11}}$ and B= $a_{12}HT^{b_{12}}$, then formula (8) can be obtained.

$$M = a_{11}HT^{b_{11}}N - a_{12}HT^{b_{12}}N^2 \qquad ...(8)$$

Based on formula (8), a curve can be obtained that shows a relationship between growing stock and tree height. When tree height is given a specific value, several corresponding values of M and N could be obtained. Contour lines of constant tree height would finally take shape when tree height is given different values.

Contour line of constant degree of closeness: In the relational function of the contour line of constant tree height, *p* represents the degree of closeness of a stand, M_p represents the growing stock of a stand that is reached when the degree of closeness is *p*, and N_p represents the stock number of a stand that is reached when the degree of closeness is *p*. Formula (9) indicates the relationship between density and degree of closeness of a stand, in which K_p can be obtained based on formula (10) with different values of *p*.

$$M_p = K_p N_p^{\,1-K_3} \qquad ...(9)$$

$$K_p = \frac{a_{11}}{f_p}\left(\frac{f_p - 1}{f_p}\frac{a_{11}}{a_{12}}\right)^{K_3} \qquad ...(10)$$

In formula (10), f_p represents the degree of differentiation that is reached when the degree of closeness is *p*, the value of which is the ratio of v_m, the average volume of each Larch that is not influenced by other trees, to v_f, the timer volume of each Larch that has entered the stage of differentiation effected by density (v_m/v_f). f_p is obtained from formula (11). K_3 is a parameter obtained from formula (12). When the degree of density ranges from 0 to 1, and when different values are given in accordance with a tolerance of 0.1, different formulas can be obtained and they can construct the contour line of constant degree of closeness.

$$f_p = (2 - 2\sqrt{1-p})/p \qquad ...(11)$$

$$K_3 = b_{11} / (b_{12} - b_{11}) \qquad ...(12)$$

Natural thinning line: The timber volume of each Larch would decrease with the increase of stand density; timber volume per Larch *v* has a first power relation with stand density, as shown in formula (13). Formula (14) can thus be derived to show stand stock.

$$v = \alpha N^{-1} - \beta \quad ...(13)$$

$$M = \alpha - \beta N \quad ...(14)$$

The relation among initial density N_0, stand stock M and density N can be obtained from taking the derivative of lgN through lgM with formula (14) in a logarithmic coordinate system, as shown in formula (14).

$$M = K_5 (N_0 - N) N_0^{-K_3} \quad ...(15)$$

In formula (15), N_0 represents initial density; K_5 and K_3 are parameters. K_3 can be obtained from formula (12), and K_5 can be obtained from formula (16).

$$K_5 = K_4 (K_3 - 1) \left(\frac{K_3 - 1}{K_3} \right)^{-K_3} \quad ...(16)$$

$$K_4 = \frac{a_{11}}{2} \left(\frac{a_{11}}{2a_{12}} \right)^{K_3} \quad ...(17)$$

In formula (16), K_4 is a parameter, obtained from formula (17). In formula (17), a_{11} and a_{12} are parameters, obtained through the fitting of formula (8). In formula (14), when different values are given to N_0, a natural thinning line can be constructed.

Contour line of constant diameter at breast height: Since contour line of constant diameter at breast height is also an important component of a stand density management diagram, this paper uses a power function of diameter at breast height to show the relation among stand stock M, diameter at breast height D, and Larch number N, as shown in formula (18).

$$M = aD^b N^c \quad ...(18)$$

In formula (18), a, b and c are parameters. When the average diameter at breast height is fixed at a certain value, M and N would obtain their corresponding values, respectively. Different values of the diameter at breast height finally can construct contour lines of constant diameter at breast height.

Crown width line: Based on the sectional area ratio between a real-life stand and a standard stand under the same site conditions, or based on their stock ratio, the degree of closeness can be calculated. Though crown density is also an indicator of the Larch number that has been retained in forest thinning, this index is difficult to be determined. In field, nevertheless, observation of crown width can help decide whether there is any competition among trees or not. Reasonable stand density ensures that each tree can obtain the nutrition necessary for the appropriate growth of their crowns, and that the restriction imposed by competition can be reduced. In addition, crown width can be used to predict the crow density of a stand. For the ease of calculation, a simple linear regression model is applied to show the relationship between diameter at breast height and crown width, as shown in formula (19).

$$CW = d + eD \quad ...(19)$$

In formula (19), CW represents crown width and D represents diameter at breast height; d and e are parameters. Diameter at breast height can be measured on each tree, and crown width can be calculated through formulas. With these two elements, average crown area can finally be calculated. When hectare area is divided by crown area, the appropriate number of Larch per hectare can be obtained, as shown in formula (20). Each value given to each crown width would invariably correspond to certain values of stock M and Larch number N, and those values can construct a line called crown width line.

$$N = \frac{40000}{\pi CW^2} \quad ...(20)$$

RESULTS AND APPLICATION

Results of model fitting: SPSS is applied to the model fitting and non-linear regression analysis is adopted for analysis. Model parameters are shown in Table 2. Parameters of the contour lines of constant degree of closeness and constant density can only be obtained from a fitting of the parameters of the contour line of tree height. Calculation results are given in Table 3.

Experimental results: Based on the model fitting results as well as the calculation results, this research constructs a stand density management diagram with the software of Origin Pro2016 in a double logarithm coordinate taking 10 as the bottom. The abscissa of the coordinate represents Larch density, while the ordinate represents per hectare stand stock; in light of real-life conditions, Larch density should be set within the range of 500 plants.hm^{-2} to 10,000 plants.hm^{-2}, while per hectare stand stock should be put within the range of 10 m^3 to 600 m^3. In this stand density management diagram, the dotted line that goes toward the upper right, with the increase in density, is the contour line of constant tree height, its unit being "m"; the full line that goes toward the upper right is the contour line of constant diameter, its unit being "cm"; the full line that goes toward the bottom right, with the increase in density, is the contour line of constant degree of closeness; the parabola is the line of natural thinning, its unit being "Larch.hm^{-2}". More details are shown in Fig. 2.

Model Application

Predict stand condition at any stage: With already-known

Table 2: Table of model fitting results.

Model name	Model formula	Parameter	Parameter value	R2
Contour Line of Constant Tree Height	$M = a_{11}HT^{b_{11}}N - a_{12}HT^{b_{12}}N^2$	a_{11}	8.641E-5	0.722
		b_{11}	1.267E-9	
		a_{12}	2.691	
		b_{12}	3.628	
Contour Line of Constant DBH	$M = aD^bN^c$	a	0.043	0.863
		b	1.562	
		c	0.561	
Crown Width Line	$CW = d + eD$	d	1.3873	0.692

Table 3: Table of parameters calculation results.

Model name	Model formula	Parameters	Parameters Value
Contour Line of Constant Degree of Closeness	$M_p = K_pN_p^{1-K_3}$	K(p=1)	449119356.93
		K(p=0.9)	198435461.59
		K(p=0.8)	118471491.53
		K(p=0.7)	71204040.38
		K(p=0.6)	41393589.69
		K(p=0.5)	22553183.44
		K(p=0.4)	11051000.30
		K(p=0.3)	4536090.47
		K(p=0.2)	1336104.90
		K3	2.87163
Natural Thinning line	$M = K_5(N_0\text{-}N)N_0^{-K_3}$	K5	2873707285.36
		K4	449119356.93

dominant height of a stand and the initial density, the density management diagram can help calculate the time of initial forest thinning, the average diameter at breast height before and after a forest thinning, the growing stock in forest thinning and the number of Larches retained after forest thinning. If the dominant height is 6.5 m and the initial density is 3,000 plants.hm^{-2}, then the degree of closeness of a stand ranges from 0.6 to 0.7 (find in Fig. 2 the point of 3,000 plants.hm^{-2} on the natural thinning line and the point of 6.5 m on the tree height line). If the initial forest thinning is carried out when the degree of closeness of a stand reaches 0.9, then it can be inferred from the figure that the average of diameter at breast height is 9 cm, the dominant height is 11.5 cm and the stand stock is 100 m^3. With these figures, it can be learned through calculation that it is at the tree age of 18 that the initial thinning is carried out. When the degree of closeness is 0.7 after low thinning, then the average diameter at breast height is 10 cm, the stand stock is 55 m^3, the thinning stock is 45 m^3 (100 m^3 minus 55 m^3), and the stand density is 1,800 plants.hm^{-2}.

Make thinning plans: Suppose there is a small China fir forest that has an initial density of 4,000 plants.hm^{-2}. For a stand stock that is larger than 300 m^3 to be obtained in the harvest cutting, plans should be made to instruct the time of thinning, the intensity of thinning and the cutting rotation age.

According to Fig. 2, the natural thinning line of 4,000 plants.hm^{-2} should be made to go upward in a way that trees could grow with full use of their site conditions. The time of initial thinning, therefore, should be made at a dominant height of 10 m; from Fig. 2, it can be learned that the degree of closeness of a stand is 0.95, the average diameter of a stand is 7 cm, the stand stock is 82 m^3, and the operational density after natural thinning is 3,700 plants.hm^{-2}. Based on these figures, it can be concluded that the tree age of thinning is 16 years. Since small trees are cut down while big ones are retained in a low thinning, the influence of thinning upon the dominant height could be ignored. Trace the point where the contour line of the tree height of 10 m meets with that of the crown width, and it can be learned that the average diameter of a stand is 7.5 cm, the stand stock is 70 m^3, the number of plants retained is 2,650 plants.hm^{-2}, the degree of closeness is 0.8, the intensity rate of thinning is 28.4% and the thinning stock is 10 m^3. At another point where the natural thinning line that crosses this point to meet the contour line of the tree height of 16 m, a second thinning can be carried out. At this point, the degree of density is 0.93, the tree age is 29, the average diameter at breast height before the thinning is 14.0 cm, the stand stock is 200 m^3, and the stand density is 2,200 plants.hm^{-2}. At another point where the contour line of constant tree height goes left to meet the crown width line, the degree of closeness is 0.71, the average diameter at breast height is 14 cm, the stand stock is 150 m^3, the operational density is 1,400 plants.hm^{-2}, the intensity rate of the second thinning is 36.4%, and the thinning stock is 50 m^3. When the natural thinning line goes forward across the second thinning point to stop at the point where the average dominant height is 22 m, it can be learned through calculation that the tree age is 42, the degree of closeness of a stand is 0.85, the average diameter is 19.5 cm, and the stand stock is 250 m^3. At this point, harvest cutting can be performed. The total stock from the two thinning activities and the harvest cutting, therefore, is 310 m^3 (250 m^3 plus 50 m^3 plus 10 m^3).

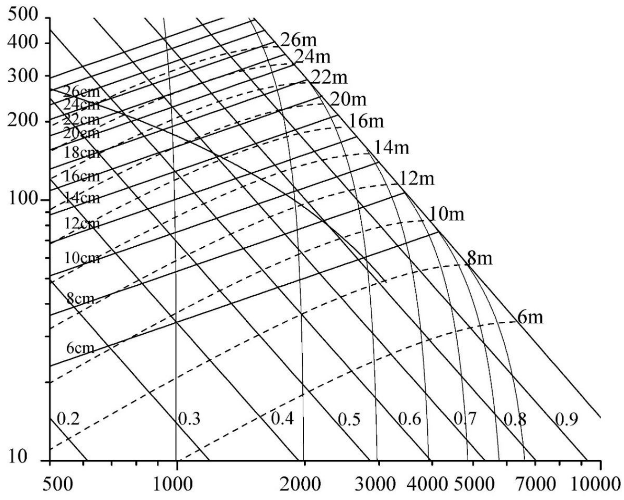


Fig. 2: Larch stand density management diagram.

CONCLUSIONS

Given such environmental problems as smog, sand storm and land desertification, together with such ecological challenges as paucity of forests, low quality of forests and biodiversity, this paper proposes that stand density management diagram should be adopted to guide forest management and to improve forest quality.

In this paper, formulas of contour line of constant tree height, contour line of constant degree of closeness, natural thinning line and contour line of constant diameter at breast height are discussed. The traditional stand density management diagram is improved by an addition of crown width that could exert influence upon the growth of forests, so that a reasonable stand density can be determined. The density management diagram of a man-made Larch forest can show, in a simple and clear way, the relationship between growing stock and stand density, thus helping with the prediction of forest growth and harvest as well as the investigation into forest resources. At the same time, this diagram could provide reference as to how ecological benefits of a forest could be reached to solve the problems of inappropriate stand density and forest management measures as well as poor conditions of forest growth, and to help forests fulfil their functions of wind break and sand fixation, water conservation and carbon sequestration.

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