A Study on Stand Density Management Diagram for Chinese Fir

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Abstract: Stand density management diagram（SDMD） for plantation of Chinese fir (*Cunninghamia lanceolata*) is constructed. This study assesses thinning process the three different management goals: (1) thinning process taking into account the stability of the stand; (2) thinning process considering the risks of crown fire; (3) thinning process no taking into account the stability of the stand and crown fire risk. Result shows: retaining crown bulk density (CBD) threshold below 0.1kg m^{-3}, considering crown fire risk, the yield of thinning arrangement was significantly lower than the other two schemes. On the contrary, there is no significant difference between the total harvest for the other two schemes and the amount of mean annual increment (MAI).

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Key words: Plantation of Chinese fir (*Cunninghamia lanceolata*); Stand density management diagram（SDMD）;Thinning

Stand density management diagram（SDMD）is a production model of the stand level, is described by different stages of the development of production, the relationship between productivity, density and death. In1968, Japanese Ando T. first proposed the stand density management diagram (Ando T, 1968), its theoretical basis were from the yield - density effect (Kira T, Ogawa H.,Sakazaki N, 1953), C-D competition density (Shinozaki K, Kira T, 1955) and self thinning rule (Yoda K, Kira T, Ogawa H et al, 1963). The stand density management diagram reflects dynamic schema model (Newton P, 1997), the expression of the basic relationship among the tree size, stand density, site productivity and the natural thinning between (Jack S, Long J, 1996). In 1977 years stand density management diagram was introduced to the UK (Drew T, Flewelling J, Drew T Flewelling, 1977;J, 1979). The world has developed Slash pine (Drew T, Flewelling J, 1977), Balsam fir (Penner M, Swift D, Gagnon R et al,2006), Pedunculate oak (Barrio Anta M, Gonzalez A,2005), Pinus ponderosa (Long J, Shaw J,2005), *Pinus sylvestris* (Vacchiano G, Motta R,Long J et al,2008),*Pinus banksianae* (Penner M,Swift D, Gagnon R et al,2006), *Pinus halepensis* and *Pinus pinaster* (Valbuena P,Peso C,Bravo F,2008) and other timber species. Main applications are to quantify cutting, prediction of production, resource inventory, silvicultue design and other managements. In 1978, Yin Tailong introduced SDMD to China （Yin Tailong， Han Fuqing et al,1978）. Other Chinese scholars developed SDMD of *Cunninghamia lanceolata* (Liu Jingfang, Tong Shuzhen and 1980), *Pinus kesiya var. 1angbianensis* (Song Yongjun, Guo Zhikun, 2002), *Cryptomeria fortunei* (Lin Xiaomei, 2002), *Fokienia hodginsii* (Zhang Huiguang, 2006). Application in forestry production has played an important role. Stand density management diagram (SDMD) mainly includes silvicultural density, time, period, intensity of thinning, the determent of reserved density, prediction of stand growth and statistics of out-turn of wood sort. The reasonable density of stand control may promote the standing trees growth, enhance the standing trees' quality, improve the hygiene condition of stand, enlarge out-turn of wood sort, realize the maximum of the social benefit, the economic benefit and the ecological benefit of forest.

1 Basic SDMD construction method

The relative spacing index (RSI) is used to describe the relationship between the average size of trees and forest density in this study. In addition, the construction and forest stand average diameter divided contour volume is also involved in SDMD. The basic SDMD is formed by RSI and three equations. The ratio of RSI to the average distance between trees and dominant height, expressed as a percentage, it can be calculated as follows:

$$RSI(\%) = \frac{10{,}000}{\sqrt{N} \cdot H_0} \quad (1)$$

Where N is the number of trees per hectare, H0 is the dominant height.

The use of RSI to express stand volume is mainly due to its following advantages:

(1) RSI was independent of site and stand age (Schutz, 1990);

(2) From a biological perspective, the dominant height is the best index between thinning interval s (Kenk, 1980; Duplat, 1996);

(3) The contact between the growth and productivity of forest dominant height, promotes the further study of these for forest management purposes.

The first equation will associate stand average square diameter, stand density and dominant height (equation 2), the second equations will associate stand volume and stand average diameter, stand density and dominant height (equation 3), the third equations will associate above ground biomass and stand mean diameter, dominant height and stand density (equation 4):

$$d_g = \beta_0 \cdot N^{\beta_1} \cdot H_0^{\beta_2} \tag{2}$$

$$V = \beta_3 \cdot d_g^{\ \beta_4} \cdot H_0^{\beta_5} \cdot N \tag{3}$$

$$W_t = \beta_6 \cdot d_g^{\beta_7} \cdot H_0^{\beta_8} \cdot N^{\beta_9} \tag{4}$$

Where dg is the stand average diameter (cm), N is stand density (stems $\cdot ha^{-1}$), H0 (m) is dominant height, V（$m^3 \cdot ha^{-1}$） is stand volume, βi (i=0-9) is the regression coefficients.

The contours of RSI, DG and V are obtained by solving the equation (3):

$$N = \left(\frac{10{,}000}{RSI \cdot H_0}\right)^2 \tag{5}$$

$$N = \left(\frac{d_g}{\beta_0 \cdot H^{\beta_2}}\right)^{\frac{1}{\beta_1}} \tag{6}$$

$$N = \left[\frac{V}{(\beta_3 \cdot \beta_0^{\ \beta_4}) \cdot H^{(\beta_2 \cdot \beta_4 + \beta_5)}}\right]^{\frac{1}{(\beta_1 \cdot \beta_4 + 1)}} \tag{7}$$

Although as long as the density and height of dominant tree are known, it is easily calculated ground biomass through the equation, but no Wt contour.

2 Basic parameters of SDMD

All equation regression parameters are shown in Table 1.The result shows these equations precision is very high, the residual error examination assumes the normal distribution, it enplanes regression mode fitting effect is good.

Table 1 Coefficients estimation of Nonlinear regression of mean diameter (dg)，total stand volume (V)，and above ground biomass for *Cunninghamia lanceolata* plantation

Equation (2)	β_0	β_1	β_2		RMSE	R^2
Estimate	1.6317	-0.0899	0.8723		1.8637	0.7141
Asymptotic standard error	0.1820	0.0101	0.0275			
Equation (3)	β_3	β_4	β_5		RMSE	R^2
Estimate	5.495×10^{-5}	2.5080	0.2293		7.1106	0.9940
Asymptotic standard error	2.028×10^{-6}	0.0140	0.0172			
Equation (4)	β_6	β_7	β_8	β_9	RMSE	R^2
Estimate	0.1339	2.1929	0.1265	0.9854	1050.50	0.9980
Asymptotic standard error	0.0021	0.0037	0.0039	0.0013		

The transverse axis is the height of dominant trees, ordinate is trees of each hectare. Putting the relative space index (RSI) contour, stand average diameter contour and contour of the total volume to the above-mentioned the coordinate system, a basis for the SDMD (Fig. 1) of *Cunninghamia lanceolata* is established. The range of transverse axis of dominant height from 8 to 40 m, the range of ordinate of density is from 100 to 5000, as in a logarithmic representation.

The RSI is used to define the amount of thinning. SDMD provides the RSI contour. The top-most RSI contour corresponds to the value of 6%, similar to minimum value of RSI in the data set. This value is considered to be the maximum density reasonable approximation of *Cunninghamia lanceolata*, the value represents highest number of trees per hectare to the fullest extent the combination in the stand of *Cunninghamia lanceolata*. SDMD also provides contour of the average diameter and stand volume. The stand average diameter is from 6 cm to 26 cm. The contour increases gradually from left to right. The range of stand volume is from 10 to 400m^3. The contour increases gradually from left to right. This is consistent with important principle of a positive correlation of productivity and growth of dominant height. The value range of transverse axis and ordinate is consistent with the value in table 1. In order to evaluate the stand for stability and crown fire risk, the corresponding values for slenderness coefficient (SC) is from 40 to 110, contour and corresponding of crown bulk density (CBD) value is the scope of the contour 0.1~0.4, putting together on the base of SDMD stacked (Fig. 2).

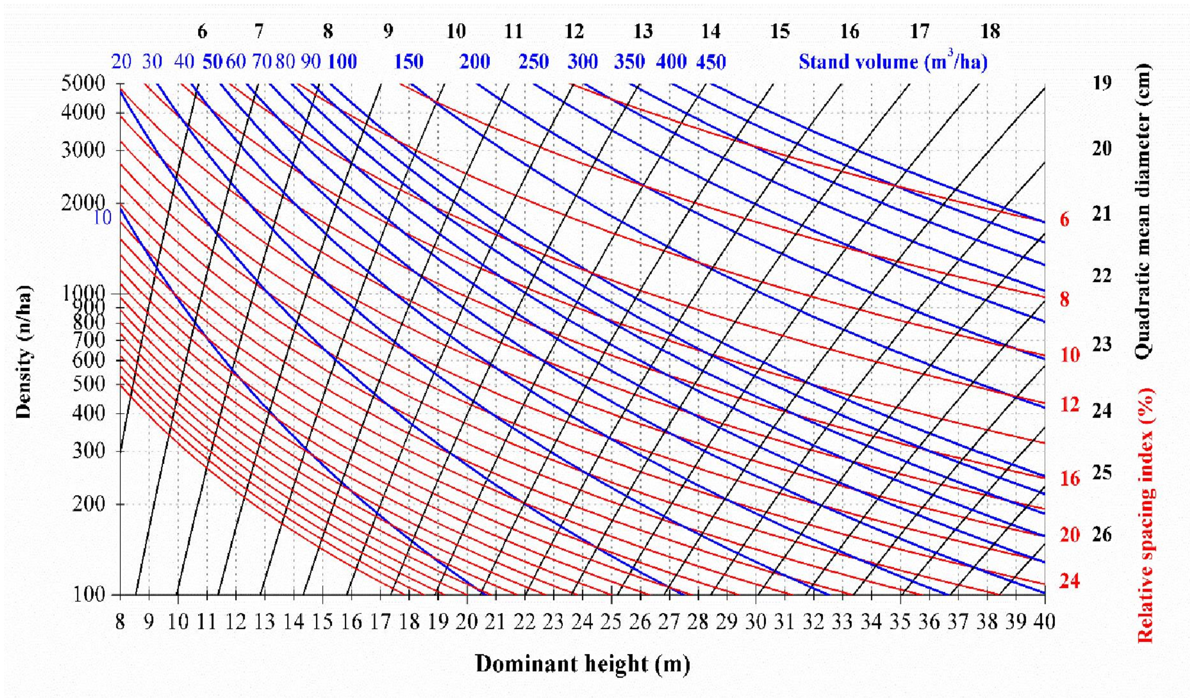

Fig. 1 Basic SDMD for *Cunninghamia lanceolata* stands

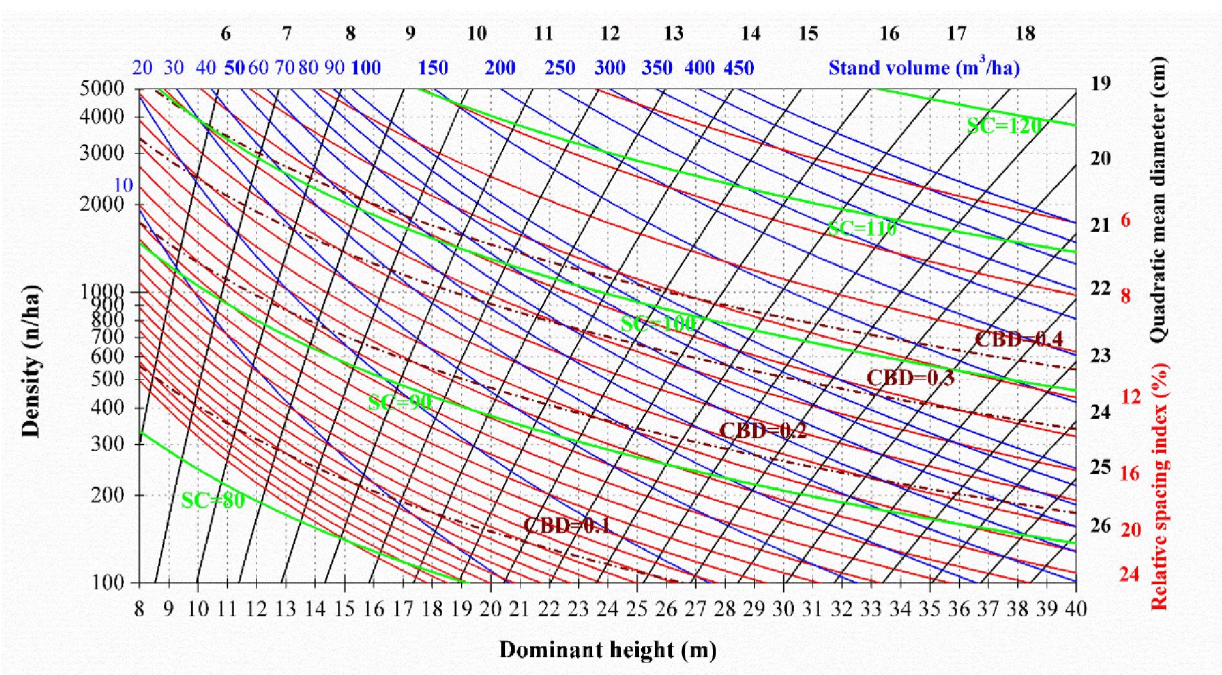

Fig. 2 SDMD for *Cunninghamia lanceolata* stands including the contour of stand stability (SC) and risk of crown fire (CBD)

3 Applications of SDMD in the Arrangement of Thinning

The main application of SDMD is through the design, display and evaluation of different thinning programs to determine the best thinning goal according to specific management. The determination of thinning arrangement needs to define the goal stand condition and the upper and lower limits of stand volume in one rotation. According to SDMD, goal stand can be defined with any two parameters of flowing stand parameters: height of dominant trees, stand average diameter, the number of trees per hectare, and the total stand volume.

The principle to determine lower limit of stand volume is as much as possible to use the woodland space maximum Comparatively speaking, the upper limit of stand volume the need to set at a high level, but to avoid to critical density caused by a natural factor of withering and also to learn to maintain the vitality of the trees (Antaand gonzález, 2005; Castedo-dorado et al, 2009). In addition, if you must take into account the stability and the risk of canopy fire, the expansion of SDMD needs including defined the relevant threshold value by SC (stability) and the CBD (crown fire risk).

In this study, 24% is chosen the upper limit of RSI, which is lower than the density, may occur related mortality. In accordance with relevant research of Becquey, Riou-Nivert, Parde and Bouchon, this study considers 90 is the threshold value of SC. If the SC is less than 90, the stand is considered to be stronger to resist wind, snow disaster; On the contrary it may suffer from natural disasters. Same with Gomez-Vazquez et al (2014), in order to set to minimize the risk of the crown fire, this study consider that the CBD requires lower than 0.1kg·m^{-3}. The *Cunninghamia lanceolata* SDMD with thinning established by this study is shown in Fig 5-3. In order to identify the appropriate thinning time under different site condition, this study uses *Cunninghamia lanceolata* site index table by Meng Xianyu (2006).

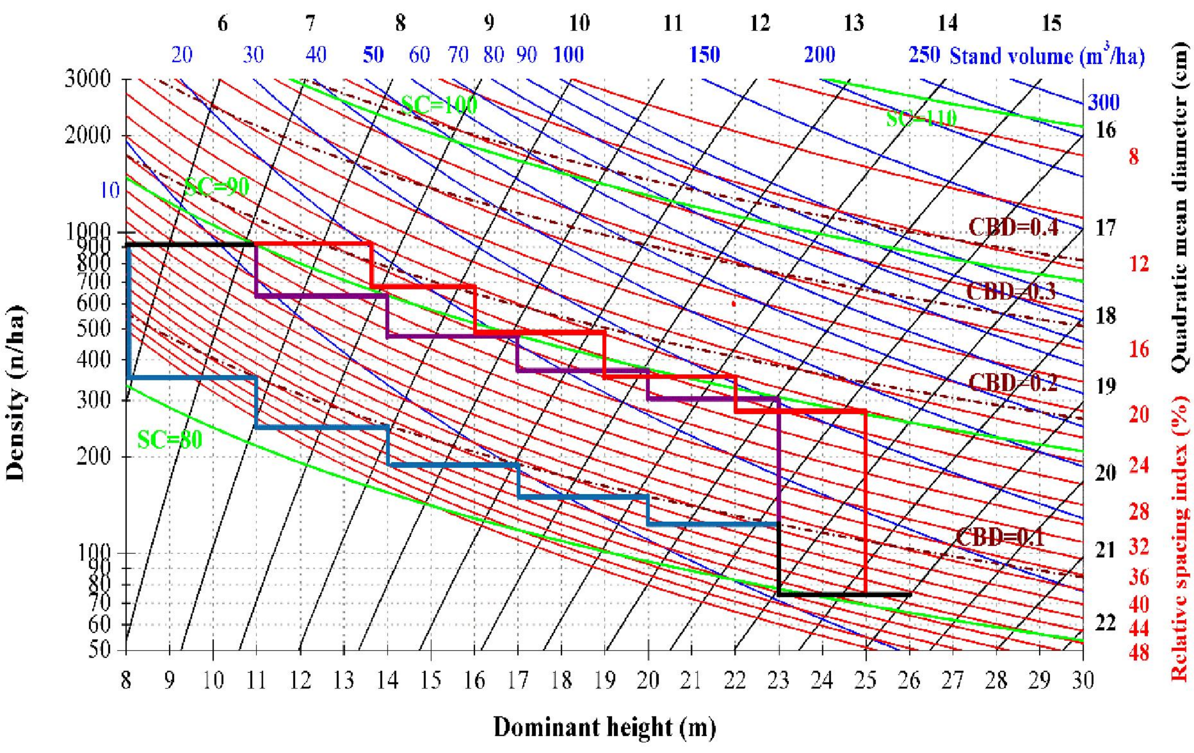

Fig. 3 SDMD for *Cunninghamia lanceolata* stands including thinning sequence for three management regimes: thinning with consideration of stand stability (purple continuous line), thinning with consideration of crown fire risk (blue continuous line) and thinning without consideration of stand stability and crown fire risk (red continuous line).

The black continuous lines were shared by the management regimes.

In order to illustrate the use of SDMD, this study assesses thinning process the three different management goals: (1) thinning process taking into account the stability of the stand; (2) thinning process considering the risks of crown fire; (3) thinning process no taking into account the stability of the stand and crown fire risk. Assumption of 10 stands for the status, the base age is 20 years, stand average diameter is 5.42 cm, and stand density is 912 per hectare. The objective is to 26 m high, stand average advantage diameter is 19 cm.

Table 2. Comparison of three alternative management goals

	Stand age	Stand height	Stand density (trees/hm^2)		Average diameter (cm)		Stand volume
	(year)	(m)	Before thinning	After thinning	Before thinning	After thinning	(m^3·ha^{-1})
Scheme 1							
CT1	6	11	912	636	7.16	7.40	2.95
CT2	9	14	636	477	9.13	9.37	3.27
CT3	12	17	477	376	11.10	11.34	3.55
CT4	18	20	376	306	13.06	13.30	3.79
CT5	24	23	306	74	15.03	17.07	20.61
Cutting	30	26	74		19		13.87
Total yield							48.04
MAI							1.60
Scheme 2							
CT1	5	8	912	355	5.42	5.90	2.91
CT2	6	11	355	251	7.79	8.04	1.37
CT3	8	14	251	190	9.92	10.17	1.55
CT4	12	17	190	151	12.05	12.31	1.70
CT5	17	20	151	123	14.18	14.44	1.83
CT6	22	23	123	74	16.31	17.07	4.98
Cutting	30	26	74		19		13.87
Total yield							28.21
MAI							0.94
Scheme 3							
CT1	8	13.8	912	678	8.73	8.96	4.29
CT2	10	16	678	481	10.20	10.52	5.56
CT3	16	19	481	359	12.22	12.54	5.61
CT4	22	22	359	278	14.25	14.59	5.64
CT5	28	25	278	74	16.31	18.36	22.45
Cutting	30	26	74		19		13.87
Total yield							57.42
MAI							1.91

4 Summary

From Fig. 3 and table 2, we can see that:

1. The forest thinning (purple line continuously, scheme 1) under the condition of the stability, the total yield is 48.04 m^3 / hm^2. Thinning is occurred in 6, 9, 12, 18 and 24 years, 34.17 m^3 / hm^2 yield can be obtained. Eventually harvest age is 30 years, the harvest is 13.87 m^3 / hm^2, mean annual increment (MAI) is 1.60 m^3 / hm^2·a.

2. Thinning arrangement (blue line continuously, scheme 2) when considering crown fire risk, thinning is occurred in 5, 6, 8, 12, 17, 22 years, yield is 14.34 m^3 / hm^2. Eventually harvest time is 30 years, mean annual increment (MAI) is 0.94 m^3 / hm^2·a.

3. Thinning arrangements (red lines in a row, 3) without considering the stand stability and crown fire risk, thinning is occurred in 8, 10, 16, 22, 28 years, a total yield of 43.55 m^3 / hm^2. Eventually harvest time is 30 years, mean annual increment (MAI) is 1.91 m^3 / hm^2·a.

4.Retaining CBD threshold below 0.1kg m^{-3}, considering crown fire risk, the yield of thinning arrangement was significantly lower than the other two schemes. On the contrary, there is no significant difference between the total harvest for the other two schemes and the amount of mean annual increment (MAI). While considering the stability of stand thinning amount smaller than that without considering the stability and crown fire risk thinning value however, considering the stability of stand thinning arrangement is preferred

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