Development of stand density management diagrams for Chinese fir plantations

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Abstract

Stand density management diagrams (SDMDs) are powerful tools for the design, display and evaluation of different density management regimes derived without long-term thinning trials in the field. The SDMDs can be used to predict the future stand development based on specific thinning schedules and optimize the forest management. In this study, SDMDs, generated from common one-time inventory data, provided information about the evolution of quadratic mean diameter, stand volume, stem and aboveground biomass with stand development for the widely planted Chinese fir (*Cunninghamia lanceolata* [Lamb.] Hook) plantations in southern China. A system of four equations was fitted simultaneously to the data collected from 74 inventory plots. The relative spacing index was used to characterize the growing stock. These SDMDs can be used by local forest managers to estimate the stand volume, stem and aboveground biomass, and could be the reference tools to determine optimum thinning schedules.

Keywords: stand density management diagrams, stand volume, biomass, forest management

Introduction

An increasing number of forest products, such as timber and bioenergy, are required for the development of society and economy and the improvement of people's lives. To meet these demands, large-scale afforestation and reforestation activities have been conducted in China during recent decades, resulting in large plantation areas constituting nowadays about one-third of total global forest plantation area (SFA, 2008). Chinese fir (*Cunninghamia lanceolata* [Lamb.] Hook) is one of the most important plantation tree species with good timber quality, fast growth and >1000 years of cultivation history in southern China (Zhao et al., 2009; Chen et al., 2013). Currently, Chinese fir plantations cover an area of 8.54 million ha, which corresponds to 21 per cent of the total plantation area in China according to the seventh national forest inventory (Jia et al., 2009). Chinese fir plantations are usually managed in a clear-cutting system with a rotation period of 25 years, with variations from 20 to 30 years depending on site quality (Wu, 1984). Chinese fir is now one of the most important timber species in the Chinese forest product industry. The country has committed to increase its total forest area by 40 million hectare in the next few decades, and the number and area of Chinese fir plantations will likely increase as well (Xu, 2011; Hu et al., 2014). In order to improve timber output and economic benefits, as well as ecological functions, suitable forest management is required.

Thinning plans are essential to control tree competition, resulting in an improvement in stand stability and wood quality. To achieve these goals, stand density management diagrams (SDMDs) have widely been used in forest plantation management (Castedo- Dorado et al., 2009; Schnell et al., 2012; Castaño-Santamaría et al., 2013).

Stand density management, conceptually, is the process of controlling tree competition through density regulation to meet different management targets (Newton, 1997). Normally, stand development is displayed by an increase of tree dimensions with decreasing numbers of trees per hectare (Long et al., 2004). One useful approach to describe stand development is the application of SDMDs, which integrate the relationship between stand density, stand structure, canopy dynamics and production efficiency. This application links quantitative silviculture to ecology (Jack and Long, 1996). In contrast to long-term observation plots, SDMDs can quickly be adapted to different site conditions and management objectives, overcoming the restrictions of complex and time-consuming measurement series in the field that are commonly focused on specific site conditions and silvicultural targets (Schnell et al., 2012). Therefore, the application of SDMDs can be considered as one of the most effective methods for the design, display and evaluation of different density management regimes in even-aged stands (Jack and Long, 1996). Nevertheless, real observations of field thinning experiments that look into cause and effect mechanisms are certainly the best and most reliable way to design thinning (Schnell et al., 2012). On the other hand, in the absence of long-term observations or experiments, SDMDs offer the possibility of deriving basic stand growth models whenever immediate results with limited resources are needed.

SDMDs represent a system of empirical quantitative functions that illustrate the cumulative effects of various competition processes on tree and stand yield variables (Newton and Amponsah, 2005). The main axes usually are the average size of tree attributes (e.g. the height of dominant trees, diameter or volume) and stand density. The first SDMD was proposed by Ando (1962), who presented competition and yield functions (based on the stand density) and the self-thinning rule in a two-dimensional graphical format. Afterwards, yield variables in the form of stem biomass, total aboveground biomass (Barrio-Anta et al., 2006), empirical- based volume functions (Newton and Weetman, 1994), above- ground bioenergy and cellulose production (Pérez-Cruzado et al., 2011) have been included in SDMDs for different forest types. SDMDs were also used to control shrub growth in the early stages of stand development (Smith, 1989), reduce stand susceptibility to pests (Long and Shaw, 2005), assess crown fire potential (Gomez-Vazquez et al., 2014) and optimize wildlife habitats (Sturtevant et al., 1996).

Although the importance of stand management in Chinese fir plantations has been highlighted for several decades, there is no realistic, simple, and easy to follow operating guidance to implement management. Thinning is considered to be a good management practice to improve stand production in Chinese fir plantations based in some case studies (Bingshuan, 1989; Liu and Yang, 2008); unfortunately, these approaches remain at a theoretical level. As a result, forest managers and owners have difficulty applying these silvicultural treatments because of a lack of forest decision support tools to design, display, evaluate and optimize stand management for different purposes. SDMDs can overcome these limitations and allow managers to simulate different silvicultural alternatives. However, to our knowledge, no SDMD has yet been proposed for Chinese fir plantations. Thus, the objective of this study was to develop SDMDs for Chinese fir plantations based on a relative spacing index to characterize stand volume, stem and aboveground biomass. These SDMDs allow forest managers to estimate growth and yield variables of Chinese fir plantations under several management regimes and implement thinning schedules for a wide range of site qualities and management objectives. This study can also fill the gap between the theoretical and practical management of Chinese fir plantations and can be a reference tool to optimize stand management.

Materials and methods

Study area

The study was conducted in Shitai county (29° 59′ –30° 24′ N, 117° 12′ – 117° 59′ E, Figure 1), Anhui province, China. Eighty per cent of this county is covered by forest. It is a mountainous area with an elevation range of 50 – 1000 m and steep slopes with an average of 66 per cent. The region has a mid-subtropical, humid, mountainous climate with distinct seasonality (Geng and Wang, 2011). The annual average temperature is 16°C with an annual mean maximum of 40.9°C and an annual mean minimum of -13.2°C (Lu, 2010). The mean annual precipitation is ~1668 mm with high inter-annual variability, and with ~70 per cent of the precipitation occurring in rainy seasons (Geng and Wang, 2011). Average annual sunshine duration is 1704 h, and evaporative capacity is 1256 mm (Lu, 2010).

Plot design

This study is a part of the Lin^{4}carbon project (http://www.lin2value. uni-goettingen.de/), in which three different scales of inventories are distinguished: (1) a land use and forest inventory (LUI/FI) that produce information over the whole extent of a sampling frame based on systematic grids at 3 × 3 km; (2) a forest management inventory for those stands with forest management information with a 500× 500 m systematic grid, which is also part of a Sustainable Forest Management (SFM) Cooperation Project between the Shitai Forest Bureau and the German Development Bank (KfW); and (3) a stand inventory of selected stands with a 100 × 100 m systematic grid. Seventy-four nested circular plots in the Chinese fir plantations were established. In circular plots of 6 m radius, trees were measured for 10 cm, dbh, 20 cm while in 10-m radius plots, trees with dbh of .20 cm were measured. A slope correction was conducted automatically using Vertex III (Haglöf Sweden AB) during forest inventory. Tree diameters were measured with a diameter tape to the nearest 0.1 cm and heights of one or two dominant, one co-dominant and one suppressed trees were measured in each plot, respectively. A height– diameter relationship was fitted to the subsample of trees with height measurements using the model proposed by Pretzsch (2009):

$$h = 1.3 + {\frac{d}{2.0208 + 0.3461 \times d}}^{3} \qquad R^2 = 0.7286,\ \mathrm{RMSE} = 1.6006,\ (1)$$

where h is the total height of the tree (m), and d is the diameter at breast height (1.3 m) in cm.

Biomass and volume estimation

The following stand variables were calculated for each plot: the number of trees per hectare (N), quadratic mean diameter (d_g), mean height (H_m), dominant height (H_d, defined as the mean height of 100 thickest trees per hectare), stand volume (V), stem biomass (B_s) and aboveground biomass (B_{agb}).

Allometric models (equations 2 – 4), developed in the same study area in Shitai county (Guisasola-Rodríguez, 2014), were used to estimate stem, branch and leaf biomass. Total aboveground biomass was calculated as the sum of these components ($B_s + B_b - B_l$). Equation 5, developed as a compatible taper function for this species (Tang et al., 2015), was used to calculate individual tree volume. Individual tree-level biomass and volume were scaled to stand level in terms of expansion factors of 31.8 for 10-m radius plots and 88.4 for 6-m radius plots.

$$B_S = 0.020232 \times (d^2 \times h)^{0.9674} \quad R^2 = 0.9764,\ \mathrm{RMSE} = 0.0179, \quad (2)$$

$$B_b = 0.011774 \times d^{3.7416} \times h^{-1.6029} \quad R^2 = 0.9722,\ \mathrm{RMSE} = 0.0294, \quad (3)$$

$$B_l = 0.031911 \times d^{3.207} \times h^{-1.5105} \quad R^2 = 0.9522,\ \mathrm{RMSE} = 0.0363, \quad (4)$$

$$V_s = 0.000071 \times d^{1.7512} \times h^{1.0417} \quad R^2 = 0.9878,\ \mathrm{RMSE} = 0.0243, \quad (5)$$

where B_s, B_b, B_l and V_s represent stem biomass, branch biomass, leaf biomass (kg) and stem volume (m^3) of the individual tree, respectively. d is the diameter at breast height at 1.3 m (cm), h is the total tree height (m), R^2 is the coefficient of determination and RMSE is the root mean square error.

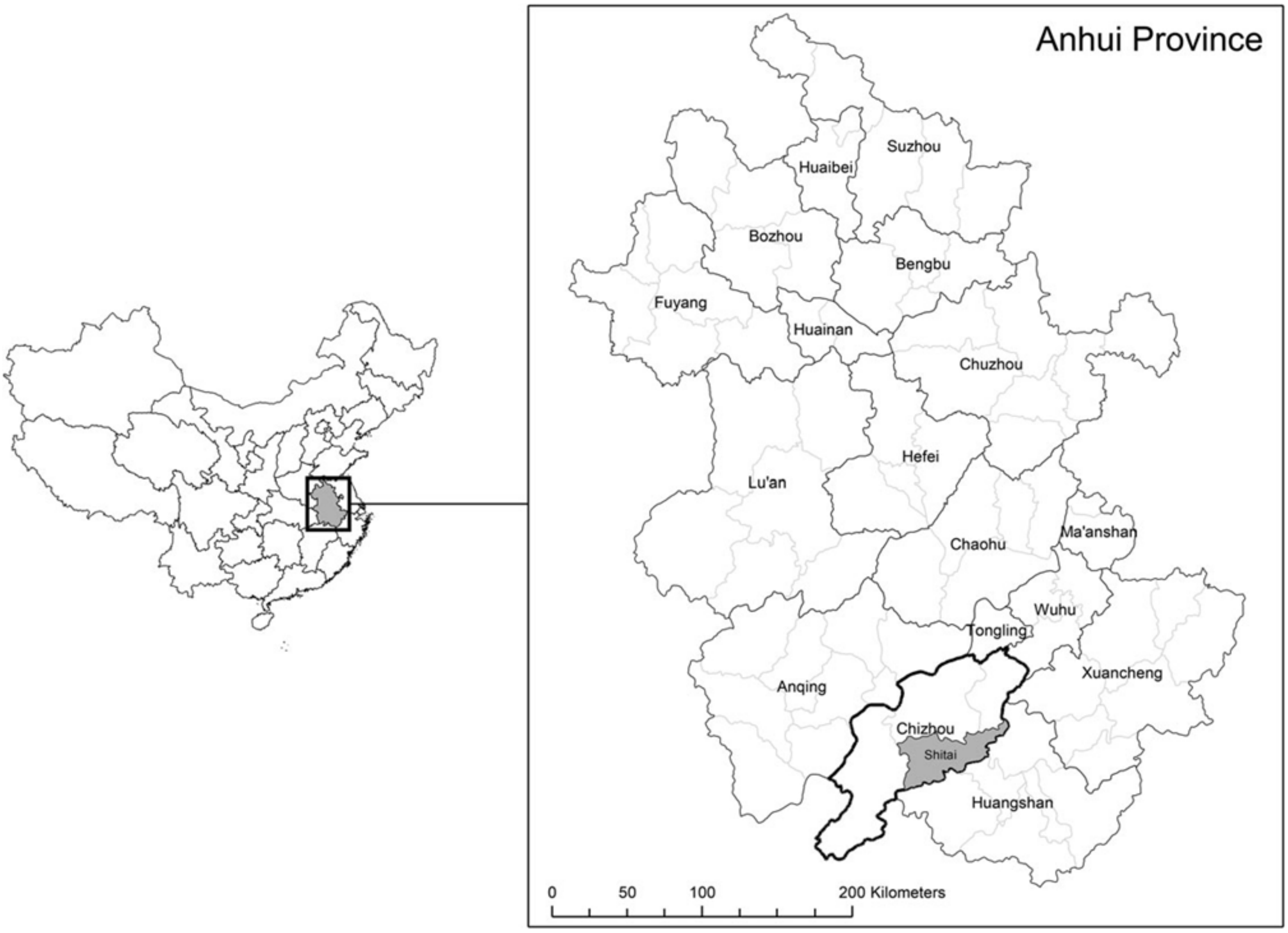


Figure 1 Location of Shitai County in the southern part of Anhui Province, South-East China.

Development of SDMDs

In our study, SDMDs consisted of four equations and a relative spacing index (RS) as the basic components. The RS (%) used to characterize the growing stock level was calculated as the ratio between the average distance among the trees and dominant height, expressed as a percentage (Castedo-Dorado et al., 2009; Pérez-Cruzado et al., 2011):

$$\mathrm{RS} = \frac{100}{\sqrt{N} \times H_\mathrm{d}} \times 100, \qquad (6)$$

where RS is relative spacing index (per cent), *N* is the number of trees per hectare, and H_d is dominant tree height (m).

To describe stand stability, a slenderness coefficient (SC) is often used (Wang et al., 1998; Wilson and Oliver, 2000). In this study, SC is defined as the ratio of mean stand height (H_m) to the mean diameter at breast height (d_m), expressed as:

$$\mathrm{SC} = \frac{H_\mathrm{m}}{d_\mathrm{m}}. \qquad (7)$$

The first step to model SDMDs was to fit a non-linear system of equations 8 – 11. In the system, *N* and H_d are exogenous variables (defined as independent of the system), while V, B_s and B_{agb} are endogenous variables (variables that the model predicts), and dg is an endogenous instrumental variable (Pérez-Cruzado et al., 2011; Castaño-Santamaría et al., 2013). These equations are very flexible and have already been successfully applied in different tree species, such as *Eucalyptus* species (Pérez-Cruzado et al., 2011) and *Quercus pyrenaica* forests (Castaño-Santamaría et al., 2013).

$$d_\mathrm{g} = a_1 \times N^{a_2} \times H_\mathrm{d}^{a_3}, \qquad (8)$$

$$V = a_4 \times d_\mathrm{g}^{a_5} \times H_\mathrm{d}^{a_6} \times N^{a_7}, \qquad (9)$$

$$B_\mathrm{S} = a_8 \times d_\mathrm{g}^{a_9} \times H_\mathrm{d}^{a_{10}} \times N^{a_{11}}, \qquad (10)$$

$$B_\mathrm{agb} = a_{12} \times d_\mathrm{g}^{a_{13}} \times H_\mathrm{d}^{a_{14}} \times N^{a_{15}}. \qquad (11)$$

where a_1, a_2 ….a_{15} are the fitted coefficients; d_g is quadratic mean diameter (cm); H_d is mean height of the 100 thickest trees per hectare (m); *N* is the number of the trees per hectare (trees ha^{-1}); *V* is stand volume (m^3 ha^{-1}); BS is stem biomass and B_{agb} is aboveground biomass (t ha^{-1}).

Because of correlations between error components of the independent variables and dependent variables, the full information maximum likelihood method was used in the fitting process (Pérez-Cruzado et al., 2011). Equations8

– 11 were fitted simultaneously using the MODEL procedure in SAS 9.2 (SAS Institute, Inc., 2007). The convergence level was set at 0 001. Some characteristics of the inventory stands are given in Table 1.

Construction of the SDMDs involved the following steps: (1) plotting the height of dominant trees on the x-axis and the number of trees per hectare on the y-axis (logarithmic scale); (2) representation of isolines of the relative spacing index (*RS*); (3) representation of isolines for quadratic mean diameter using equation (7) by setting dg constant and solving for the number of trees (N) through a range of dominant heights (H_d); and (4) representing isolines for additional variables (V, B_s and B_{agb}). These isolines were determined by substituting dg in equations 9 – 11 by equation 8 and solving for the number of trees (N) through a range of dominant height (H_d) by setting the additional variables (V, B_s and B_{agb}) constant. The SDMDs were drawn in R 3.0.2 (R Core Team, 2014).

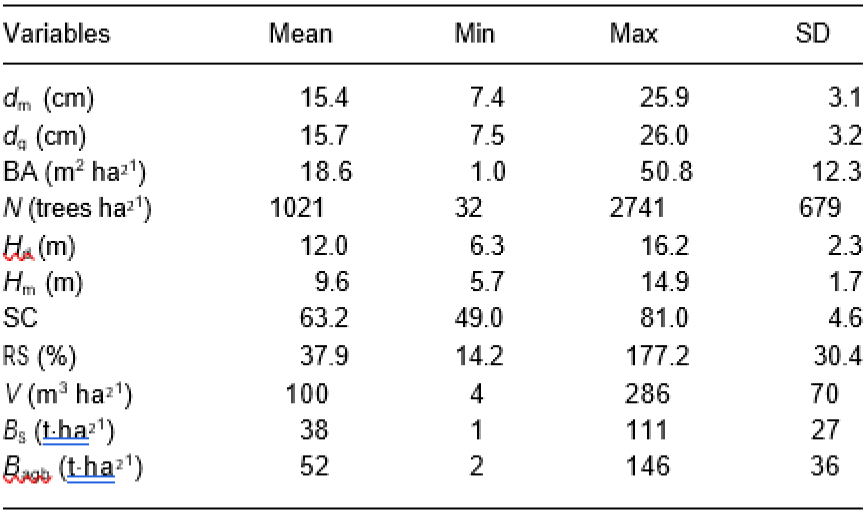
Results and discussion

The coefficients and statistics of non-linear regressions (equations 8 – 11) are shown in Table 2. All coefficients were significant at the level of 0.05. These equations explained 79 percent of the observed variability of quadratic mean diameter and 99 per cent for V, B_s and B_{agb}. As expected, the quadratic mean diameter was least precisely modelled. These results are common for static stand-level models (Pérez-Cruzado et al., 2011; Schnell et al., 2012; Castaño-Santamaría et al., 2013). The high variability explained by the stand volume, stem biomass and aboveground biomass models is consistent with other studies (Barrio-Anta et al., 2006; Castaño-Santamaría et al., 2013).

Construction of SDMDs

Three SDMDs were constructed for stand volume, stem biomass and aboveground biomass (Figures 2 – 4) by superimposing the expected size-density trajectories. The dominant height was set on the x-axis whereas the number of trees per hectare was set on the y-axis. The tree height axis ranged from 6 m to 24 m, whereas the number of trees ranged from 30 to 3000 according to the observed sample plots (Table 1). Stand stability (expressed by the SC), relative spacing (RS) and the quadratic mean diameter (dg) were shown in isolines.

Table 1 Main stand characteristics in the sample plots



Variables	Mean	Min	Max	SD
d_m (cm)	15.4	7.4	25.9	3.1
d_q (cm)	15.7	7.5	26.0	3.2
BA (m^2 ha^{-1})	18.6	1.0	50.8	12.3
N (trees ha^{-1})	1021	32	2741	679
H_d (m)	12.0	6.3	16.2	2.3
H_m (m)	9.6	5.7	14.9	1.7
SC	63.2	49.0	81.0	4.6
RS (%)	37.9	14.2	177.2	30.4
V (m^3 ha^{-1})	100	4	286	70
B_s (t·ha^{-1})	38	1	111	27
B_{agb} (t·ha^{-1})	52	2	146	36

d_g is quadratic mean diameter, d_m is mean diameter; BA is stand basal area; *N* is the number of the trees .10 cm *dbh* per hectare, H_d is dominant height, H_m is stand mean height, SC is the slenderness coefficient, RS is the relative spacing index; V is stand volume, $\underline{B_s}$ is stand stem biomass per hectare, B_{agb} is total aboveground biomass per hectare and SD is the standard deviation of means.

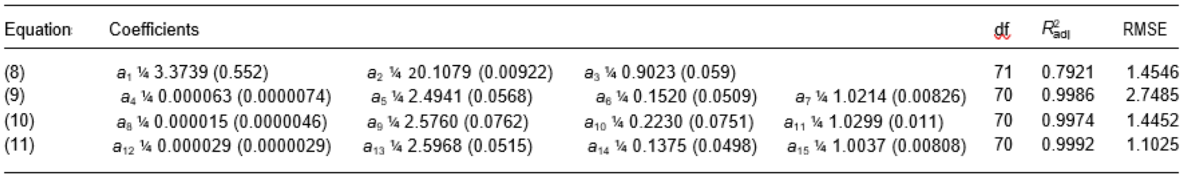
Some studies have only focused on the stability of the largest 100 – 250 trees per hectare because these trees tend to have the highest timber, aesthetic and habitat values (Cremer et al., 1982). However, some other studies also considered stand stability aspects using SC as the ratio of the mean stand height and mean stand diameter, therefore including suppressed trees as well (Hinze and Wessels, 2002; Castedo-Dorado et al., 2009). They found that the average SC of 90 was a reasonable stability threshold for, e.g. *Pinus radiata* forests. When the SC was above 90, the stand was unstable for wind or snow damage, while a mean SC below 60 indicated stable conditions. The inclusion of the average stand SC is conditioned by other variables represented in the diagram (Hinze and Wessels, 2002; Castedo-Dorado et al., 2009). In our study, if we take an SC of 90 as a reference threshold, the SC ranged from 49 to 81 (Table 1) indicating that the Chinese fir plantations in our study area were relatively stable against wind or snow damage. However, there was no more information available about critical SC values in Chinese fir plantations, which is necessary for future Chinese fir plantation management.

The open circular dots in in Figures 2 – 4 represent field measured data based on *N* and H_d, demonstrating the range of applicability of the models. The RS isolines drawn in black lines slope down from left to right with values of 8 – 56 per cent were similar to those in other studies (Barrio-Anta, 2005; Castedo-Dorado et al., 2009). d_g is represented in red lines and runs upwards from right to left. As confirmed by other authors (Schnell etal., 2012), dg was found to be highly sensitive to stand density, ranging from 6 to 40 cm. For constant H_d, d_g decreased with increasing *N* because of increasing competition for resources in the stands, leading to a smaller average tree dimension (Curtis, 1970; Dean and Long, 1992; Pérez-Cruzado et al., 2011). The observed values ranging from 4 to 286 m^3 ha^{-1} for *V*, from 1 to 111 t ha^{-1} for B_s and 2 to 146 t ha^{-1} for B_{agb} represented in blue lines slope downwards from left to right (Figures 2– 4). For a constant N, the growing stock (expressed by *V*, B_s and B_{agb}) increased with an increase of H_d. This result is consistent with the principle that stand productivity is strongly related to tree height development (Schnell et al., 2012).

Comparisons with yield tables

Statistically, yield tables are constructed from a large monitoring data, long-term experimental data or permanent inventory plots and allow estimation of site-dependent volume production (Pretzsch, 2009). This makes the volumes from yield tables and SDMDs comparable. Since there was no yield table of our study area, a yield table built on similar stand and climate conditions as ours for Chinese fir plantations was taken to compare our results (Jiang et al., 1996). A strong relationship between predicted volume from our models and volume from the yield table up to a dominant height of 22 m was observed (Figure 5). The result illustrated the reliability of SDMDs for estimating stand volume, even for a dominant height above 17 m where there were no observed data. However, predicted volume from our study was lower than that in some other studies (e.g. Li et al., 1988; Jiang et al., 1997). This could be due to differences in site quality, climatic conditions and threshold diameters used in forest inventory. For example, the threshold diameter was 10 cm in our study, compared with 5 cm for other researches (Li et al., 1988; Jiang et al., 1997).

Table 2 Coefficients (including standard errors) and goodness-of-fit statistics obtained with non-linear regression models using simultaneous fitting of the four equations system predicting quadratic mean diameter (equation 8, d_g), stand volume (equation 9, v), stem biomass (equation 10, b_s) and aboveground biomass (equation 11, b_{agb})



Equation	Coefficients				df	R^2_{adj}	RMSE
(8)	a_1 ¼ 3.3739 (0.552)	a_2 ¼ 20.1079 (0.00922)	a_3 ¼ 0.9023 (0.059)		71	0.7921	1.4546
(9)	a_4 ¼ 0.000063 (0.0000074)	a_5 ¼ 2.4941 (0.0568)	a_6 ¼ 0.1520 (0.0509)	a_7 ¼ 1.0214 (0.00826)	70	0.9986	2.7485
(10)	a_8 ¼ 0.000015 (0.0000046)	a_9 ¼ 2.5760 (0.0762)	a_{10} ¼ 0.2230 (0.0751)	a_{11} ¼ 1.0299 (0.011)	70	0.9974	1.4452
(11)	a_{12} ¼ 0.000029 (0.0000029)	a_{13} ¼ 2.5968 (0.0515)	a_{14} ¼ 0.1375 (0.0498)	a_{15} ¼ 1.0037 (0.00808)	70	0.9992	1.1025

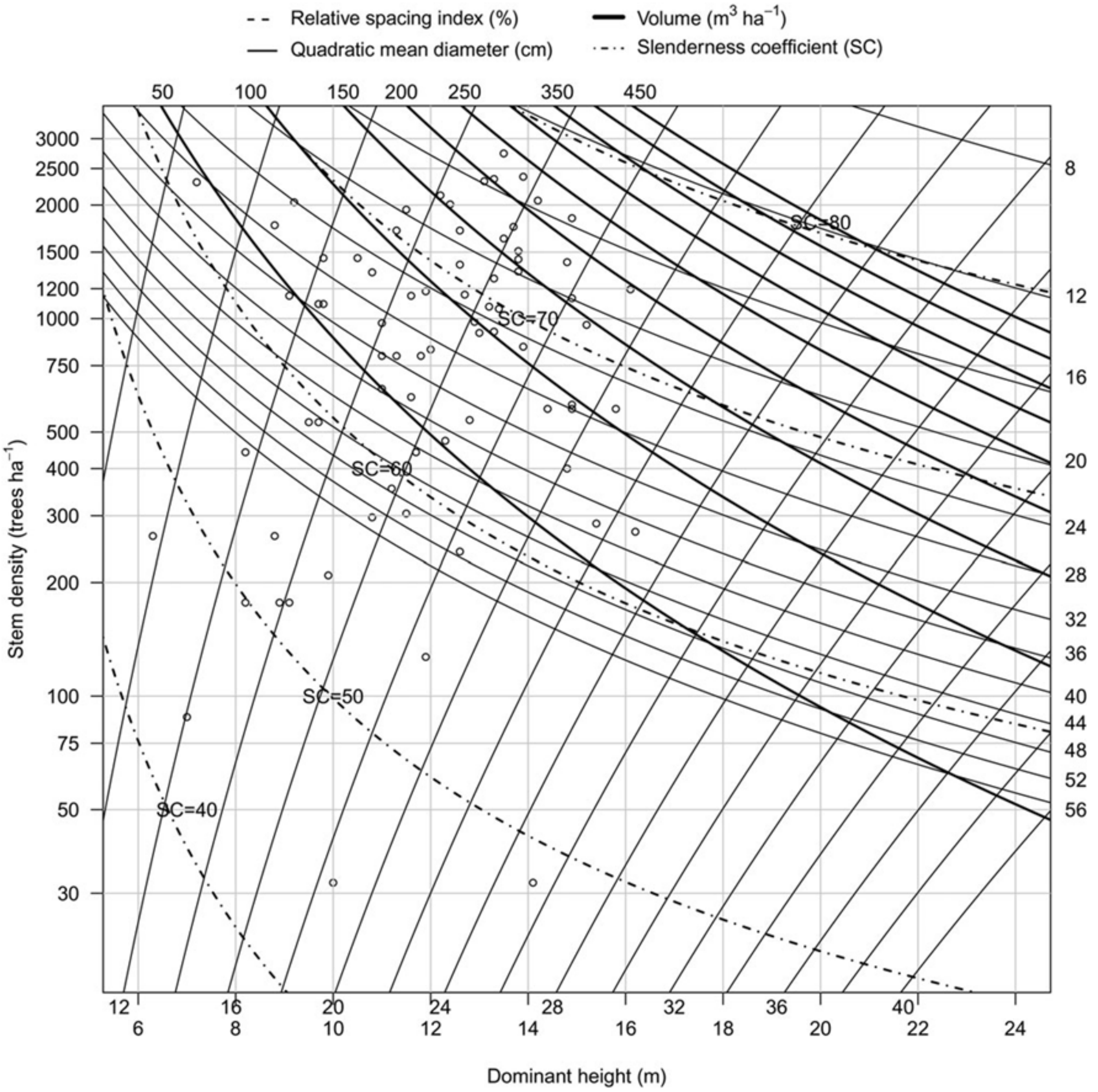


Figure 2 Stand density diagram for Chinese fir plantations in relation to stand volume. The open circles represent measured field data used to fit the models. Dominant height is the mean height of the 100 thickest trees. Other variables are explained in the text.

Therefore, the SDMDs developed in this study should be preferably applied in the local study area or the stands with similar site and climatic conditions as those in the area used for this study.

Practical examples

Stand management is recognized as an important practice for increasing stand productivity (Liu et al., 2013; Gao et al., 2014). However, management in Chinese fir plantations is commonly associated with the application of short rotations, monoculture, clear-cuts and high-level removal of biomass or volume driven by economic benefits. With the expansion of plantation area, repeated establishment of plantation by sprouts or new seedlings on the same sites is normal with a short rotation of 25 years (Wu, 1984; Wei et al., 2012). Continuous cultivation of plantations on the same sites or monoculture has resulted in a decline in production (Bi et al., 2007), increased susceptibility to insect and diseases (Ye et al., 2010) and decreased stand stability (Zhou et al., 2011). Although thinning trials are observed in some case studies in China (Cheng et al., 2014), a lack of management knowledge and technical training has limited expansion of thinning treatments. It is expected that the proposed SDMDs could provide a theoretical guideline for the management of Chinese fir plantations. Therefore, two thinning trials with the same target are presented below to illustrate how to use SDMDs.

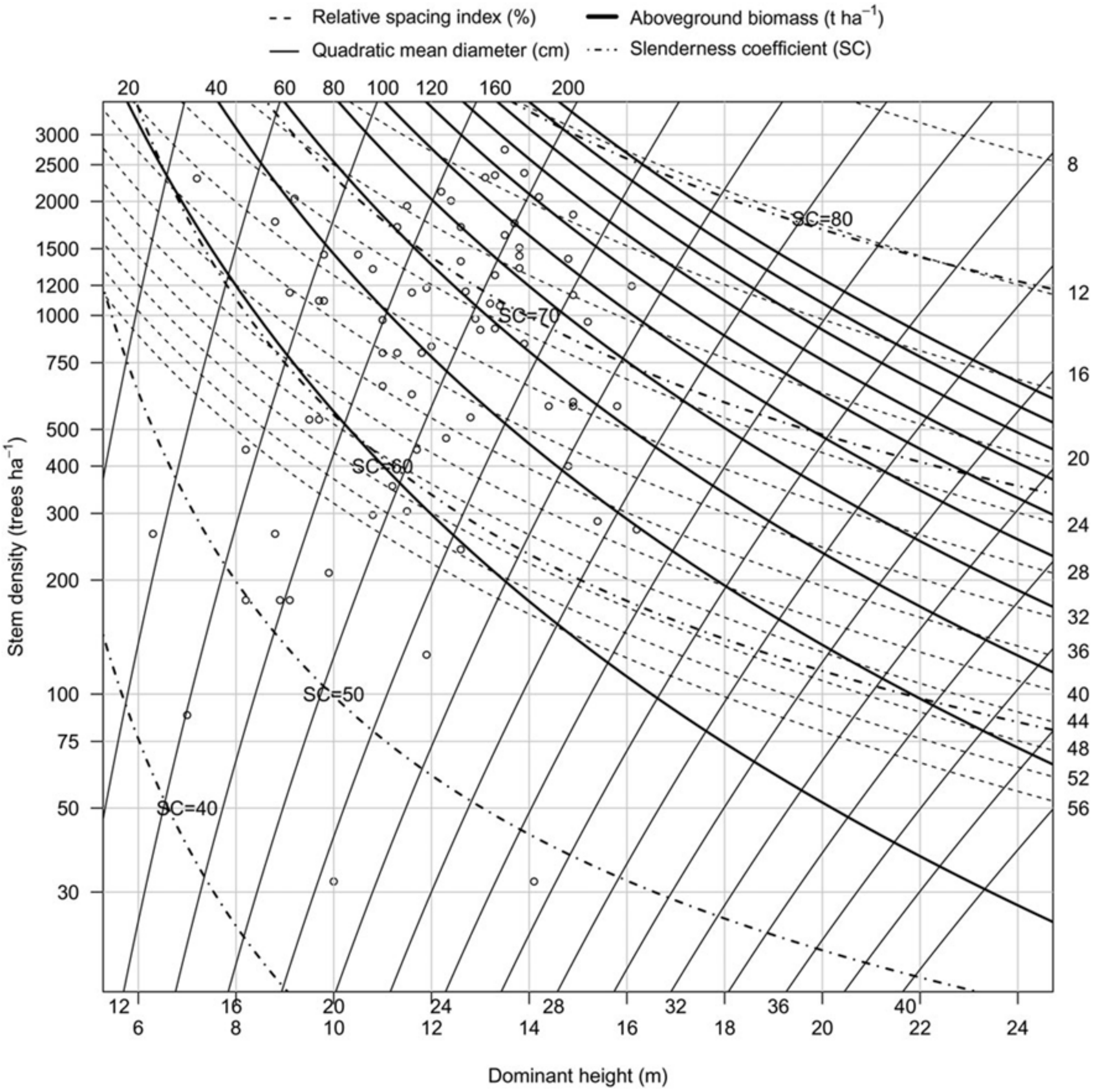


Figure 3 Stand density management diagram for Chinese fir plantation in relation to aboveground biomass ($t\ ha^{-1}$). Open circles represent measured field data used to fit the models. Dominant height is the mean height of the 100 thickest trees. Other variables are explained in the text.

In the practical application of SDMDs, two factors determine the thinning schedules: the target stand dimension at rotation age and upper and lower growing stock limits (Barrio-Anta, 2005; Barrio- Anta et al., 2006; Schnell et al., 2012). The first factor could be defined by any logical combination of two of the following variables: dominant height, quadratic mean diameter, number of the trees per hectare, total stand volume, aboveground biomass depending on the final management target or stand variable used to develop in the SDMDs (Schnell et al., 2012; Castaño-Santamaría et al., 2013).

The second factor should be the maximum growth on the stand or on the tree level, but these cannot be maximized simultaneously (Schnell et al., 2012). Therefore, the selection of the upper and lower stocking limits represents a compromise between stand growth and individual tree growth (Long, 1985), as well as stand stability. The upper growing stock limit can be set higher than the determined RS to avoid density-caused mortality and maintain an adequate live-crown ratio for good tree vigour, while the lower growing stock limit could be set to maintain adequate site occupancy using RS. For example, an RS of 16 per cent seems a reasonable upper growing stock limit to maintain live-crown ratios for good tree vitality and to avoid density-dependent mortality in radiata pine (*Pinus radiata*) plantations in temperate regions (Rodríguez et al., 2002). An alternative method of setting constant RS values is to define thinning trials considering height growth combined with an upper growing stock limit, or with thinning intensity defined as the increment of the RS values that ensure stand stability (Barrio-Anta, 2005).

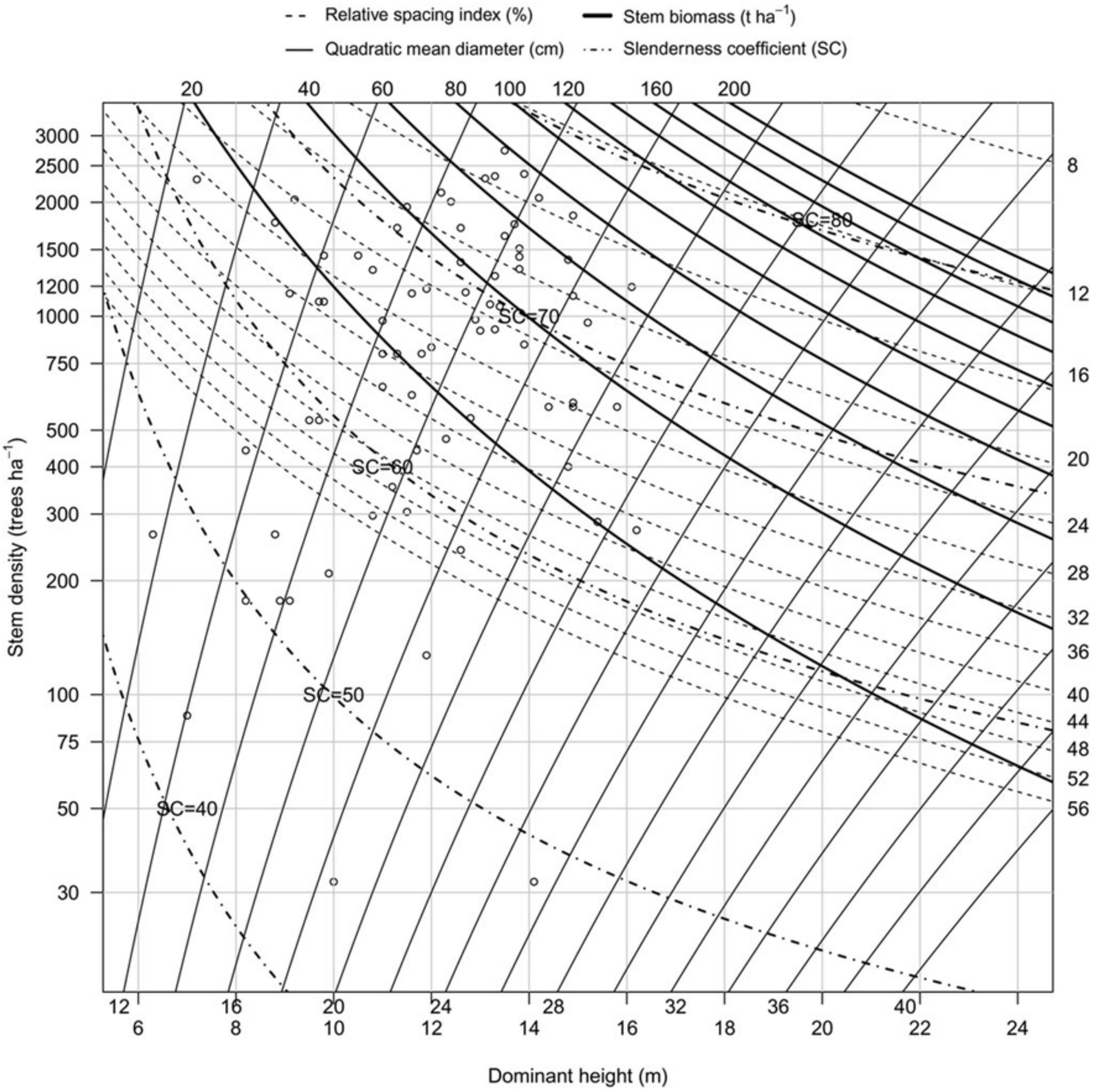


Figure 4 Stand density management diagram for Chinese fir plantation in relation to stem biomass(tha^{-1}). Open circles represent the measured field data used to fit the models. Dominant height is the mean height of the 100 thickest trees. Other variables are explained in the text.

When applying SDMDs to describe the thinning schedules, there are two assumptions. The first assumption is that no mortality happens during stand development after the first thinning. If the upper and lower stock limits are selected in a way that ensures natural mortality does not occur, this assumption seems to be reasonable. However, mortality caused by incidents such as wind, snow, ice or lightning damage is not included. To account for such issues, a mortality model could be included in the SDMDs (Castedo-Dorado et al., 2009; Pérez-Cruzado et al., 2011). However, in our study, density-independent mortality was not considered due to a lack of information. The second assumption is that thinning has no effect on the dominant height, as this variable is site-dependant.

The sequence of thinning was plotted by a backward stair- stepping procedure considering the upper growth limit and thinning interval. Therefore, the vertical (y-axis) and horizontal segments (x-axis) of the steps represent thinning and post- thinning stages. The theoretical development of a Chinese fir plantation under a particular management strategy is shown in Figure 6. Assumed target dimensions were 22 m (dominant height) and 30 cm (quadratic mean diameter) (Figure 6K). The lower growing stock limit was defined by a relative space index of 24 per cent, similar to that in other studies (e.g. Castaño-Santamaría et al., 2013). Because the average spacing index in our study was 38 per cent and no dead trees were found in the sample plots (Table 1), 36 per cent was defined as the upper stock limit in our study. The starting density of the plantations was defined at 3000 trees per hectare with a dominant height of 7 m because the planting distance between each seedling was 2 m 1.5 m with about a 90 per cent survival rate in our study area according to reports from the local forest administration (unpublished data).

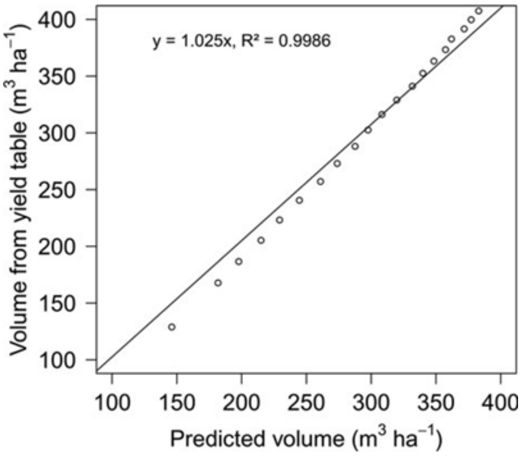


Figure 5 The relationship between predicted volume from our models and volume from the yield table proposed by Jiang et al. (1997) for Chinese fir plantations.

Theoretically, in order to achieve the target harvest stage (Point K, Figure 6), two thinning schedules are simulated based on observed stand characteristics and on standard silvicultural practice for Chinese fir in the region. The first example (dark green) shows a thinning schedule based on low-intensity interventions which may maximize site occupancy and production with an increment of dominant height of 3 m within one thinning interval. The stair-stepping procedure is drawn in Figure 6 taking stand volume as an example. Therefore, thinning related V_t, N and d_g can be read directly from different SDMDs. For example, during the five thinning operations, 20, 30, 31, 31 and 57 m^{3} ha^{-1} were theoretically removed, respectively. At rotation age stand volume reached 125 m^{3} ha^{-1} (Table 3). Including the thinning volume, a total yield of 292 m^{3} ha^{-1} was produced in the Chinese fir plantation.

The second alternative responds mainly to economic aspects (dashed blue, Figure 6), as the lower number of interventions indicates that all removals have commercial value either because of the size of the extracted trees or because of the total amount of extracted biomass. Similarly, including thinning volume, a total yield of 287 m^{3} ha^{-1} was produced in the Chinese fir plantation until the harvest stage (pion K, Figure 6), which was similar to the first thinning example. However, the stand stability resistant to natural disasters, such as wind and snow damage, should be considered because each thinning removes half or even more than half of the standing trees.

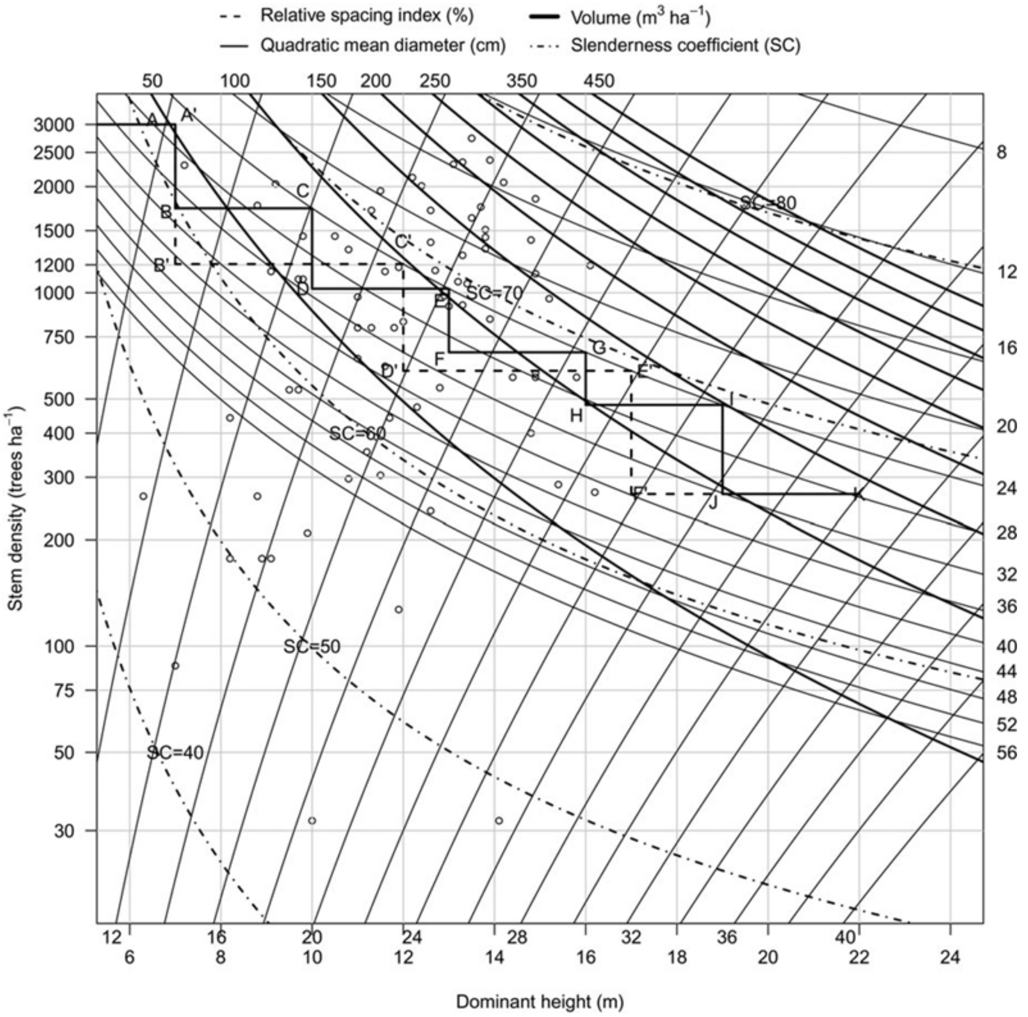


Figure 6 Examples for two different thinning schedules in Chinese fir plantations. Open circles represent measured field data used to fit the models. Dark lines (Example 1) and dash lines (Example 2) show describe simulated thinning schedules, respectively.

Table 3 Stand data modelled for two different thinning scenarios (see also Figure 6)

Example 1	Before thinning				Thinning			After thinning				Total
H_d	N	d_q	BA	V_b	N	BA	V_t	N	d_q	BA	V_a	V_{total}
7	3000	8.2	16.0	58	1264	5.6	20	1736	8.7	10.4	38	58
10	1736	12.0	19.8	90	709	6.7	69	1027	12.7	13.1	61	110
13	1027	16.2	21.0	114	349	5.9	31	678	16.9	15.2	84	163
16	678	20.4	22.1	138	197	5.2	31	481	21.1	16.9	106	217
19	481	24.7	23.0	161	212	8.4	57	269	26.3	14.6	104	272
22	269	28.0	16.6	125								292
Example 2												
7	3000	8.2	16.0	58	1794	8.1	29	1206	9.1	7.8	29	58
12	1206	14.8	20.7	106	605	8.7	43	601	15.9	12.0	63	135
17	601	21.8	22.4	146	332	10.5	66	269	23.8	11.9	80	218
22	269	30.0	19.0	149								287

N is the number of the trees per ha, d_g is quadratic mean diameter (cm), BA is basal area (m^2 ha^{-1}), V_b is stand volume (m^3 ha^{-1}) before thinning, V_t is thinning volume (m^3 ha^{-1}), Va is stand volume (m^3 ha^{-1}) after thinning, V_{total} is total stand volume (m^3 ha^{-1}).

In our SDMDs, aside from stand volume, aboveground biomass through thinning schedules can be optimized as well. Combining the variables in Table 2, the stand-level biomass could easily be estimated based on knowledge of stand basal area and dominant height. This could be an alternative to individual-tree biomass estimations.

Conclusions

To our knowledge, this is the first study where SDMDs of stand volume, stem and aboveground biomass were developed for Chinese fir plantations. SDMDs could be a useful tool to support and optimize forest management according to different owner objectives. These diagrams also allow for rapid estimations of stand volume, stem and aboveground biomass for a range of planting densities and rotation ages. This information may help managers control for several indicators of SFM (e.g. stand volume, stand biomass). Further risk indices depending on stand characteristics are easy to superimpose on the proposed diagrams, allowing forest managers to make better technical decisions. The fitted stand-level volume and biomass models can be used as alternatives to the individual-tree models for making predictions at stand level. This study could fill the gap between theoretical and practical management in Chinese fir plantations and the SDMDs proposed could be a decision support tool to optimize stand management of these forests for different management purposes.

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