RESEARCH ARTICLE

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Projecting Stand Survival and Basal Area Based on a Self-Thinning Model for Chinese Fir Plantations

Xiongqing Zhang, Quang V. Cao, Hanchen Wang, Aiguo Duan, and Jianguo Zhang

The self-thinning rule has played a critical role in controlling stand stocking and modeling stand development in forest stands. Chinese fir (*Cunninghamia lanceolata*) is a native and fast-growing tree species used for timber production and is widely grown in southern China. Effective management of this important tree species requires accurate and reasonable predictions of stand growth and survival. Remeasured data from 48 plots distributed in Fujian, Jiangxi, Guangxi, and Sichuan provinces were used to develop models to predict stand survival and basal area based on the self-thinning trajectories. These trajectories were constructed using a self-thinning slope of −1.605, as suggested by Reineke (1933) (Method 1), and the slopes estimated either from two groups of sites (Method 2) or from climate variables (Method 3). Results indicated that the stand growth and survival models using Method 3 performed best, followed by Method 2 and Method 1. In addition, stand growth and survival curves predicted from Method 3 were more similar in shape to those from the observed values, as compared with Method 1. Overall, the models based on the self-thinning lines using climate-sensitive slopes provided reasonable predictions of the stand development dynamics. Therefore, these results facilitate modeling of the relation between stand growth/survival and self-thinning under climate change.

Study Implications: The self-thinning rule describes the mortality related to competition among trees within even-aged stands, and it is a basic topic of research and discussion for more than 80 years. Chinese fir (*Cunninghamia lanceolata*), a native and fast-growing tree species used for commercial plantation establishment, is widely grown in southern China. For Chinese fir plantations, however, it has been reported that the self-thinning slope varied with site and climate. Remeasured data from 48 plots distributed in Fujian, Jiangxi, Guangxi, and Sichuan provinces were used to develop models to predict stand survival and basal area based on self-thinning trajectories. These trajectories were constructed using the slope of −1.605, as suggested by Reineke (1933) (Method 1), with the slopes estimated either from two groups of sites (Method 2) or from climate variables (Method 3). Results indicated that stand survival and basal area models using Method 3 performed best, followed by Method 2 and Method 1. In addition, stand growth and survival curves predicted from Method 3 were more similar in shape to those from the observed values than those from Method 1. Because the models developed in this study are based on the self-thinning rule, they are compatible with the dynamics of stand development and therefore should be able to provide reasonable predictions outside the range of the data.

Keywords: Chinese fir, self-thinning rule, stand survival, stand basal area

The self-thinning rule (Reineke 1933, Yoda et al. 1963) describes mortality in relation to competition for light, water, and soil nutrients among trees in even-aged stands. Although this rule has been discussed for over 80 years, it still continues to attract researchers' attention (VanderSchaaf and Burkhart 2007, Cao and Dean 2008, Burkhart 2013, Condés et al. 2017, Zhang et al. 2018). The rule has been widely used to construct relative density indices (Sterba 1987, Woodall et al. 2005),

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construct stand density management diagrams (Williams 1994, Luis and Fonseca 2004), and establish yield tables (Tang et al. 1994, Lhotka and Loewenstein 2008).

Because self-thinning usually occurs during the stand development process (Yoda et al. 1963, Weller 1987), stand growth is influenced by density changes in the stand. The self-thinning rule has therefore been incorporated in forest growth and mortality models (Smith and Hann 1986, Lloyd and Harms 1986). Cao (1994) developed tree survival and diameter growth equations of loblolly pine (*Pinus taeda* L.) under the self-thinning rule framework and reported that the system explained 98 percent of the variation. Because the self-thinning slope varied among species (Pretzsch and Biber 2005), Monserud et al. (2004) mentioned that a species-specific mortality model based on the self-thinning rule is needed. Berger et al. (2004) modeled the effects of growth limitation, neighborhood competition, and the self-thinning rule on forest production to explain the causes of production decline. Ogawa et al. (2010) founded a gross primary production model of hinoki cypress (*Chamaecyparis obtusa* [Sieb. et Zucc.] Endl.) that accounted for the influences of self-thinning on leaf mass of a tree in a stand. Ogawa et al. (2017, 2018) proposed leaf biomass models of hinoki cypress based on the self-thinning rule. As a result, forest growth models under the self-thinning law should provide reasonable predictions since they were based on the biological relations between trees growing in a stand.

Chinese fir (*Cunninghamia lanceolata*), widely distributed in southern China, is a native and fast-growing tree species and commonly used for timber production (Wu 1984). It has more than 1,000 years of planting history because of its high-quality timber with straight shape and high resistance to bending and decay (Zhu et al. 2019). The species occupies 19.01 percent of all forested land (8.93 million hectares) and 25.18 percent of all plantation stocking (625.40 million m^3) in China based on the 8th National Forest Inventory (SFA 2013, Zhu et al. 2019). Effective management of this vastly distributed tree species needed accurate and reasonable predictions of stand growth and survival. Zhang et al. (2016) used segmented regression to model the self-thinning lines of Chinese fir plantations in southern China and reported that their slopes were much steeper than the value of –1.605 as proposed by Reineke (1933). Based on that research, Zhang et al. (2018) incorporated climate factors into the segmented regression to model self-thinning trajectories of Chinese fir plantations and confirmed that the slopes were not invariant and can be predicted by climate variables.

The aim of this study was (1) to develop stand growth and survival models based on self-thinning trajectories using each of the slopes from Reineke (1933), Zhang et al. (2016), and Zhang et al. (2018), respectively, and (2) to evaluate the three methods in predicting growth and survival of Chinese fir plantations. The findings will be useful for forest managers to obtain reasonable projections for stand growth and survival of Chinese fir plantations in southern China.

Materials and Methods

Study Sites and Data Collection

The study sites were located in Fujian, Jiang, Guangxi, and Sichuan provinces. The climate in Fujian, Jiangxi, and Sichuan belongs to the middle-subtropical climate zone. Guangxi, on the other hand, belongs to the southern-subtropical climate zone (Figure 1, Table 1). Chinese fir is distributed widely in these four provinces. Stands were planted using bare-root seedlings in 1981 in Jiangxi, and in 1982 in Fujian, Guangxi, and Sichuan. In each site, the plantations contain four levels of spacings: 2 m × 1.5 m (3,333 trees/hectare), 2 m × 1 m (5,000 trees/hectare), 1 m × 1.5 m (6,667 trees/hectare), and 1 m × 1 m (10,000 trees/hectare), with each spacing in a randomized block design with three replications, resulting in a total of twelve 0.06-ha plots in each site. There was a buffer zone that consisted of two rows of similarly treated trees surrounding each plot.

Diameter at breast height (dbh, cm) was recorded for all trees after height exceeded 1.3 m, with remeasurements every 2 or 3 years, starting in 1983. Also, over 50 trees in a plot were tagged and measured for total height. In each plot, the stand dominant height (*H,* m) was calculated as the mean height of the six tallest trees. Because of a snow storm in Jiangxi in 1998 that led to the death of a large number of trees, the data after 1999 in Jiangxi were not used. Summary statistics of stand variables by site are shown in Table 2.

Self-Thinning Model

Zhang et al. (2016) modeled the self-thinning trajectories of Chinese fir through the following segmented regression:

$$\begin{aligned} y_2 = y_1 + \alpha_3 \Big\{ &(x_2 - \alpha_1 - \alpha_2 y_0)^2 I_{12} \\ &- \left(x_2 - \alpha_1 - \alpha_2 y_0 - \frac{c}{2\alpha_3}\right)^2 I_{22} \\ &- (x_1 - \alpha_1 - \alpha_2 y_0)^2 I_{11} \\ &+ \left(x_1 - \alpha_1 - \alpha_2 y_0 - \frac{c}{2\alpha_3}\right)^2 I_{21} \Big\} \end{aligned} \tag{1}$$

where $I_{1i} = \begin{cases} 1, \text{ if } x_i > \alpha_1 + \alpha_2 y_0 \\ 0, \text{ otherwise} \end{cases}$, $I_{2i} = \begin{cases} 1, \text{ if } x_i > \alpha_1 + \alpha_2 y_0 + \frac{c}{2\alpha_3} \\ 0, \text{ otherwise} \end{cases}$, i = 1, 2;

x_i and y_i denote ln(Dq) (Dq, stand quadratic mean diameter, cm) and ln(N) (N, number of trees per hectare) at time i, respectively; y_0 = ln(N_0); N_0=initial density; c is the self-thinning slope; and α_1, α_2, and α_3 are parameters to be estimated. Zhang et al. (2016) reported that the segmented regression performed well on modeling the self-thinning lines of Chinese fir plantations (Figure 2), with the site-specific slope c = –2.4453 for Fujian, Guangxi, and Jiangxi and –4.2169 for Sichuan. Based on Zhang et al.'s (2016) study, Zhang et al. (2018) modeled the climate-sensitive self-thinning lines of Chinese fir and found that the slopes were significantly related to mean annual temperature (MAT), annual precipitation (AP), degree-days below 0° C (DD_0), summer mean maximum temperature (SMMT), and winter mean minimum temperature (WMMT). The self-thinning slopes ranged from –4.1647 to –1.6355. The above climate variables were incorporated into Zhang et al.'s (2016) segmented equation as follows:

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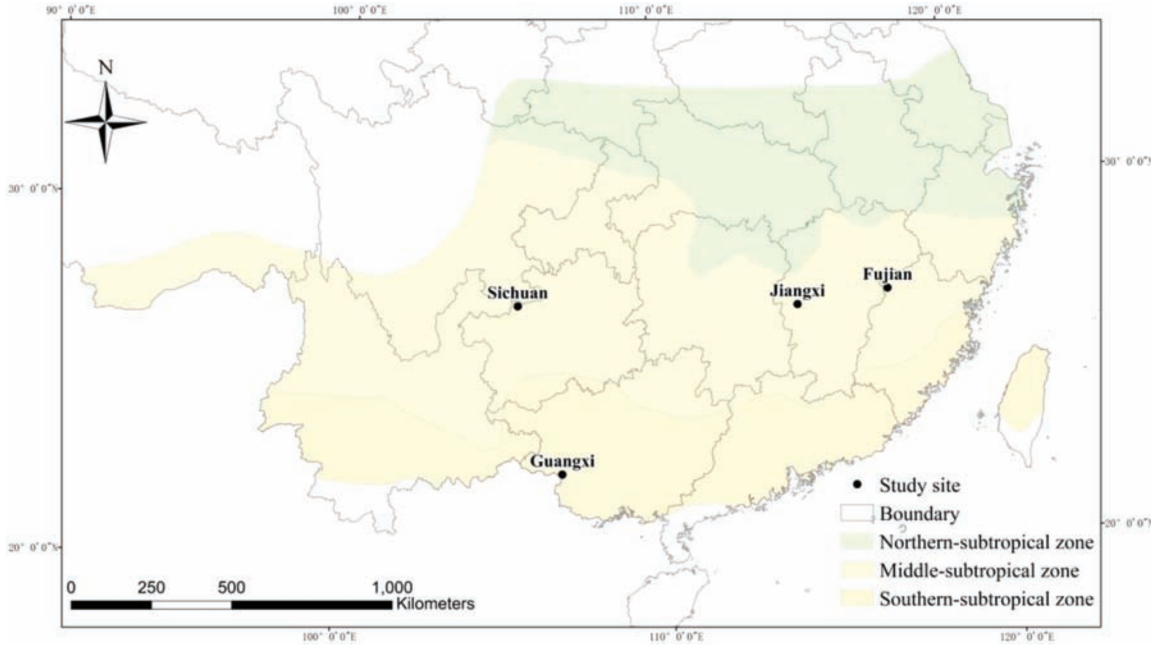

Figure 1. Study sites located in subtropical climate zones in this study.

Table 1. Annual precipitation, mean annual temperature, soil type, and measurement years, by site.

Site	Annual precipitation (mm)	Mean annual temperature (°C)	Soil type	Measurement time
Fujian	1,767	17.7	Laterite	1985–90: every year 1990–2010: every 2 years
Jiangxi	1,656	16.8	Laterite, yellow	1985–89: every year 1989–99: every 2 years
Guangxi	1,400	19.9	Laterite	1990–95: every year 1995–2009: every 2 years
Sichuan	1,182	17.5	Laterite	1985–90: every year 1993–95:every year 1995–2013: every 2 or 3 years

$$\left\{\begin{array}{l} y_2 = y_1 + \alpha_3 \left\{ (x_2 - \alpha_1 - \alpha_2 y_0)^2 I_{12} \right. \\ \quad -\left(x_2 - \alpha_1 - \alpha_2 y_0 - \frac{c}{2\alpha_3}\right)^2 I_{22} \\ \quad -(x_1 - \alpha_1 - \alpha_2 y_0)^2 I_{11} \\ \quad \left. +\left(x_1 - \alpha_1 - \alpha_2 y_0 - \frac{c}{2\alpha_3}\right)^2 I_{21} \right\} \\ c = c_0 + c_1 \times \mathrm{MAT} + c_2 \times \mathrm{AP} + c_3 \\ \quad \times \mathrm{DD\_0} + c_3 4 \times \mathrm{SMMT} + c_5 \times \mathrm{WMMT} \end{array}\right\}. \tag{2}$$

where c_0–c_5 are regression parameters, and their values can be found in Zhang et al. (2018).

Projecting Stand Growth and Survival Based on the Self-Thinning Model

The stand basal area and survival models based on the self-thinning model for predicting growth of Chinese fir were developed in this study. The first step involved modeling stand dominant height (H) using Bailey and Clutter's (1974) equation:

$$H_{t+q} = \exp\{\beta_1 + [\ln(H_t - \beta_1)](A_{t+q}/A_t)^{\beta_2}\} \tag{3}$$

where H_t *and* H_{t+q} are the stand dominant heights at ages At and At+q, respectively; q is the growth interval in years; and β_1 and β_2 are the parameters to be estimated.

Annual growth projection accounting for different growth intervals ensures step invariance of model predictions (Ochi and Cao 2003, Qin and Cao 2006, Cao and Strub 2008, Zhang et al. 2010). Stand growth and survival were predicted in a recursive manner as follows:

Year (t + 1):

$$\hat{D}\mathrm{q}_{t+1} = \exp\left\{\left(\frac{A_t}{A_{t+1}}\right)\ln(\mathrm{Dq}_t) + \left(1 - \frac{A_t}{A_{t+1}}\right) [\gamma_0 + \gamma_1 A_t + \gamma_2 H_t + \gamma_3 \mathrm{Dq}_t + \gamma_4 \ln(N_t)]\right\} \tag{4}$$

$$\begin{aligned} \hat{y}_{t+1} = & y_t + \alpha_3 \left\{ (x_{t+1} - \alpha_1 - \alpha_2 y_0)^2 I_{12} \right. \\ & - \left(x_{t+1} - \alpha_1 - \alpha_2 y_0 - \frac{c}{2\alpha_3}\right)^2 I_{22} \\ & - (x_t - \alpha_1 - \alpha_2 y_0)^2 I_{11} \\ & \left. - \left(x_t - \alpha_1 - \alpha_2 y_0 - \frac{c}{2\alpha_3}\right)^2 I_{21} \right\} \end{aligned} \tag{5}$$

$$\hat{B}_{t+1} = (\pi/40,000)\hat{N}_{t+1} Dq^2_{t+1} \tag{6}$$

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Table 2. Statistics (mean ± SD) of stand factors of Chinese fir plantations in each site.

Site	*n*	*A*	*N*	*B*	Dq	*H*
Fujian	192	15 ± 8.05	5,120 ± 2,262	45.79 ± 20.72	11.26 ± 4.35	13.77 ± 6.20
Jiangxi	124	12 ± 4.60	5,871 ± 2,180	38.07 ± 13.55	9.35 ± 2.34	10.83 ± 2.90
Guangxi	132	19 ± 6.34	3,627 ± 11,815	34.11 ± 6.79	11.83 ± 2.9	15.25 ± 3.61
Sichuan	192	15 ± 7.20	4,646 ± 2,212	30.25 ± 8.57	9.70 ± 2.42	11.54 ± 3.58

Note: n, number of measurements for all plots; SD, standard deviation; *A*, stand age; Dq, stand quadratic mean diameter (cm); *N*, living number of tree/hectare; *B*, stand basal area (m^2/hectare); and *H*, stand dominant height (m).

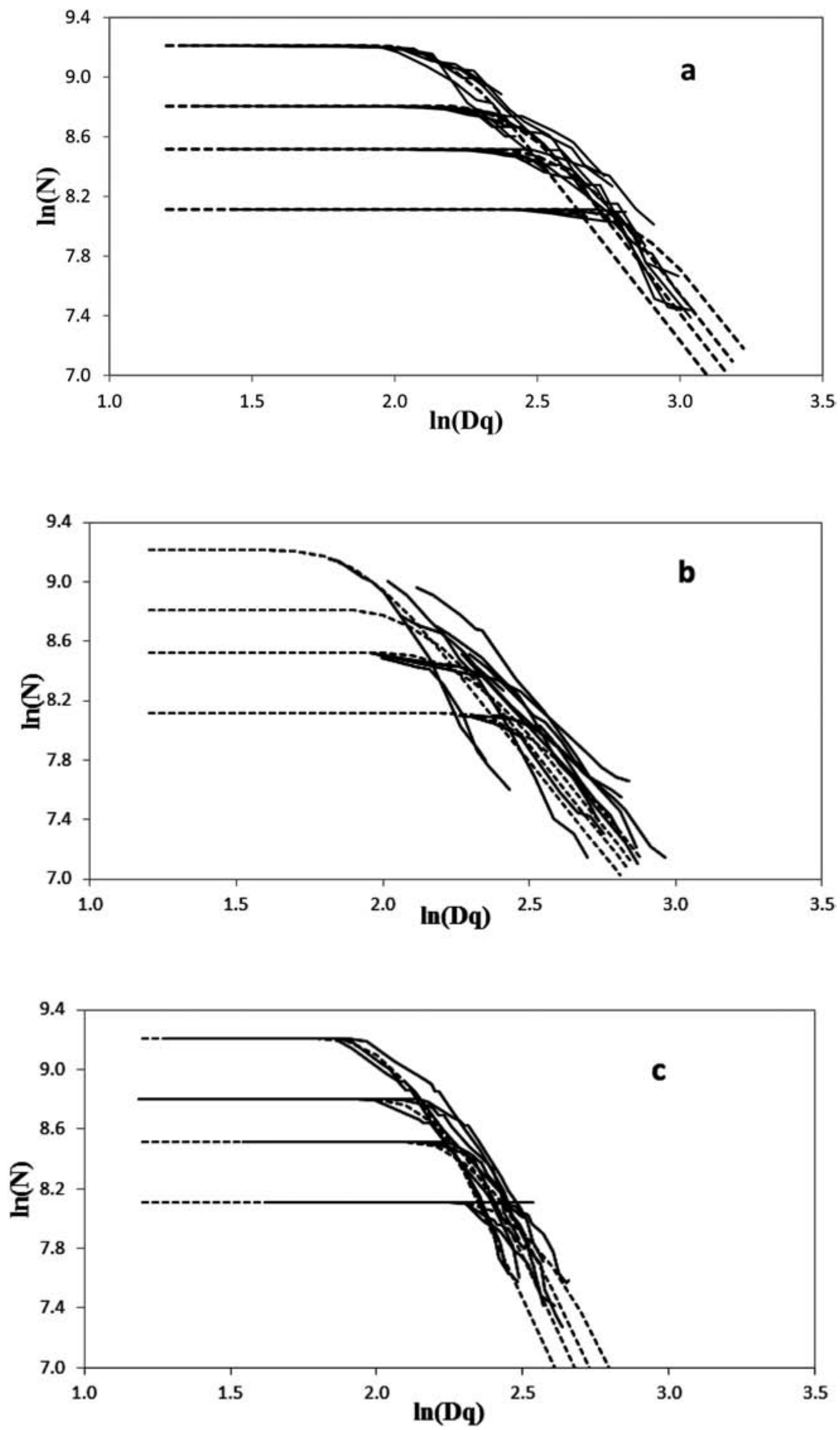

Figure 2. Observed (solid lines) and predicted (dotted lines) size–density trajectories for the provinces (a: Jiangxi and Fujian; b: Guangxi; c: Sichuan) (Zhang et al. 2016), where ln(*Q*) = ln(Dq).

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Year ($t + q$):

$$\hat{D}q_{t+q} = \exp\left\{\left(\frac{A_{t+q-1}}{A_{t+q}}\right)\ln(Dq_{t+q-1}) + \left(1-\frac{A_{t+q-1}}{A_{t+q}}\right)\left[\gamma_0+\gamma_1 A_{t+q-1} + \gamma_2 H_{t+q-1} + \gamma_3 Dq_{t+q-1} + \gamma_4 \ln(N_{t+q-1})\right]\right\} \quad (7)$$

$$\hat{y}_{t+q} = y_{t+q-1} + \alpha_3\left\{(x_{t+q}-\alpha_1-\alpha_2 y_0)^2 I_{12} - \left(x_{t+q}-\alpha_1-\alpha_2 y_0 - \frac{c}{2\alpha_3}\right)^2 I_{22} - (x_{t+q-1}-\alpha_1-\alpha_2 y_0)^2 I_{11} - \left(x_{t+q-1}-\alpha_1-\alpha_2 y_0 - \frac{c}{2\alpha_3}\right)^2 I_{21}\right\} \quad (8)$$

$$\hat{B}_{t+q} = (\pi/40,000)\hat{N}_{t+q} Dq^2_{t+q} \quad (9)$$

where B is the observed stand basal area in m²/hectare; $x = \ln(Dq)$; $y = \ln(N)$; $y_0 = \ln(N_0)$; the γ values are regression parameters; the ^ symbol indicates predicted values; and subscripts denote measurement times.

Because of the cross-equation correlations among the error components of these equations, the seemingly unrelated regression method was used to estimate the parameters of the above system. This method was implemented in SAS using procedure MODEL (SAS Institute Inc 2011).

Three methods based on different values of the self-thinning slope were evaluated in this study.

Method 1

The slope c was fixed at –1.605 (Reineke 1933).

Table 3. Parameter estimates (and standard errors) of the dominant height–age model by site.

Site	β_1		β_2	
Fujian	5.5010	(1.7460)	–0.2834	(0.1229)
Guangxi	4.0871	(0.2905)	–0.4305	(0.0821)
Jiangxi	3.2725	(0.1503)	–0.7530	(0.1309)
Sichuan	2.8054	(0.0263)	–1.6160	(0.1005)

Note: All parameters were significant at the 0.05 level.

Method 2

The slope c was site-specific, –2.4453 for Fujian, Jiangxi, and Guangxi, and –4.2169 for Sichuan (Zhang et al. 2016).

Method 3

The slope c ranged from –4.1647 to –1.6355, computed from climate variables for each plot (Zhang et al. 2018).

Model Evaluation

In this study, the threefold cross-validation scheme was used for model validation. This scheme involved fitting the models on two replications (fit data) and then using the resulting parameters to predict the remaining replication (validation data). The procedure was repeated so that each replication took turns to act as the validation data. The following three statistics were computed from the pooled validation data:

$$\text{Mean error} = \sum(y_i - \hat{y}_i)/n \quad (10)$$

$$\text{Mean absolute error} = \sum|y_i - \hat{y}_i|/n \quad (11)$$

$$\text{Fit index},\ R^2 = 1 - \sum(y_i-\hat{y}_i)^2/\sum(y_i-\bar{y})^2 \quad (12)$$

where y_i is the observed stand basal area or survival for the ith observation; n is the total number of observations; and $\hat{y}_i$ and $\bar{y}$ are the predicted and average basal area or survival, respectively. A model with smaller absolute values of mean error (ME), smaller mean absolute error (MAE) values, and larger R^2 values indicates better prediction of stand basal area and survival.

Results

Model Comparisons

Parameter estimates and their standard errors of the stand dominant height growth model (Equation 3) are shown in Table 3 for each province. Table 4 presents the parameter estimates and their standard errors for the stand growth and survival models (Equations 4–9) for each of the three methods. These estimates were from models fitted to all replications. All parameters of these models from Tables 3 and 4 were significant ($P < .05$).

Method 3 was clearly the best among the three methods, ranking first in terms of MAE and R^2, and second in terms of ME (Table 5). These results also showed that both Methods 2 and 3 with the self-thinning slope obtained from the Chinese fir data performed better than Method 1, which was based on Reineke's (1933) slope. On the

Table 4. Parameter estimates (and standard errors) of the stand growth and survival models for the pooled data, by method.

Parameter	Method 1		Method 2		Method 3	
α_1	5.6856	(0.5666)	5.6936	(0.4059)	5.7416	(0.4334)
α_2	–0.4351	(0.0640)	–0.4275	(0.0458)	–0.4334	(0.0492)
α_3	–1.1124	(0.1265)	–2.4625	(0.2406)	–2.1547	(0.2231)
γ_0	6.9443	(0.8686)	5.2733	(0.6074)	5.4467	(0.6392)
γ_1	0.0722	(0.0080)	0.0513	(0.0051)	0.0533	(0.0062)
γ_2	0.1118	(0.0166)	0.0536	(0.0091)	0.0587	(0.0108)
γ_3	–0.1769	(0.0296)	–0.0732	(0.0172)	–0.0844	(0.0216)
γ_4	–0.5549	(0.0863)	–0.3862	(0.0595)	–0.4008	(0.0625)

Note: All parameters were significant at the 0.05 level. Method 1, self-thinning line slope from Reineke (1933); Method 2, self-thinning line slope from Zhang et al. (2016); Method 3, self-thinning line from Zhang et al. (2018).

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Table 5. Model evaluation statistics of the three methods using the threefold cross-validation.

Variable	Statistics	Method 1	Method 2	Method 3
N	Mean error	–34.59	***–2.19***	4.44
	Mean absolute error	176.38	166.25	***161.76***
	R^2	0.9827	0.9841	***0.9842***
Basal area	Mean error	***–0.58***	1.55	1.04
	Mean absolute error	4.14	3.60	***3.46***
	R^2	0.9800	0.9857	***0.9866***

Note: Method 1, self-thinning line slope from Reineke (1933); Method 2, self-thinning line slope from Zhang et al. (2016); Method 3, self-thinning line from Zhang et al. (2018). For each evaluation statistic, a bold italic number denotes the best among the three methods.

other hand, Method 3 with separate slopes for different plots based on climate variables was slightly better than Method 2, which used the same slope for the entire province.

The behavior of the models can be seen from the relations within each province between ln(*N*) and ln(Dq) (Figure 3), number of trees per hectare and age (Figure 4), and stand basal area and age (Figure 5). Each figure contains graphs of the observed data and of predicted values from Methods 1 and 3. Because the graphs for Methods 2 and 3 are similar, only graphs for Method 3 are shown in these figures. Overall, curves predicted from Method 3 are more similar in shape to those from the observed values than those from Method 1.

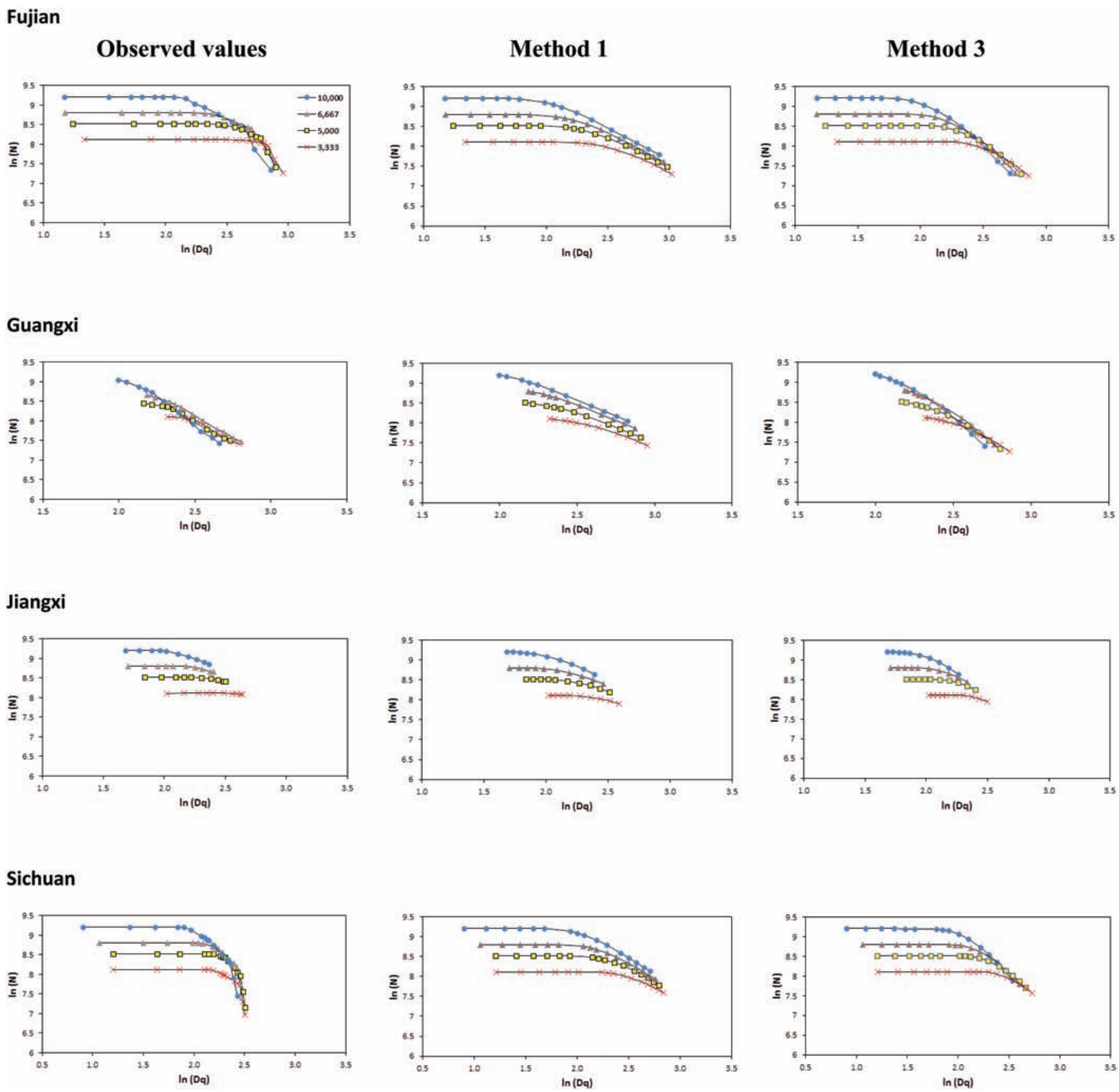

Figure 3. Relations between stand density (ln *N*) and size (ln Dq) by province and method. From left to right are observed values and predicted values from Method 1 and Method 3, respectively.

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Self-Thinning Trajectories

The observed self-thinning trajectories for Guangxi province were closer to those predicted from Method 3 than from Method 1 (Figure 3). The self-thinning slope of –1.605 from Method 1 was apparently not steep enough for the Chinese fir data used in this study. The observed and predicted trajectories from Method 3 are similar for Fujian and Jiangxi. For Sichuan province, the observed trajectories exhibit a steeper slope for the last two measurements (ages 28 and 30) than the slopes from Methods 1 and 3 (Figure 4). The reason for this is traced back to low predictions of the self-thinning slopes from Methods 1 and 3, which led to over-predictions of both stand survival and growth at these measurements.

Stand Survival versus Age

As expected, self-thinning began earlier in sites of higher planting densities than those of lower planting densities (Figure 4). Self-thinning at Fujian and Jiangxi occurred later than as predicted from the three methods. The reverse is true for Guangxi and Sichuan. This is evident for sites with the highest planting density (10,000/hectare). For Guangxi province, self-thinning was well under way at the first measurement (age 11) for the two highest planting densities (Figure 4), but the predicted survival curves for these two densities show that self-thinning just got started. In addition, stand survivals from four planting density levels were almost equal at age 30 from observed data and Method 3 in Fujian, Guangxi, and Sichuan.

Stand Basal Area versus Age

Figure 5 shows that the observed stand basal area growth followed different trends depending on the location. Stand basal area (a) changed little over time (Guangxi), (b) continued to increase over time (Jiangxi), (c) increased up to age 26, then decreased (Fujian),

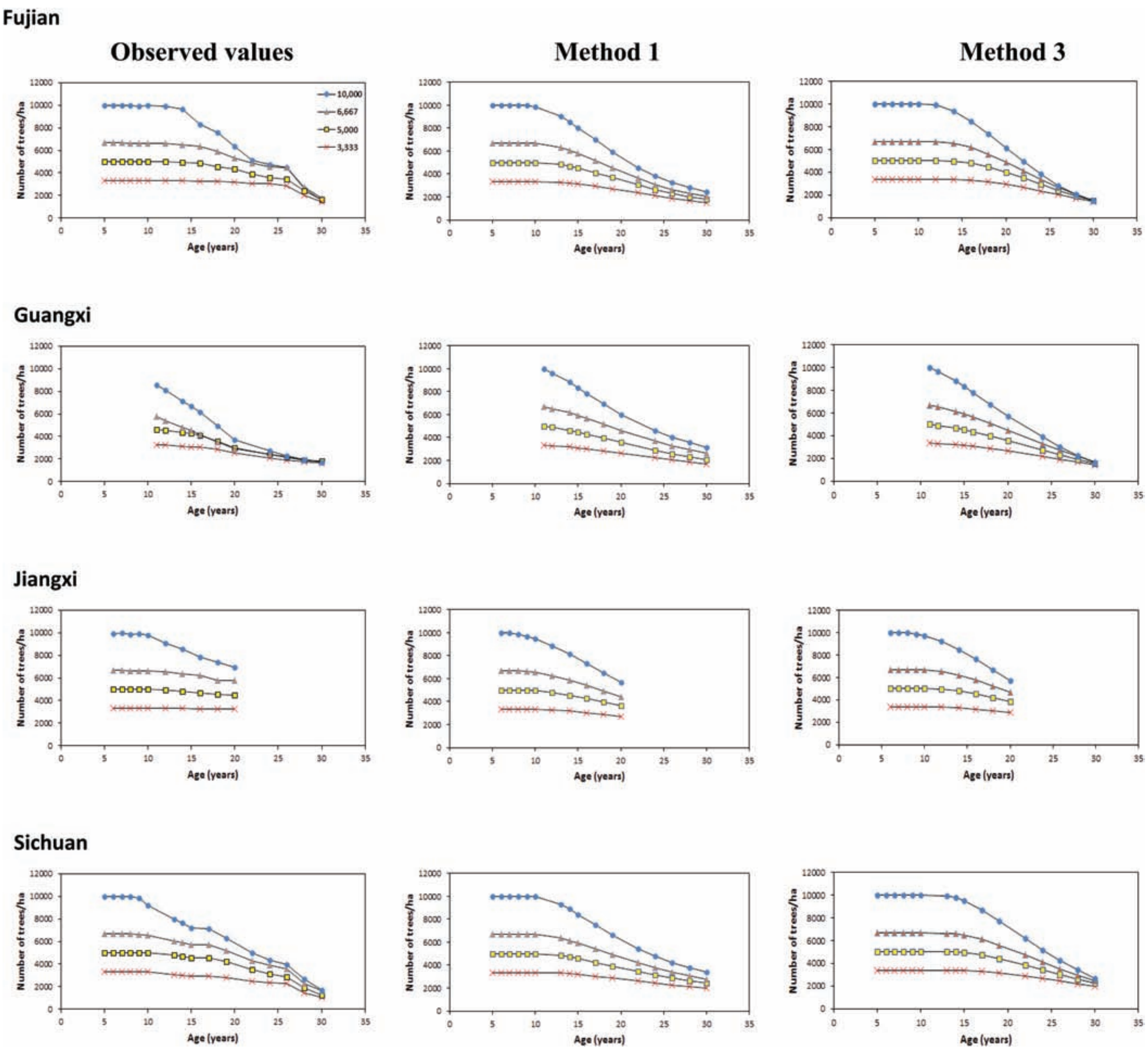

Figure 4. Relations between number of trees per hectare and stand age by province and method. From left to right are observed values and predicted values from Method 1 and Method 3, respectively.

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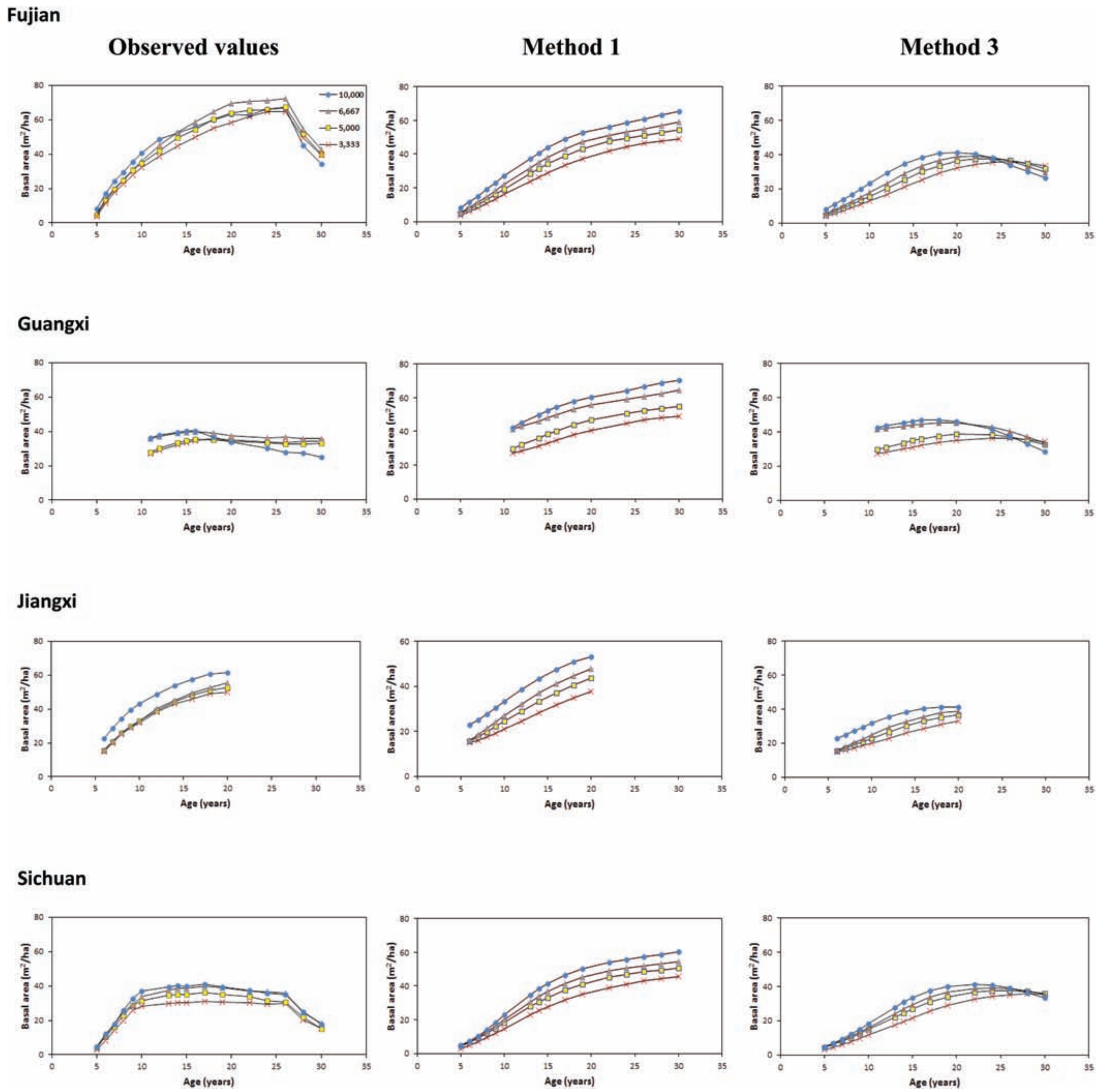

Figure 5. Relations between basal area per hectare and stand age by province and method. From left to right are observed values and predicted values from Method 1 and Method 3, respectively.

or (d) increased up to age 10, stabilized, then decreased after age 26 (Sichuan). Furthermore, the stand basal areas at the highest planting density (10,000/hectare) in Fujian and Guangxi were the smallest of the four planting densities after 25 years from both observed data and Method 3.

Method 1 did not model these trends well; predicted stand basal area continued to increase over time for all four provinces. Method 3, on the other hand, matched the above trends adequately. The predicted levels of stand basal area from Method 3, however, were lower than the observed values for Fujian and Jiangxi provinces. For Sichuan, the predicted values from Method 3 were higher than the observed values for the last two measurements (ages 28 and 30), because of over-prediction for both stand survival and quadratic mean diameter growth. This problem was previously seen in Figure 3.

Discussion

The self-thinning rule has been frequently employed in modeling forest growth and mortality (Mitchell 1975, Cao 1994, Berger et al. 2004). In the present study, stand basal area growth and stand survival models were developed based on the self-thinning lines with three different slopes from Reineke (1933), Zhang et al. (2016), and Zhang et al. (2018). The annual projection method used in this study allowed the depiction of stand development over long growth

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periods. Method 1 with a slope of –1.605 did not perform as well as the other two methods (Table 5).

Reineke (1933) stated that the slope of the self-thinning trajectories of 12 out of 14 tree species were invariant with a value of –1.605. In contrast, other researchers found that the slope varied by tree species and sites (Pittman and Turnblom 2003, Weiskittel et al. 2009, Rivoire and Le Moguedec 2012). Poage et al. (2007) reported a large difference in self-thinning slopes (ranging from –2.192 to –1.310) in 40 hemlock-Sitka spruce stands. Charru et al. (2012) also stated that the slope ranged from –1.941 to –1.615 for 11 temperate tree species in France. In addition, several substantial differences in environment may affect the self-thinning trends (Pretzsch 2002, Condés et al. 2017, Kweon and Comeau 2017). Brunet-Navarro et al. (2016) found that self-thinning lines were influenced by tree species, as well as climatic conditions.

Most of the above studies reported slope values larger than –2. Under the pipe model theory (Shinozaki et al. 1964), slope values larger than –2 indicate that maximum stand basal area increases with increasing mean diameter. However, in the Zhang et al. (2016, 2018) studies, most of the slope values were lower than –2, indicating that the maximum stand basal area decreases with accelerative mean diameter. This could be because a concomitant change exists in the functional allometry of the trees (e.g., a considerable change occurs in hydraulic architecture) with a decline in available resources, or the lower use efficiency because of limiting resources with accelerative size (Condés et al. 2017, Zhang et al. 2018). Generally, tree size (diameter) is regarded as a proxy of tree age (Yao et al. 2001). Maximum stand basal area generally decreased with increasing stand age. The exception was at the Jiangxi site for the observed data and Method 3 (Figure 5). In short, when the self-thinning slope was site-specific (Method 2) or climate-sensitive (Method 3), the resulting stand growth and survival models provided improved performance as compared to Reineke's constant slope of –1.605 (Method 1).

Because the models developed in this study are based on the self-thinning rule, they are compatible with the dynamics of stand development and therefore should be able to provide reasonable predictions outside the range of the data. Also, these models can be helpful for providing more precise silvicultural practices for constructing stand density management diagrams of Chinese fir plantations in southern China.

Conclusions

In this study, we developed stand basal area and survival models based on self-thinning lines using the slope of –1.605 as suggested by Reineke (1933) (Method 1), or the slopes estimated either from two groups of sites (Method 2) or from climate variables (Method 3). Results indicated that models from Methods 2 and 3 performed better than those from Method 1. Also, Method 3 with separate slopes for different plots was slightly better than Method 2 that used the same slope for an entire province. In addition, stand basal area and survival curves predicted from Method 3 were similar in shape to those from the observed values. Overall, projecting stand growth and survival based on the self-thinning trajectories that used climate-sensitive slopes could provide reasonable predictions during forest succession under climate change.

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