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Segmented taper models form for Manchurian fir and Korean spruce in northeastern China

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FOREST MANAGEMENT

ABSTRACT

Background: Manchurian fir (*Abies nephrolepis* Maxim) and Korean spruce (*Picea koraiensis* Nakai) are primary conifer species of economic and ecological importance in northeast China. Several taper studies have analyzed for fir and spruce species in the countries harboring the boreal forests. However, taper models do not exist for Manchurian fir and Korean spruce in China or abroad. This study aimed to develop stem taper models for these species. A dataset of 188 destructively sampled trees (Manchurian fir 123 and Korean spruce 65) was used to evaluate eight well-known taper models. These models were fitted with generalized non-linear least squares by using 3,570 diameter and height measurements. We incorporated a first-order continuous-time error structure to adjust the inherent autocorrelation.

Results: The form-class segmented model of Clark et al. (1991) best predicted the diameter, merchantable volume, and stem volume of the species when the upper stem diameter at 5.3 m was available or predicted.

Conclusion: When diameter measurements at 5.3 m were not available, the Kozak (2004) and Max and Burkhart (1976) models were superior to other models in estimating the diameter of both species and volume of Korean spruce. For Manchurian fir, the Fang et al. (2000) model was more accurate in volume estimates.

Keywords: Form-class, Stem diameter, Merchantable volume, Variable form model

HIGHLIGHTS

Eight taper models were evaluated for natural stands of two conifer species (Manchurian fir and Korean spruce) in NE China.
The Clark et al. (1991) model was superior to other models in estimating diameter, merchantable volume, and total volume.
The prediction method used in Clark et al. (1991) model did not affect its overall superiority.
The models of Kozak (2004), Max and Burkhart (1976), and Fang et al. (2000) performed well when diameter measurements at 5.3 m were not available.

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INTRODUCTION

Manchurian fir (*Abies nephrolepis* Maxim) and Korean spruce (*Picea koraiensis* Nakai) are valuable conifer species of northeast China. Fir and spruce forests occupy 3.1 million ha and 4.3 million ha areas, respectively. The corresponding standing volume of *Abies nephrolepis* and *Picea koraiensis* is 1135.6 million m^3 and 1001.6 million m^3 (Xu et al., 2019). *Picea koraiensis* is the leading species of spruce forests with *Abies nephrolepis* as a major associate in NE China. This region maintains about 30% of the total forest area in China and is recognized as a national base of wood products as well as a region of ecological importance. Almost half of the national ecosystem carbon is stored in this region (Zhang and Liang, 2014). NE China hosts different forest types, ranging from temperate broadleaf forest to boreal taiga forest. Coniferous forest mainly includes larch (*Larix gmelinii* Rupr.), fir (*A. nephrolepis*), Korean pine (*Pinus koraiensis* Siebold & Zucc.), and spruce (*P. koraiensis*). The region falls under the boreal continental climate and is characterized by the southern border of the discontinuous permafrost zone (Shi et al., 2001; Cai et al., 2012).

Manchurian fir and Korean spruce provide timber, plywood and veneer, soundboards for musical instruments, and raw materials for the pulp industry. The versatility in their uses requires accurate estimates of diameter and volume for different merchantability limits, which is not possible with the conventional volume tables. Besides timber production, forest management objectives in China include biodiversity conservation, soil protection, and carbon sequestration (Dong et al., 2019). Taper models have been used to estimate tree volume and biomass simultaneously, which allows for extending the timber inventories to ecological studies (MacFarlane and Weiskittel, 2016). In this context, stem taper models are required for the sustainable management of these species to support the industrial and ecological advances in Chinese forestry.

Stem taper models can predict the stem diameter (d) accurately at any height (h), along with merchantable and total stem volumes (Trincado and Burkhart, 2006; Li and Weiskittel, 2010). These models supersede the volume models as they can estimate d, merchantable height to any diameter above ground, the volume of a log at any length, and at any height from the ground beside the merchantable and total stem volume (Kozak, 2004). Additionally, taper models are useful in timber quality studies and modeling of carbon allocation in different stem sections. They are also helpful in assessing the impact of a silvicultural treatment on stem taper (Fonweban et al., 2011).

Since the last century, many taper models have been developed. At present, a detailed discussion is available about different types and forms of these models (e.g. Sakici et al., 2008; Crecente-Campo et al., 2009; Burkhart et al., 2019). Of the many model forms, segmented or variable form taper models are often recommended based on taper studies (Berhe and Arnoldsson, 2008; Özcelik and Brooks, 2012; Sakici and Ozdemir, 2018). Rojo et al. (2005) and Sakici et al. (2008) suggested variable form taper models for maritime pine (*Pinus pinaster)* in Spain and Bornmullerian fir (*Abies nordmanniana* subsp. *bornmulleriana*) in Turkey, respectively. However, they did not evaluate the taper models for volume estimates. Doyog et al. (2017) recommended variable form models for diameter and volume estimates of Japanese larch (*Larix kaempferi*) in South Korea. Some studies ranked the segmented models higher than variable form models, e.g., Diéguez-Aranda et al. (2006) for scots pine (*Pinus sylvestris*) in northwestern Spain and Özcelik and Dirican (2017) for Lebanon cedar (*Cedrus libani*) and Cilicica fir (*Abies cilicica*) in Bucak region, Turkey. Simultaneously, segmented and variable form models showed a similar response for Kazdagi fir (*Abies nordmanniana* subsp. *equi-trojani*) and Oriental beech (*Fagus orientalis*) in Turkey (Sakici and Ozdemir, 2018), and white birch (*Betula platyphylla*) in NE China (Shahzad et al., 2019). Therefore, it is useful to perform a systematic analysis of these taper models so that their application should be extended to other species.

Several taper studies have accounted for the fir and spruce species in the world (Kozak et al., 1969; Newnham, 1992; Sharma and Zhang, 2004; Westfall and Scott, 2010; Li et al., 2012; Ung et al., 2013; Özcelik et al., 2019). These studies covered Engelmann spruce (*Picea engelmannii*), white spruce (*Picea glauca*), black spruce (*Picea marina*), Norway spruce (*Picea abies*), red spruce (*Picea rubens*), alpine fir (*Abies lasiocarpa*), and balsam fir (*Abies balsamea*) growing in different countries. As far as we know, taper models do not exist for *Abies nephrolepis* and *Picea koraiensis*. This study aimed to assess the performance of eight famous taper models and select the best model that could deliver accurate predictions of diameter at any height, total volume, and merchantable stem volume of Manchurian fir and Korean spruce in NE China.

MATERIAL AND METHODS

Study area

The study site is located in Taipinggou forest farm (130°31′ –130°50′ E, 48°3′ –48°21′ N), administered by Dahailin forest bureau of Heilongjiang province, NE China. The size of study area is 27642 ha. The elevation range of the area is 72 to 556 m above sea level. The prevailing climate is continental with summer monsoon. The temperature varies from to -40°C in winter to 36°C in summer. The average annual precipitation is about 596 mm, and around 111 days is a frost-free period. The predominant forest types are *Larix gmelinii*, *Picea koraiensis*, *Abies nephrolepis*, and deciduous broadleaf mixed forest. Other prominent species include *Pinus koraiensis*, *Picea jezoensis*, *Fraxinus mandshurica*, *Phellodendron amurense*, *Quercus mongolica, Ulmus japonica*, *Acer mono*, *Betula costata, B. davurica*, *B. platyphylla, Tilia amurensis*, and *Populus davidiana* (Tan et al., 2007; Ma et al. 2014). The typical soil of the area is dark brown forest soil (Burger and Shidong, 1988).

Data description

A sample of 188 trees was selected from uneven-aged natural stands of Manchurian fir and Korean spruce. The sampled trees covered the existing range of diameter and height classes. Diameter at breast height over bark (D, 1.3 m) was measured to the nearest 0.1 cm for all trees. Trees were felled to measure total heights (H) and diameters over bark (d) at the heights (h) of 0.3, 0.6, 1, 1.3, and 2 m. After the height of 2 m, d measurements were taken at a fixed distance of 1 m. Measurement range fluctuated from 0.3 to 1 m along the stem except for the top section, which was considered as a cone. Smalian's formula was used to calculate log volumes that were added to the volume of the cone to get total stem volume. The summary statistics of the datasets are shown in Tab.1.

Tab. 1 Summary statistics of the datasets by species.

Species	Variable*	n	Min	Mean	Max	SD
Manchurian Fir	D (cm)	123	17.1	25.6	37.7	3.8
	H (m)	123	10.1	17.2	23.6	1.7
	d (cm)	2339	0.5	19.5	46.9	8.1
	h (m)	2339	0.3	7.5	23.6	5.4
Korean Spruce	D (cm)	65	10.0	25.9	42.0	5.6
	H (m)	65	9.1	17.3	21.4	2.1
	d (cm)	1231	0.2	19.8	59.0	8.8
	h (m)	1231	0.3	7.4	21.4	5.5

*D, diameter at breast height over bark; H, total tree height; d, diameter at height h over bark; SD, Standard deviation.

Taper models

Eight taper models were selected from the literature (Sakici et al., 2008; Li and Weiskittel, 2010; Özcelik and Crecente-Campo, 2016). These models represent four segmented (Max and Burkhart, 1976; Clark et al., 1991; Fang et al., 2000) and four variable form taper models (Bi, 2000; Lee et al., 2003; Kozak, 2004; Sharma and Parton, 2009). Table 2 shows the selected taper models along with the source of each model.

The model of Clark et al. (1991) requires an additional measurement of diameter at 5.3 m height. At first, these measurements were attained by linear interpolation (Figueiredo-Filho et al. 1996; Li and Weiskittel 2010), as actual diameter measurements at 5.3 m were not available. Afterward, they were predicted with the equation proposed by Clark et al. (1991) (Tab. 2). The Clark et al. (1991) Model 1 and Clark et al. (1991) Model 2 represented interpolation and prediction methods, respectively.

The selected models have shown good results for many species. For example, Max and Burkhart (1976) for

Tab. 2 Tested stem taper models.

Models	
Max and Burkhart (1976)	
$d = D\left[b_1(Z-1)+b_2(Z^2-1)+b_3(a_1-Z)^2 I_1+b_4(a_2-Z)^2 I_2\right]^{0.5}$	[1]
$\begin{cases} I_1 = 1, \text{if } Z \le a_1; 0 \text{ otherwise} \\ I_2 = 1, \text{if } Z \le a_2; 0 \text{ otherwise} \end{cases}$	[1.1]
Clark et al. (1991)	
$d = \begin{cases} I_S\left[D^2\left(1+(b_2+b_3/D^3)((1-Z)^{b_1}-(1-1.3/H)^{b_1})/(1-(1-1.3/H)^{b_1})\right)\right] \\ +I_B\left[D^2-(D^2-F^2)((1-1.3/H)^{b_4}-(1-Z)^{b_4})/(1-1.3/H)^{b_4}-(1-5.3/H)^{b_4}\right] \\ +I_T\left[F^2\left(b_6((h-5.3/H-5.3)-1)^2+I_M(1-b_6/b_5^2)(b_5-(h-5.3/H-5.3))^2\right)\right] \end{cases}$	[2]
$I_S = \begin{cases} 1 & h < 1.3 \\ 0 & \text{otherwise} \end{cases}$	[2.1]
$I_T = \begin{cases} 1 & h > 5.3 \\ 0 & \text{otherwise} \end{cases}$	[2.2]
$I_M = \begin{cases} 1 & h < (5.3 + b_5(H-5.3)) \\ 0 & \text{otherwise} \end{cases}$	[2.3]
$F: F = D(a_1 + a_2(5.3/H)^2)$	[3]**
Fang et al. (2000)	
$d = c_1\sqrt{H^{(k-b_1)/b_1}(1-Z)^{(k-b)/b} q_1^{I_1+I_2} q_2^{I_2}}$	[4]
$c_1 = \sqrt{a_0 D^{a_1} H^{(a_2-k)/b_1} / b_1(t_0-t_1) + b_2(t_1-q_1 t_2) + b_3 q_1 t_2}$	[4.1]
$\begin{cases} q_1 = (1-p_1)^{(b_2-b_1)k/b_1 b_2} \\ q_2 = (1-p_2)^{(b_3-b_2)k/b_2 b_3} \end{cases}$	[4.2]
$\begin{cases} t_1 = (1-p_1)^{k/b_1} \\ t_2 = (1-p_2)^{k/b_2} \end{cases}$	[4.3]
$t_0 = 1$	[4.4]
$\begin{cases} I_1 = 1, \text{ if } p_2 \ge Z \ge p_1; 0 \text{ otherwise} \\ I_2 = 1, \text{ if } 1 \ge Z \ge p_2; 0 \text{ otherwise} \end{cases}$	[4.5]
$b = b_1^{1-(I_1+I_2)} b_2^{I_1} b_3^{I_2}, k = 0.0000785, Z = h/H$	[4.6]
Bi (2000)	
$d = D\left[\ln\sin\left(\frac{\pi}{2}Z\right)/\ln\sin\left(\frac{\pi}{2}t\right)\right]^{b_0+b_1\sin\left(\frac{\pi}{2}Z\right)+b_2\cos\left(\frac{3\pi}{2}Z\right)+b_3\sin\left(\frac{\pi}{2}Z\right)/Z+b_4 D+b_5 Z\sqrt{D}+b_6 Z\sqrt{H}}$	[5]
Lee et al. (2003)	
$d = b_1 D^{b_2}(1-Z)^{b_3 Z^2+b_4 Z+b_5}$	[6]
Kozak (2004)	
$d = b_0 D^{b_1} H^{b_2} x^{b_3 Z^4+b_4(1/e^{D/H})+b_5 x^{0.1}+b_6(1/D)+b_7 H^w+b_8 x}$	[7]
$x = w/(1-(1.3/H)^{1/3}), w = 1-Z^{1/3}$	[7.1]
Sharma and Parton (2009)	
$d = D\left[b_0\left(\frac{H-h}{H-1.3}\right)\left(\frac{h}{1.3}\right)^{b_1+b_2 Z+b_3 Z^2}\right]$	[8]

*D, diameter at breast height over bark (cm); H, total tree height (m); h, height above ground (m); d, diameter at height h over bark (cm); Z, h/H; t, 1.3/H; a_i, b_i, and pi are model parameters.
** F = diameter at 5.3 m height, b_i = regression coefficients for different stem sections i.e., b_1, b_2, and b_3 for < 1.3 m, b_4 for 1.3 to 5.3 m, and b_5, b_6 for > 5.3 m. Clark et al. (1991) proposed an equation to predict

Lebanon cedar (Cedrus libani) and Cilicica fir (Abies cilicica) in Turkey; Clark et al. (1991), Fang et al. (2000), and Bi (2000) for balsam fir (Abies balsamea), red spruce (Picea rubens), and white pine (Pinus strobus) in North America; and Kozak (2004) for several conifer species including balsam fir, red spruce, black spruce, and jack pine in North America (Brooks et al., 2008; Li and Weiskittel, 2010; Li et al., 2012).

Model fitting

The model parameters were estimated with the MODEL procedure of SAS using the generalized non-linear least-squares method (SAS Institute Inc. 2008). It was rational to expect spatial correlation within the observations due to hierarchical data of the study. We instituted a first-order continuous autoregressive error structure (CAR (1)) to adjust the innate autocorrelation in the data. This specified error structure allows the practical use of a model for irregularly spaced and unbalanced data (Grégoire et al., 1995). The multicollinearity in the models was assessed by using condition numbers. Programming for CAR (1) structure was worked out in the MODEL procedure of SAS (SAS Institute Inc. 2008).

Model comparisons

The accuracy of diameter and volume estimates was evaluated by graphical and numerical assessments of the residuals. The measured diameters were used to calculate sectional volumes, which were added to obtain observed total and merchantable volumes. Similarly, the predicted diameters were utilized to calculate the predicted total and merchantable volumes. For merchantable volume, the merchantable height was 90% of the total height (H_{90}). We used interpolation to estimate the top diameter at that height (H_{90}). Both observed and predicted volumes (total and merchantable) were calculated with Smalian's formula, as in similar studies (Li et al., 2012; Schröder et al., 2014). Three goodness-of-fit statistics were calculated: mean percentage of bias (MPB), root mean square error (RMSE), and Fit index (FI). The notations for these statistics are as under; Where y_i, $\hat{y}_i$ and $\bar{y}_i$ stand for measured, predicted, and average values of the response variable, respectively; n symbolizes the total number of observations, and p is the number of parameters.

$$MPB = 100 \times \frac{\sum_{i=1}^{n} |y_i - \hat{y}_i|}{\sum_{i=1}^{n} y_i} \quad [9]$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n - p}} \quad [10]$$

$$FI = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y}_i)^2} \quad [11]$$

The models were also assessed by box plots of d residuals against position (relative heights of 5%, 15%, 25%, up to 95%). Likewise, the total volume residuals were plotted against diameter classes. These graphs portray the domains of inadequate or acceptable estimates (Kozak and Smith, 1993).

Model validation

For comparing taper models, Kozak and Kozak (2003) used two methods based on the analysis of fit statistics or prediction errors obtained from ordinary residuals. The first method relies on the entire dataset, while the second method uses a validation dataset. Kozak and Kozak (2003) suggested that the validation data rarely provides additional information compared to the method based on the entire dataset. Accordingly, in this study, we used entire data sets for model evaluation.

Ranking of models

The models were compared using the ranking method of Poudel and Cao (2013). Where R_i indicates the relative rank of a model i (i = 1, 2, 3…m), S_i is the goodness of fit statistics delivered by model i, and S_{max} and S_{min} correspond to the maximum and minimum values of S_i. Rank 1 represents the best model, while m shows the poorest model. The ranking method was applied using MPB, RMSE, and FI statistics for diameter, total volume, and merchantable volume to calculate the average rank of each model. Next, the mean of average ranks was taken to determine the overall ranks of the models for the four variables.

$$R_i = 1 + \frac{(m - 1)(S_i - S_{\min})}{S_{\max} - S_{\min}} \quad [12]$$

RESULTS

The initial fitting of the models without the error structure resulted in significant autocorrelation at lag–1 (Figure 1a), which suggests that the residual series follows a first-order continuous autoregressive error structure CAR (1) process. This correlation trend was accounted for when a CAR (1) was added in the model fit (Fig. 1b).

All parameters were significantly different to zero at 5% of significance level (α =0.05) (Tab. 3, 4). The removal of nonsignificant parameters did not affect the RMSEs in the Bi (2000) and Kozak (2004) models. Thus, they were taken as such in the models. Tab. 5 highlights the fit-statistics and condition number of the models. The models of Clark et al. (1991) Model 1, Clark et al. (1991) Model 2, Kozak (2004), Max and Burkhart (1976), and Fang et al. (2000) showed the lowest ranges of RMSE (0.89–1.15 cm) and MPB (3.16%–3.80%) in estimating diameter for both species. The RMSEs of these models were almost 7% lower than the rest of the models. The models of Bi (2000) and Sharma and Parton (2009) were less accurate, although they fit the data well. The extent of multicollinearity in the models was low to moderate except for the Bi (2000), which showed relatively higher condition numbers.

In predicting volume, Clark et al. (1991) Model 1 sustained the top position (Tab. 6). For total and merchantable volume, its RMSEs were above 13% and 9% lower than the next best models, Clark et al. (1991) Model 2 and Kozak (2004) for Manchurian fir and Korean spruce, respectively. The models of Fang et al. (2000), Max and Burkhart (1976), and Bi (2000) produced good results with competitive values (RMSE, 0.0094–0.0137m^3 and MPB,

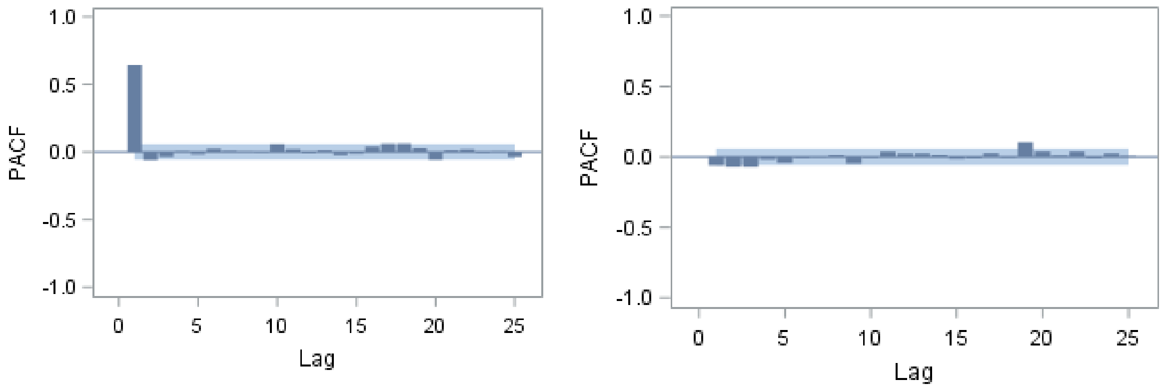

Fig. 1 An example of partial autocorrelation plotted against lag for Clark et al. (1991) Model 1 fit without considering the autocorrelation parameters (a) and using a first-order (b) continuous autoregressive error structure for Korean spruce.

Tab. 3 Parameter estimates with approximate standard errors for Manchurian fir.

	Max and Burkhart (1976)		Clark et al. (1991) Model 1		Clark et al. (1991) Model 2		Fang et al. (2000)	
	Estimate	Approx. std. error	Estimate	Approx. std. error	Estimate	Approx. std. error	Estimate	Approx. std. error
a_0							2×10^{-5}	3.0E-6
a_1	0.752	0.050			0.858	0.004	2.075	0.048
a_2	0.047	0.001			0.555	0.044	1.133	0.069
b_1	-2.699	0.308	37.590	1.416	37.594	1.418	7.505	1.7E-7
b_2	1.152	0.175	0.671	0.016	0.671	0.016	3×10^{-5}	4.0E-7
b_3	-0.685	0.180	-1263.01	236.4	-1263.61	237.3	6×10^{-5}	7.9E-6
b_4	193.832	10.490	1.986	0.453	2.030	0.462		
b_5			1.026	0.012	1.037	0.014		
b_6			-10.126	4.931	-6.798	2.859		
p_1							0.041	0.001
p_2							0.957	0.006
	Bi (2000)		Lee et al. (2003)		Kozak (2004)		Sharma and Parton (2009)	
	Estimate	Approx. std. error	Estimate	Approx. std. error	Estimate	Approx. std. error	Estimate	Approx. std. error
b_0	-0.714	0.138			1.060	0.116	1.055	0.004
b_1	*0.034*	0.083	1.072	0.071	0.948	0.033	-0.006	1×10^{-4}
b_2	0.032	0.011	1.050	0.020	0.049*	0.050	0.134	0.022
b_3	0.473	0.087	1.832	0.148	0.283	0.024	0.010	0.030
b_4	0.001	2×10^{-4}	-2.847	0.195	0.265*	0.203		
b_5	0.017*	0.022	1.886	0.068	0.716	0.040		
b_6	0.094	0.038			-6.561	1.289		
b_7					0.002*	0.002		
b_8					-0.131	0.029		

*non-significant parameters at α =0.05.

1.707%–2.127% for total volume; RMSE, 0.0106–0.014m³ and MPB, 1.912%–2.232% for merchantable volume). The model of Lee et al. (2003) indicated the largest variability across the datasets. Results also showed that the Clark et al. (1991) Model 1 (interpolation method) performed better than the Clark et al. (1991) Model 2 (prediction method).

According to the average rank of diameter and volume estimates, Clark et al. (1991) Model 1 showed the lowest rank for both species (Tab. 7). When diameter measurements at 5.3m were not available, the models of Fang et al. (2000), Kozak (2004), and Max and Burkhart (1976) performed well for Manchurian fir with a similar rank, while the latter two were the leading models for Korean spruce. The rank of Clark et al. (1991) Model 2 was higher than the Clark et al. (1991) Model 1.

The box plots of *d* residuals against relative height classes reflected that the error distribution was almost similar across the models (Fig. 2, 3). The Clark et al. (1991) Model 1 best predicted the *d* at all points. The models of Clark et al. (1991) Model 2, Max and Burkhart (1976), Kozak (2004), Fang et al. (2000), and Bi (2000) delivered good estimates for the lower and middle sections in Manchurian fir. There was a general tendency of underestimation at 25–45% relative heights. However, the Clark et al. (1991) Model 1 showed minimum distortion for these classes. The model of Kozak (2004) provided slightly biased predictions near the ground (<20%) for both species.

Tab. 4 Parameter estimates with approximate standard errors for Korean spruce.

	Max and Burkhart (1976)		Clark et al. (1991) Model 1		Clark et al. (1991) Model 2		Fang et al. (2000)	
	Estimate	Approx. std. error	Estimate	Approx. std. error	Estimate	Approx. std. error	Estimate	Approx. std. error
a_0							3×10^{-5}	7.7E-6
a_1	0.841	0.028			0.872	0.007	1.889	0.056
a_2	0.056	0.002			0.755	0.071	1.165	0.109
b_1	-4.965	0.856	30.39	1.883	30.46	1.888	9.417	3.043
b_2	2.416	0.461	0.666	0.016	0.666	0.016	3×10^{-5}	7.6E-7
b_3	-1.960	0.461	524.26	177.0	524.48	177.5	3×10^{-5}	8.1E-7
b_4	170.87	12.84	4.383	0.749	4.290	0.787		
b_5			0.784	0.024	0.777	0.027		
b_6			2.413	0.170	2.241	0.182		
p_1							0.074	0.002
p_2							0.565	0.028

	Bi (2000)		Lee et al. (2003)		Kozak (2004)		Sharma and Parton (2009)	
	Estimate	Approx. std. error	Estimate	Approx. std. error	Estimate	Approx. std. error	Estimate	Approx. std. error
b_0	-0.256	0.191			0.661	0.072	1.093	0.007
b_1	0.318	0.114	1.453	0.102	0.866	0.031	-0.006	3×10^{-4}
b_2	0.087	0.019	0.967	0.021	0.315	0.054	0.125	0.037
b_3	0.177*	0.119	3.095	0.251	0.433	0.032	0.109	0.049
b_4	-1×10^{-4}*	3×10^{-4}	-4.377	0.314	-0.512	0.128		
b_5	0.097	0.021	2.371	0.102	0.592	0.033		
b_6	-0.089*	0.047			-0.007	9×10^{-4}		
b_7					0.661	0.072		

*non-significant parameters at $\alpha=0.05$.

Tab. 5 Fit statistics of taper models in estimating diameter (cm).

Models*	Manchurian fir				Korean spruce			
	MPB	RMSE	FI	CN*	MPB	RMSE	FI	CN
Max and Burkhart (1976)	3.2697	0.9175	0.9871	108	3.5932	1.0965	0.9845	190
Clark et al. (1991) Model 1	3.1607	0.8932	0.9878	18	3.4374	1.0545	0.9857	4
Clark et al. (1991) Model 2	3.2370	0.9046	0.9875	12	3.6054	1.0808	0.9849	3
Fang et al. (2000)	3.2941	0.9387	0.9865	107	3.7924	1.1511	0.9830	109
Bi (2000)	3.4599	0.9952	0.9848	383	3.9337	1.2439	0.9801	321
Lee et al. (2003)	3.8953	1.1060	0.9813	53	4.1621	1.2420	0.9801	40
Kozak (2004)	3.2453	0.9080	0.9874	186	3.5697	1.1010	0.9844	109
Sharma and Parton (2009)	3.4265	0.9590	0.9859	5	3.7844	1.1593	0.9827	6

*Clark et al. (1991) Model 1, diameters at 5.3 m were obtained by linear interpolation; Clark et al. (1991) Model 2, diameters at 5.3 m were obtained by prediction method; CN, condition number.

Tab. 6 Evaluation statistics of taper models in estimating total and merchantable stem volume.

Models*	Manchurian fir				Korean spruce			
	Vol (T)*		Vol (M)*		Vol (T)		Vol (M)	
	MPB	RMSE	MPB	RMSE	MPB	RMSE	MPB	RMSE
Max and Burkhart (1976)	1.7881	0.0097	2.0165	0.0111	2.0055	0.0132	2.0929	0.0135
Clark et al. (1991) Model 1	1.4078	0.0078	1.6742	0.0096	1.7051	0.0103	1.8268	0.0112
Clark et al. (1991) Model 2	1.6512	0.0090	1.9006	0.0106	2.0682	0.0126	2.2004	0.0133
Fang et al. (2000)	1.7073	0.0094	1.9125	0.0106	2.1270	0.0137	2.2323	0.0140
Bi (2000)	1.8481	0.0104	2.0400	0.0117	2.0691	0.0133	2.1225	0.0139
Lee et al. (2003)	2.4288	0.0132	2.6347	0.0143	2.3957	0.0151	2.5093	0.0156
Kozak (2004)	1.7665	0.0099	1.9630	0.0113	1.9710	0.0120	2.0428	0.0125
Sharma and Parton (2009)	1.9678	0.0105	2.1941	0.0120	2.0500	0.0141	2.0930	0.0141

*Vol (T), total volume (m3); Vol (M), merchantable volume (m^3).

Tab. 7 Average ranks of the models by attribute from Tables 5–6 and final average rank.

Models*	Manchurian fir				Korean spruce			
	Taper	V (T)*	V (M)*	Av. Rank	Taper	V (T)	V (M)	Av. Rank
Max and Burkhart (1976)	1.86	3.53	3.36	2.92	2.51	4.63	4.19	3.78
Clark et al. (1991) Model 1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Clark et al. (1991) Model 2	1.47	2.61	2.57	2.22	2.20	4.51	4.58	3.76
Fang et al. (2000)	2.39	3.06	2.62	2.69	4.45	5.62	5.30	5.12
Bi (2000)	4.14	4.19	3.89	4.07	7.26	5.03	4.66	5.65
Lee et al. (2003)	8.00	8.00	8.00	8.00	7.98	8.00	8.00	7.99
Kozak (2004)	1.58	3.59	3.32	2.83	2.54	3.58	3.14	3.09
Sharma and Parton (2009)	3.25	4.67	4.68	4.27	4.66	5.51	4.67	4.95

*V (T), total volume; V (M), merchantable volume.

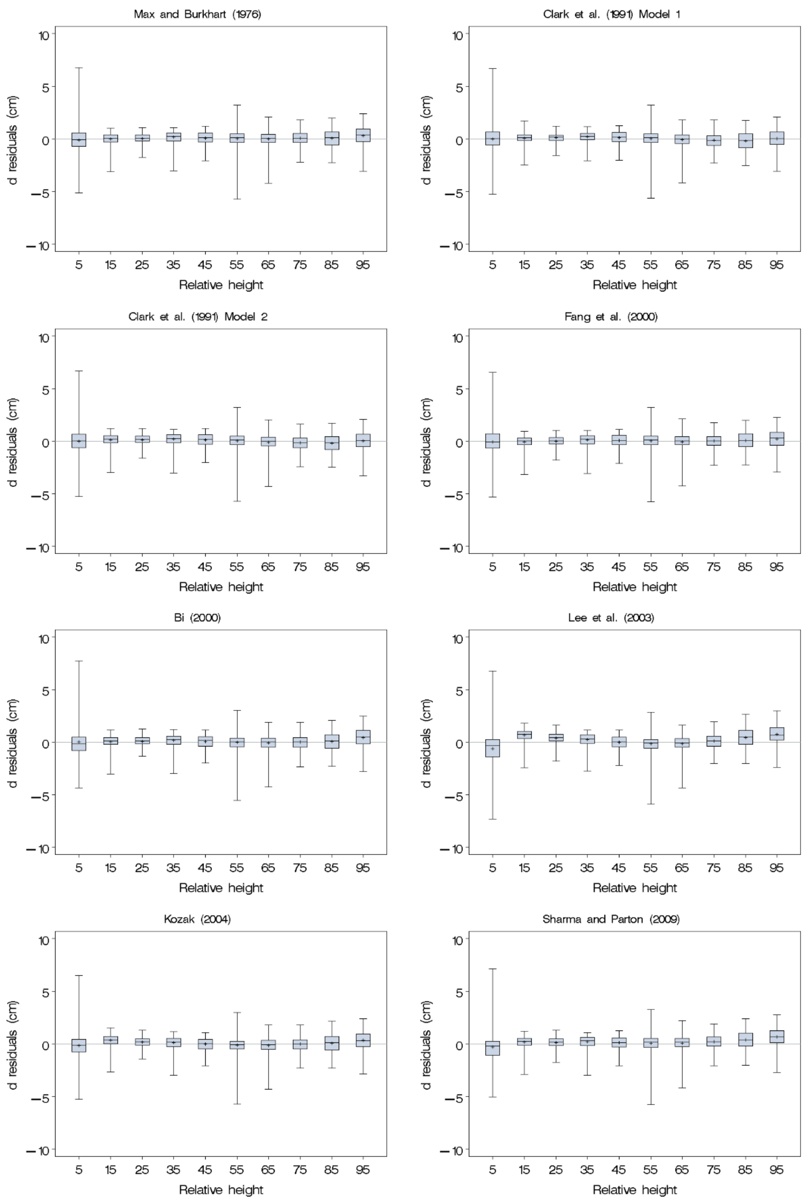

Fig. 2 Box plots of d residuals (cm) against relative heights for Manchurian Fir.

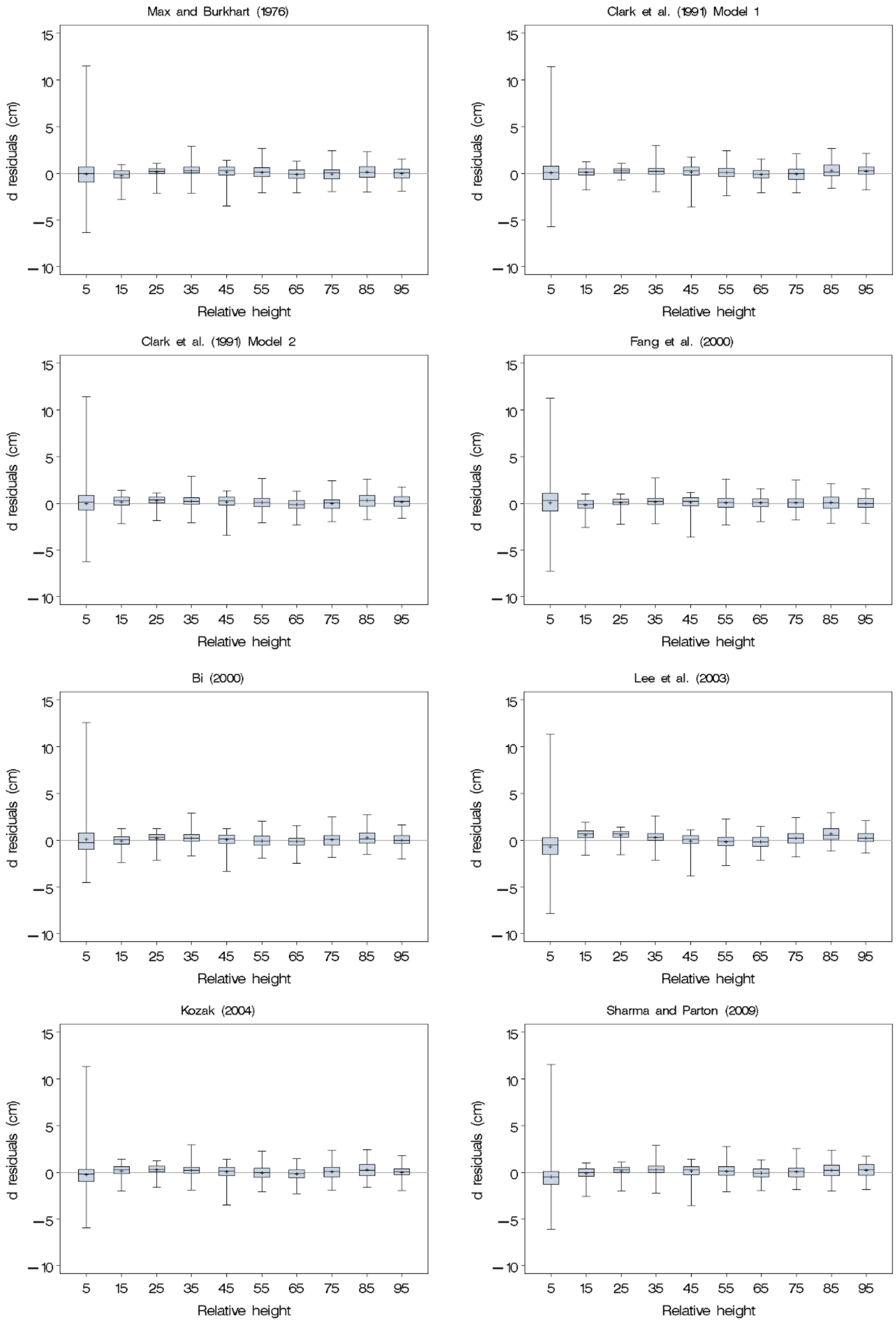

Fig. 3 Box plots of d residuals (cm) against relative heights for Korean Spruce.

The Clark et al. (1991) Model 1 predicted the total volume more accurately for all diameter classes (Fig. 4, 5). All models underestimated the 20–25 cm diameter class and overestimated the largest trees (>30 cm). The models of Clark et al. (1991) Model 2, Kozak (2004), Fang et al. (2000), and Bi (2000) provided relatively better estimates depending upon the diameter classes and the species. The models of Lee et al. (2003) and Sharma and Parton (2009) appeared to be inappropriate for this variable.

DISCUSSION

There are many references to taper studies of fir and spruce species growing in the boreal forests of the world. However, the available studies have not covered Manchurian fir and Korean spruce. This study presents stem taper models for these species, for which only biomass has been modeled so far (Dong et al., 2014; Wang et al., 2018).

The addition of CAR (1) in model fitting accounted for the correlated errors. Kozak (1997) suggested that the

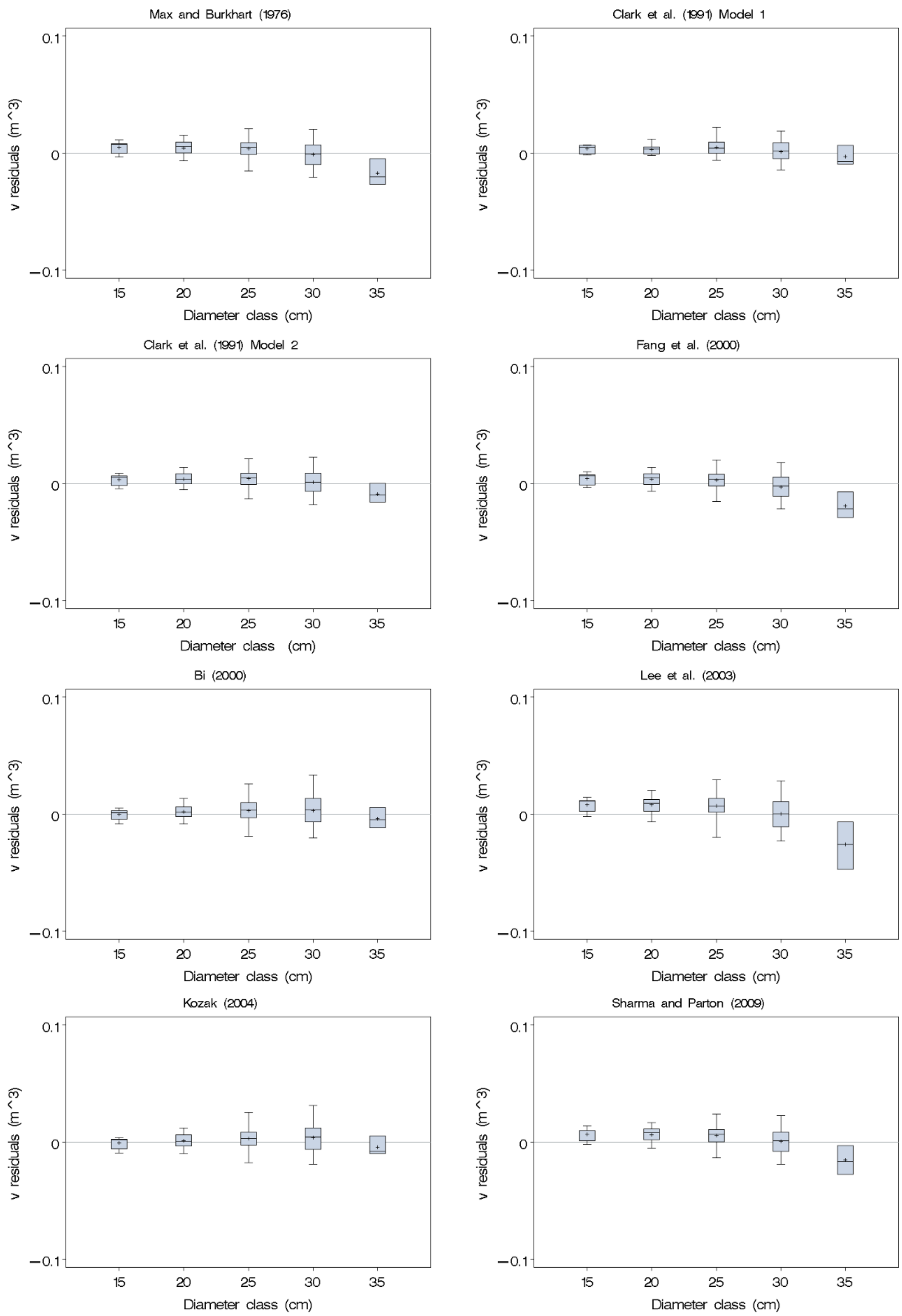

Fig. 4 Box plots of total volume residuals (m^3) against diameter classes (cm) for Manchurian Fir.

correlated error structure marginally affects the prediction accuracy of the models. Therefore, autocorrelation is usually ignored in practical applications (Rojo et al. 2005). Among the models evaluated, Clark et al. (1991) Model 1 best predicted the diameter and total or merchantable volumes across the datasets. The Clark et al. (1991) Model 1 decreased the RMSE by 13.33% and 9.43% in estimating total and merchantable volumes of Manchurian fir when compared to the next best model (Clark et al. 1991 Model 2). For total and merchantable volumes of Korean spruce, it provided the RMSEs that were 14.16% and 10.4% lower than the next performer (Kozak 2004). Additionally, the condition number of Clark et al. (1991) Model 1 stayed within the acceptable limit ($<1000^{0.5}$), a criterion proposed by Myers (1990). The condition numbers of Max and Burkhart (1976), Fang et al. (2000), Bi (2000), and Kozak (2004) models showed higher multicollinearity. However, the issue of multicollinearity was limited in the models. The values of condition numbers

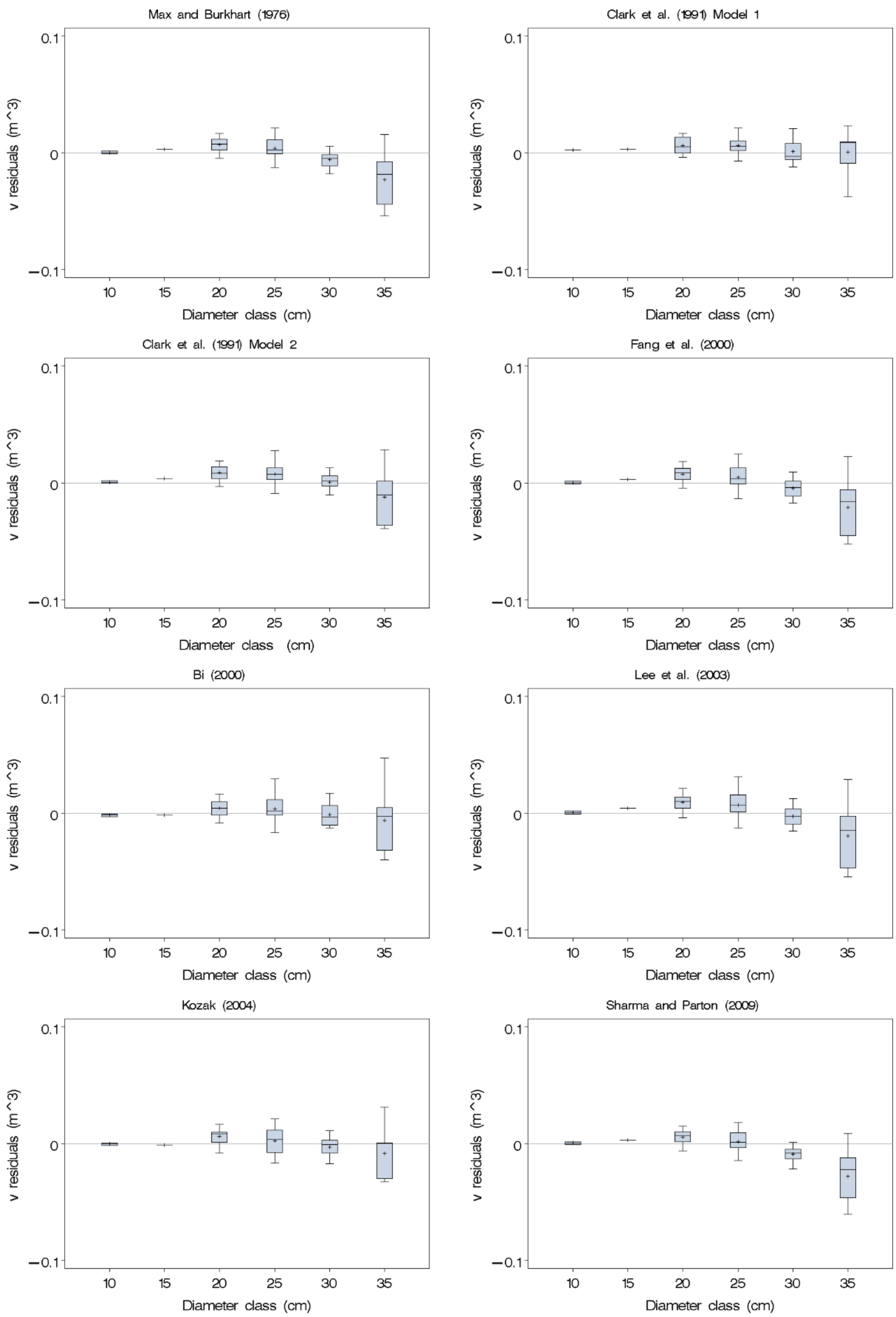

Fig. 5 Box plots of total volume residuals (m^3) against diameter classes (cm) for Korean Spruce.

were far below the range (1,000-3,000) suggested by Belsey (1991) as an indicator of severe multicollinearity issues. Although multicollinearity is not a decisive factor in the analysis of taper models, Kozak (1997) recommended that a model bearing less multicollinearity should be preferred.

The model of Clark et al. (1991) showed the best predictions across the relative height classes and diameter classes of both species (Fig. 2-5). As a whole, the models showed larger prediction errors near the ground (<10%) and at 55-65% relative heights of Manchurian fir. This deviation might be attributed to the fact that these relative height classes were associated with butt swell and the base of the live crown of sampled trees (Jiang et al. 2005). The models of Clark et al. (1991) Model 2, Max and Burkhart (1976), Kozak (2004), and Fang et al. (2000) showed god results with varying predictions depending on the variables and species. However, these models were less accurate for the lower or middle stem sections and larger trees, particularly for Korean spruce. The prediction accuracy in this part is important since it accumulates the maximum volume. Crecente-Campo et al. (2009) and Schröder et al. (2014) observed a similar pattern of diameter residuals in the models of Kozak (2004), Fang et al. (2000), and Max and Burkhart (1976) for other conifer species. Diéguez-Aranda et al. (2006) and Barrio Anta et al. (2007) observed similar errors for bigger trees. Schröder et al. (2014) attributed this anomaly to the difference in site and competition conditions that affect individual trees.

The model of Clark et al. (1991) is comprised of Schlaegel's form-class model, and Max and Burkhart's segmented model. Schlaegel's model contains Girard's form class height (5.3m above ground), which enables a single species model to predict taper formation accurately in different geographic or physiographic regions. Clark et al. (1991) tested their model for 58 tree species, including several conifers in seven regions of southern USA. The volume estimates of their model were very similar to the results of region-specific models. On the other hand, Westfall and Scott (2010) developed a mixed model for white spruce (*Picea glauca*), black spruce (*P. mariana*), red spruce (*P. rubens*), Norway spruce (*P. abies*), and balsam fir (*Abies balsamea*) in 13 states of northeastern USA. Although Westfall and Scott's (2010) model compared well with the Clark et al. (1991) model in volume estimates, it was less accurate than the locally calibrated models.

Li and Weiskittel (2010) carried out a similar analysis for balsam fir (*Abies balsamea*), red spruce (*Picea rubens*), and white pine (*Pinus strobus*) in North America. They observed that Kozak (2004) and Bi (2000) models best predicted the diameters while Clark et al. (1991) Model 1 showed the best results for volume estimates. Moreover, they found Max and Burkhart (1976) model as the poorest performer. In our analysis, Clark et al. (1991) Model 1 delivered the best predictions for all variables, and Max and Burkhart (1976) model performed well. In that study, the RMSEs of Clark et al. (1991) Model 2 were significantly higher than Clark et al. (1991) Model 1 in estimating diameter and volume (7.58%–14.24% for diameter and 26%–42% for total volume). Therefore, they preferred other well-behaved models to the prediction method. In this study, Clark et al. (1991) Model 2 increased the RMSEs by 1.26%–2.43% for diameter estimates and 13%–18% for total volume estimates, compared to Clark et al. (1991) Model 1. Although Clark et al. (1991) Model 2 was less accurate, it was still better or similar to other good performers. In case, diameter measurements at 5.3 m height are not available, other well-behaved models can be used as recommended by Li and Weiskittel (2010) and Özcelik and Crecente-Campo (2016). In this analysis, the models of Kozak (2004) and Max and Burkhart (1976) were superior to other equations in estimating diameter for both species and volume of Korean spruce. However, the model of Fang et al. (2000) performed better for volume estimates of Manchurian fir.

Similar to our study, Özcelik and Brooks (2012) suggested that Clark et al. (1991) Model 2 performed better than Max and Burkhart (1976) for Cilicica fir (*Abies cilicica*) in Isparta region, Turkey. Sakici et al. (2008) evaluated different taper models for diameter estimates of Bornmullerian fir (*Abies nordmanniana* subsp. bornmulleriana) in the Black Sea region, Turkey. They assigned a similar rank to Clark et al. (1991) Model 1 and Kozak (2004), which was not the same in this analysis. Doyog et al. (2017) ranked Clark et al. (1991) Model 2 lower than Kozak (2004) model in predicting the diameter and volume of Japanese larch (*Larix kaempferi*) in Central South Korea. However, we received similar results from these models.

Besides the diameter prediction, a taper model should also estimate stem volume accurately. We used Smalian's formula to acquire the actual stem volume, although it overestimates the volume, particularly in bigger trees (Figueiredo-Filho and Schaaf 1999). Using the Smalian's formula was considered admissible since the measurements traversed the whole stem, and they were less than or equal to 1 m apart (Li and Weiskittel 2010). Additional measurements, less than 1 m apart, were recorded for the basal log.

Finally, the Clark et al. (1991) Model 1 was the most suitable model for predicting the diameter and total or merchantable volumes of Korean spruce and Manchurian fir in NE China. Previously, Figueiredo-Filho et al. (1996) and Figueiredo-Filho and Schaaf (1999) recommended this model for diameter and volume estimates of loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*) in Brazil. Özcelik and Brooks (2012) and Özcelik and Crecente-Campo (2016) recommended this model for Cilicica fir (*Abies cilicica*), Lebanon cedar (*Cedrus libani*), and pine species (*Pinus brutia*, *Pinus nigra*, *Pinus sylvestris*) in Turkey. For Clark et al. (1991) Model 1, there were significant differences between the two species ($P < 0.0001$) using F-test (Neter et al., 1996), so separate parameter estimates by species were needed.

CONCLUSION

This study evaluated eight taper models for Manchurian fir and Korean spruce in NE China. Among the models evaluated, the Clark et al. (1991) Model 1 and Model 2 delivered excellent results across the datasets. However, the Clark et al. (1991) Model l was more accurate in estimating the diameter at any height and merchantable or total volumes of both species. As an additional benefit, this model is compatible, which can be integrated to estimate merchantable and total volume. The models of Kozak (2004), Max and Burkhart (1976), and Fang et al. (2000) performed reasonably well but behaved differently for different variables and species. The selection of the best model depends on the user. However, when diameter measurements at 5.3 m are not available, Clark et al. (1991) Model 2 still performs better or similar to Kozak (2004) and Fang et al. (2000) models for both species. Manchurian fir and Korean spruce are widely distributed in NE China. Our conclusions might not suffice for the entire region, given the small sample size and significant geographic changes within NE China. Further analysis with a larger sample can extend the scope of this study. We believe this work would contribute to the sustainable management of Manchurian fir and Korean spruce not only in China but also in other countries maintaining these species.

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AUTHORSHIP CONTRIBUTION

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Processing: AH, LJ, FL

Analysis: LJ

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Review: MKS

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