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CALIBRATING A TAPER MODEL FOR ORIENTAL SPRUCE IN TURKEY

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HIGHLIGHTS

A modified form of Max and Burkhart's (1976) taper model was used in this study.

We tested all combinations of five fitting methods and six adjustment strategies.

Mixed results were obtained when various fitting/adjustment procedures were used.

The model optimized for taper and cumulative volume and then adjusted to fit the combined estimator was the most appropriate.

Keywords:
Volume
Adjustment
Optimization
Segmented models
Diameter
Height

ABSTRACT

In this study, Max and Burkhart (1976)'s segmented taper model was used to describe stem profile and predict stem volume of oriental spruce in Turkey. Thirty procedures were evaluated, which include five fitting methods and six adjustment strategies. The fitting methods resulted in parameters that were optimized for (1) taper, (2) cumulative volume, (3) taper and cumulative volume, (4) taper and total volume, and (5) taper, cumulative volume, and total volume. The adjustment strategies are (1) unadjusted, and adjusted to match (2) DBH, (3) predicted total volume, (4) DBH and predicted total volume, (5) a combined estimator, and (6) DBH and a combined estimator. Results showed that, without adjustment, the model with parameters optimized for taper gave good prediction for both taper and cumulative volume. Mixed results were obtained when various adjustment strategies were used on different fitting techniques. The overall best-ranked procedure for predicting both taper and volume was the model optimized for taper and cumulative volume and then adjusted to fit the combined estimator.

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INTRODUCTION

Prediction of tree volume in a stand, either total volume or merchantable volume, are essential for forest management and planning. Predicting tree merchantable volume for any utilization standard can be done by use of volume ratios (Honer 1964, Burkhart 1977, Cao and Burkhart 1980; Teshome 2005) or by integrating stem profile models. Numerous taper equations, from simple to complex, have been used to describe stem profile of various tree species (Kozak 2004; Jordan et al. 2005; Diéguez-Aranda et al. 2006; Li and Weiskittel 2010; Schröder et al. 2015; Özçelik and Crecente-Campo 2016). Flexible equations such as variable-exponent taper models (Kozak 1988; Bi 2000; Kozak 2004; Newnham 1992; Sharma and Zhang 2004) cannot be analytically integrated, and therefore need to be numerically integrated for volume computation. On the other hand, volume by integration exists in closed form for segmented taper equations (Max and Burkhart 1976; Cao et al. 1980; Clark et al. 1991; Fang and Bailey 2000), which can also be directly solved to produce an estimate of merchantable height for a given top diameter (Kozak and Smith 1993).

Demaerschalk (1972) introduced the concept of a compatible taper and volume system, in which integration of the taper model produces volume that equals the volume predicted by a volume equation. This is because taper and volume are mathematically and biologically related (Munro and Demaerschalk 1974). A compatible taper equation can be obtained either by deriving from a total or merchantable volume equation (Demaerschalk 1972, Clutter 1980), or by applying constraints to ensure that its integration produces specified stem volume (Goulding and Murray 1976; Cao et al. 1980; Van Deusen et al. 1982, 1988; Reed and Green 1984; Lenhart et al. 1987; Fang and Bailey 1999; Diéguez-Aranda et al. 2006).

A method to simultaneously fit equations in the taper and volume system substantially reduced the total estimation error (Reed 1982, Reed and Green 1984). This simultaneous estimation problem was reformulated by Van Deusen (1988) as a seemingly unrelated regressions (SUR) problem, which can be easily solved using standard statistical software packages.

Oriental spruce (*Picea orientalis* L.) is an important tree species in northeastern of Turkey and it occupies an area of 328.000 ha, with the standing volume about 71.4 million m^3 (GDF 2018). This species is utilized for pulpwood and cellulose. However, because of ever-changing market conditions, existing equations and local volume tables that are based on fixed merchantability limits no longer suffice. In addition, environmental benefits from oriental spruce forests in northeastern Turkey include conservation of biological diversity, climate change mitigation and adaptation, and protection of soil and water resources. Therefore, forest managers need detailed information supplied by growth and yield prediction models, such as volume classified by merchantable products, for sustainable management of these forests.

Some taper models have been tested to describing stem profile and predict volume for some tree species in Turkey (Brooks et al. 2008; Sakici et al. 2008; Özçelik et al. 2014; Özçelik and Crecente-Campo 2016 and Özçelik and Cao 2017; Sakici and Ozdemir, 2018). Taper equations generally are specific to each species, meaning that a separate set of parameters is needed for each species to identify its unique bole shape (Sharma and Parton 2004).

The Max and Burkhart's (1976) taper equation was used in this study because it is straightforward to predict height at a given stem diameter. This model included three quadratic functions, which are joined together. The result is a continuous and smooth stem profile. For a flexible model, it was relatively simple, and therefore has been frequently used to describe stem profile of many tree species (Byrne and Reed 1986; Muhairwe 1999; Jiang et al. 2005; Diéguez-Aranda et al. 2006; Schröder et al. 2014; Scolforo et al. 2018;). Constraints have been applied to ensure that the taper curve go through diameter at breast height (DBH) (Cao 2009) and/or an upper-stem diameter (Czaplewski and McClure 1988; Cao 2009; Cao and Wang 2011; Sabatia and Burkhart 2015). Working with black pine in Turkey, Özçelik and Cao (2017) found that various fitting and adjustment strategies for taper and volume predictions did not improve performance of the taper model. However, they did not consider the possibility of adjustment based on a combined estimator, which is a weighted average of predicted stem volumes from the taper and volume models.

The objective of this study was to evaluate various combinations of methods for estimating parameters and calibrating a modified form of Max and Burkhart's (1976)'s segmented taper equation for oriental spruce.

MATERIAL AND METHODS

Data

Data used in this study consist of 5859 outside-bark diameter observations from measurements of 642 destructively sampled oriental spruce trees. The data was collected from natural stands located throughout the area of distribution of oriental spruce in northeastern Turkey. Sample trees were selected to represent diameter and height distibutions, based on information from a previous inventory. Diameter at breast height (at 1.3 m above ground level, *dbh*) and total bole length were measured to the nearest 0.1 cm and 0.01 m for each tree, respectively. Stump height averaged 0.30 m. The all data ranged from 5.2 to 74.3 cm for *dbh* and 4.1 to 37.7 m for total height. The felled trees were sectioned at 2 m intervals starting from the stump to the tree tip. Two measures of diameter outside bark (*dob*) perpendicular to each other were collected and averaged to obtain *dob* measurement up the stem. Smalian's formula was used to calculate the volume of sections in cubic meters. The volume of the last portion (from the last measurement to the tree tip) was treated as a cone. Total tree volume (above stump) was then obtained by summing up volumes of all sections. Table 1 summarizes the relevant variables (dbh, total height and total volume) for the trees used in this study.

TABLE 1 Summary statistics of data used in this study.

Groups	Variable	Min	Mean	Max
Group I (n=321)	DBH (cm)	5.80	28.29	72.60
	Total height (m)	5.00	17.26	33.00
	Total volume (m3)	0.01	0.71	3.79
	Number of sections	3.00	9.29	17.00
Group II (n=321)	DBH (cm)	5.20	27.88	74.30
	Total height (m)	4.10	16.67	37.70
	Total volume (m3)	0.01	0.71	6.07
	Number of sections	3.00	8.96	18.00

Methods

Total volume equation

A myriad of equations have been developed to predict stem volume of a tree. Schumacher and Hall's (1933) model, which has been widely used for many tree species, was applied in this study to estimate total stem volume, where V_i = total stem volume of tree *i* in m^3, D_i = diameter at breast height (dbh) of tree *i* in cm, H_i = total height of tree *i* in m, *a*, *b*, and *c* = regression coefficients, and ε_i = error.

$$V_i = aD_i^b H_i^c + \varepsilon_i \qquad [1]$$

Taper equation

The segmented taper model by Max and Burkhart (1976) is preferred because volume can be easily integrated and height prediction from diameter can be directly obtained. A modified form of this taper equation (Cao 2009) was used in this study, where: $\hat{y}$ predicted value of *y*, d_{ij} : outside-bark diameter in cm at height h_{ij} of location *j* on tree *i*, h_{ij}:height from the ground in m, $z_{ij}: 1 - h_{ij}/H_i$ = relative height from the tree tip, $I_k = \begin{cases} 1, if\ z_{ij} > a_k \\ 0, otherwise \end{cases}$, *k* = 1, 2, and a_h *and* b_h : regression coefficients.

Performance was improved when d_{ij} was used as a dependent variable rather than equation 3. The regression model is: where ε_i = error; Volume (v_i) from height h_{i1} to height h_{i2} is obtained by integrating the taper equation as follows. where *K* = 0.00007854, a constant to convert diameter in cm to area in m^2.

$$\hat{y}(z_{ij}) = b_1 + b_2 z_{ij}^2 + b_3(z_{ij} - a_1)^2 I_1 + b_4(z_{ij} - a_2)^2 I_2 \qquad [2]$$

$$y(z_{ij}) = d_{ij}^2 / D_i^2 \qquad [3]$$

$$d_{ij} = D_i \sqrt{b_1 z_{ij} + b_2 z_{ij}^2 + b_3(z_{ij} - a_1)^2 I_1 + b_4(z_{ij} - a_2)^2 I_2} + \varepsilon_{ij} \qquad [4]$$

$$\hat{v}_i = KD_i^2 H_i \left\{ \left(\frac{b_1}{2} z_{i2}^2 + \frac{b_2}{3} z_{i2}^3 + \frac{b_3}{3}(z_{i2} - a_1)^3 I_{12} + \frac{b_4}{3}(z_{i2} - a_2)^3 I_{22} \right) - \left(\frac{b_1}{2} z_{i1}^2 + \frac{b_2}{3} z_{i1}^3 + \frac{b_3}{3}(z_{i1} - a_1)^3 I_{12} + \frac{b_4}{3}(z_{i1} - a_2)^3 I_{21} \right) \right\}, \qquad [5]$$

$$z_{im} = 1 - h_{im}/H_i,\ m = 1, 2 \qquad [6]$$

$$I_{km} = \begin{cases} 1, if\ z_{im} > a_k \\ 0, otherwise \end{cases},\quad k = 1, 2;\ m = 1, 2 \qquad [7]$$

In this paper, total volume is defined as volume from the stump to the tree tip, and cumulative volume is volume from the stump to where diameter is measured.

Five different methods were employed to estimate parameters (b_1–b_4 and a_1–a_2) of the stem profile model.

Fitting method 1 – Optimized for taper

The least squares approach used in this method is commonly employed in fitting taper equations. The parameters were selected to minimize $\sum_{i=1}^{N}\sum_{j=1}^{n_i}(d_{ij} - \hat{d}_{ij})^2$, where n_i is number of diameter measurements for tree *i*, *N* is number of trees, and $\hat{d}_{ij}$ is predicted bole diameter at location *j* on tree *i*.

Fitting method 2 – Optimized for cumulative volume

The goal was to produce good prediction for cumulative volume by integrating the taper model. This was done by minimizing $\sum_{i=1}^{N}\sum_{j=1}^{n_i}(v_{ij} - \hat{v}_{ij})^2$, where v_{ij} and $\hat{v}_{ij}$ are observed and predicted cumulative volume of tree *i* from the stump to the *j*th diameter measurement, respectively.

Fitting method 3 – Optimized for both taper and cumulative volume

Both $\sum_{i=1}^{N}\sum_{j=1}^{n_i}(d_{ij} - \hat{d}_{ij})^2$ and $\sum_{i=1}^{N}\sum_{j=1}^{n_i}(v_{ij} - \hat{v}_{ij})^2$ were simultaneously minimized in this approach by use of seemingly unrelated regression (SAS proc MODEL, option SUR). This method endures that predictions for both diameter and cumulative volume are reliable.

Fitting method 4 – Optimized for both taper and total volume

Similar to the previous approach, the objective was to simultaneously minimize $\sum_{i=1}^{N}\sum_{j=1}^{n_i}(d_{ij}-\hat{d}_{ij})^2$ and $\sum_{i=1}^{N}(V_i-\tilde{V}_i)^2$, where $\breve{V}_i$ are predicted total volume of tree *i*, obtained by integrating the taper equation (3). Seemingly unrelated regression (SUR) was also used for optimizing both diameter and total volume.

Fitting method 5 – Optimized for taper, cumulative volume, and total volume

In this approach, the objective was to simultaneously minimize $\sum_{i=1}^{N}\sum_{j=1}^{n_i}(d_{ij}-\hat{d}_{ij})^2$, $\sum_{i=1}^{N}\sum_{j=1}^{n_i}(v_{ij}-\hat{v}_{ij})^2$ and $\sum_{i=1}^{N}\sum_{j=1}^{n_i}(v_{ij}-\hat{v}_{ij})^2$. SUR was again used for this approach.

In each of the five fitting methods, parameters were adjusted so that predictions from the resulting taper model that match various attributes.

Adjustment strategy 1 – Unadjusted

No adjustment was made; estimates of parameters remained unchanged.

Adjustment strategy 2 – Adjusted to match DBH

When the Max and Burkhart (1976) taper equation is applied to breast height (h= 1.30 m), predicted diameter at this point does not necessarily equal to dbh. This adjustment procedure, proposed by Cao (2009), replaced parameter b_1 with such that predicted diameter at breast height is D_i:

$$b_1^* = b_1 + \frac{1-\hat{y}(z_{iBH})}{z_{iBH}} \quad [8]$$

$$z_{iBH} = 1 - 1.3/H_i \quad [9]$$

$$b_1^* = b_1 + \frac{2(\tilde{V}_i - \breve{V}_i)}{KD_i^2 H_i z_{iS}^2} \quad [10]$$

$$z_{iS} = 1 - h_{iS}/H_i \quad [11]$$

Adjustment strategy 3 – Adjusted to match total volume

In this strategy, replaced b_1 such that the resulting total volume matches , which is predicted from the total volume equation (1), where K = 0.00007854, a constant to convert diameter in cm to area in m^2, h_{iS} = stump height for tree *i*.

Adjustment strategy 4 – Adjusted to match both DBH and total volume

In this adjustment strategy, parameters b_1 and b_2 were replaced with b_1^* and b_2^*, respectively, so that

$$b_2^* = b_2 + \frac{2z_{iBH}(\tilde{V}_i - \hat{V}_i) - KD_i^2 H_i z_{iS}^2[1-\hat{y}(z_{iBH})]}{KD_i^2 H_i z_{iS}^2(2z_{iS}/3 - z_{iBH})} \quad [12]$$

$$b_1^* = b_1 + \frac{1-\hat{y}(z_{iBH})}{z_{iBH}} - (b_2^* - b_2)z_{iBH} \quad [13]$$

predicted diameter at breast height matches D_i and the resulting total volume matches $\breve{V}_i$:

Adjustment strategy 5 – Adjusted to match combined estimator for total volume

The combined estimator for total volume ($\breve{V}_i$) is the weighted average of predicted volumes from the taper equation ($\breve{V}_i$) and the volume model ($\breve{V}_i$), where *w* is obtained by minimizing .

This is adjustment strategy 3, with the combined estimator ($\breve{V}_i$) replacing the total stem volume estimated from the total volume equation ($\breve{V}_i$).

$$\bar{V}_i = w\hat{V}_i + (1-w)\breve{V}_i \quad [14]$$

$$\sum_{i=1}^{N}(V_i - \bar{V}_i)^2 \quad [15]$$

Adjustment strategy 6 – Adjusted to match DBH and combined estimator for total volume

This strategy is identical to adjustment strategy 4, with the exception that replacing to predict total volume.

Model Evaluation

In this study, a total of 30 procedures (five fitting methods × six adjustment strategy) were evaluated. The two-fold evaluation approach was applied. For this purpose, the data were randomly divided into two groups; each containing 321 trees. The coefficients obtained by fitting data from one group were used to predict for the other group. The predicted values from both groups were then pooled to calculate evaluation statistics for both diameters and total volumes. The evaluation statistics included mean bias (*MB*) between measured and predicted values, mean of absolute bias (*MAB*), and fit index (*FI*). *MB* measures the average bias of the prediction, *MAB* measures the magnitude of the bias, and *FI* is analogous to R^2 in linear regression. These statistics are computed as follows, where x_{ij}= either diameter (d_{ij}) or volume (v_{ij}), and are predicted and average values of x_{ij}, respectively.

$$MD = \frac{\sum_{i=1}^{N}\sum_{j=1}^{n_i}(x_{ij}-\hat{x}_{ij})}{\sum_{i=1}^{N} n_i} \quad [16]$$

$$MAD = \frac{\sum_{i=1}^{N}\sum_{j=1}^{n_i}|x_{ij}-\hat{x}_{ij}|}{\sum_{i=1}^{N} n_i} \quad [17]$$

$$FI = 1 - \frac{\sum_{i=1}^{N}\sum_{j=1}^{n_i}(x_{ij}-\hat{x}_{ij})^2}{\sum_{i=1}^{N}\sum_{j=1}^{n_i}(x_{ij}-\bar{x}_i)^2} \quad [18]$$

For each procedure and for each evaluation statistic, a relative rank (Poudel and Cao 2013) was computed. The best and the worst procedures in this ranking system have relative ranks of 1 and k, respectively, where k is number of procedures being evaluated. The remaining procedures have ranks as real numbers between 1 and k. Because this scheme considers both magnitude and order of the evaluation statistic, the relative ranking system should offer more information than the traditional ordinal ranks. The sum of the relative ranks from the three evaluation statistics for each procedure was calculated and then ranked again to give an overall rank for each procedure.

RESULTS AND DISCUSSION

Total volume prediction

Table 2 shows that, based on all three statistics, total volume prediction was better from the total volume model (relative rank of 1.26) than from integrating the various taper models (relative ranks between 7.00 to 11.00). The five fitting methods attained good results in predicting total volume, explaining between 97.91% to 98.01% of the variation, but still slightly worse than 98.92% when predicted from the total volume model. Surprisingly, the inclusion of total volume in the optimization methods (fitting methods 4 and 5) did not improve total volume prediction, as compared to fitting method 1 that optimized only taper. The total volume model produced similar evaluation statistics to those obtained from the combined estimators (relative ranks between 1.00 to 1.30), which is a weighted average of total volume estimates from the total volume model and from integrating the taper equations.

TABLE 2 Evaluation statistics for total volume. Bold, italic numbers denote the best method for each criterion, whereas underlined numbers denote the worst method.

Model	Optimization	Volume calculation	MD	MAD	FI	Relative rank
Total volume			-0.0035	0.0467	0.9892	1.2622
Taper	Taper	Integration	0.0060	0.0615	0.9795	7.0036
		Combined estimator	-0.0036	0.0467	0.9893	1.2477
	Cumulative volume	Integration	0.0237	0.0675	0.9791	11.0000
		Combined estimator	-0.0039	0.0467	0.9893	1.2974
	Taper and cumulative volume	Integration	0.0229	0.0661	0.9801	10.3381
		Combined estimator	-0.0039	0.0467	0.9893	1.2974
	Taper and total volume	Integration	0.0199	0.0658	0.9796	9.9491
		Combined estimator	-0.0039	0.0467	0.9893	1.2974
	Taper, cumulative volume, and total volume	Integration	0.0226	0.0666	0.9796	10.5217
		Combined estimator	-0.0037	0.0462	0.9899	1.0000

Diameter prediction

Table 3 shows that the modified form of Max and Burkhart (1976) model was adequate in estimating tree taper for this data set, regardless of optimization

TABLE 3 Evaluation statistics for taper. Bold, italic numbers denote the best method for each criterion, whereas underlined numbers denote the worst method.

Optimization	Adjustment	MD	MAD	FI	Relative rank
Taper	Unadjusted	0.2067	1.2232	0.9845	3.9073
	DBH	0.2725	1.1693	0.9844	2.8641
	Predicted TV	0.1449	1.2311	0.9840	3.6802
	DBH and predicted TV	0.1179	1.2161	0.9824	4.6297
	Combined estimator	0.1445	1.2317	0.9840	3.7004
	DBH and Combined estimator	0.1173	1.2167	0.9824	4.6457
Cumulative volume	Unadjusted	0.5902	1.4227	0.9784	30.0000
	DBH	0.3992	1.2937	0.9806	16.7619
	Predicted TV	0.0405	1.3717	0.9794	14.6004
	DBH and predicted TV	0.0597	1.4183	0.9759	22.1091
	Combined estimator	0.0327	1.3736	0.9793	14.6662
	DBH and Combined estimator	0.0524	1.4219	0.9758	22.2665
Taper and cumulative volume	Unadjusted	0.4242	1.2789	0.9839	11.9781
	DBH	0.2251	1.1764	0.9843	2.3439
	Predicted TV	-0.1282	1.2470	0.9839	4.2257
	DBH and predicted TV	-0.1168	1.2314	0.9816	6.4519
	Combined estimator	-0.0136	1.2494	0.9838	2.0667
	DBH and Combined estimator	-0.1244	1.2346	0.9815	6.9040
Taper and Total Volume	Unadjusted	0.3969	1.2721	0.9839	11.0792
	DBH	0.2487	1.1679	0.9845	2.1567
	Predicted TV	-0.0643	1.2365	0.9840	2.2404
	DBH and predicted TV	-0.0641	1.2156	0.9821	3.8918
	Combined estimator	-0.0709	1.2383	0.9840	2.4652
	DBH and Combined estimator	-0.0705	1.2179	0.9820	4.2757
Taper, cumulative volume, and total volume	Unadjusted	0.4261	1.2857	0.9836	12.7607
	DBH	0.1851	1.1688	0.9844	1.0000
	Predicted TV	-0.0768	1.3224	0.9820	9.3875
	DBH and predicted TV	-0.0444	1.3175	0.9793	12.2395
	Combined estimator	-0.0996	1.3270	0.9820	10.0867
	DBH and Combined estimator	-0.0659	1.3212	0.9793	12.8685

techniques or adjustment strategies. The resulting taper equations produced a mean absolute difference ranging from 1.17 cm to 1.42 cm, and explained between 97.59% and 98.45% of the variation in diameter.

Without adjustment, the taper equation with parameters optimized only for cumulative volume (fitting method 2) gave the worst prediction for taper (Table 3). On the other hand, the taper optimization (fitting method 1) fared better than the other fitting methods, as expected.

The DBH adjustment constrained the taper curve to go through DBH and therefore resulted in better taper prediction than did the unadjusted taper equations (Table 3). In fact, the DBH adjustment for fitting method 5 (optimized for taper, cumulative volume, and total volume) was the best in predicting taper. The other adjustment strategies, with some exceptions, also improve taper prediction, compared to the unadjusted strategy.

Cumulative volume prediction

All of the taper equations resulting from various fitting and adjustment strategies yielded acceptable results in predicting cumulative volume, from 94.66% to 98.74% in fit index, and from 0.04 m^3 to 0.12 m^3 in mean absolute deviation (Table 4).

Table 4 also shows that, without adjustment, the taper optimization method (fitting method 1) attained the higher relative rank (1.51) than did the rest of the fitting methods (ranging from 2.48 to 3.07 in ranks).

The DBH adjustment did not help to predict cumulative volume, resulting in the worst relative ranks (23.70 to 30.00) among all methods (Table 4). Conversely, adjustment for total volume (adjustment strategies 4 and 5), by use of either prediction from a total volume model or a combine estimator, did improve the cumulative volume prediction. The improvement was enhanced when this adjustment was coupled with the DBH adjustment (adjustment strategies 4 and 6).

Diameter and cumulative volume prediction

Results from Tables 3 and 4 shows that most fitting/adjustment procedures tended to favor either cumulative volume or taper prediction, but not both. In order to evaluate each procedure based on its ability to predict both taper and volume, we summed the relative ranks for taper and cumulative volume. The sum of the relative ranks for taper and cumulative volume for each procedure was then ranked to yield an overall rank (Table 5).

Cao et al. (1980) found that a taper equation (that was optimized for taper), while being excellent in predicting predicted taper, did not predict cumulative volume as well as a volume ratio model. Results from this study tell a different story. The taper model in this study with parameters optimized for cumulative volume (fitting method 2) can be considered somewhat similar to a volume ratio model, yet ranked lower in volume prediction (3.07) than the model optimized for taper

TABLE 4 Evaluation statistics for cumulative volume. Bold, italic numbers denote the best method for each criterion, whereas underlined numbers denote the worst method.

Optimization	Adjustment	MD	MAD	FI	Relative rank
Taper	Unadjusted	-0.0008	0.0445	0.9850	1.5077
	DBH	0.1219	0.1225	0.9466	29.0472
	Predicted TV	-0.0027	0.0447	0.9847	1.7500
	DBH and predicted TV	0.0037	0.0421	0.9864	1.1377
	Combined estimator	-0.0027	0.0448	0.9846	1.7844
	DBH and Combined estimator	0.0036	0.0421	0.9864	1.1297
Cumulative volume	Unadjusted	0.0168	0.0483	0.9857	3.0734
	DBH	0.1109	0.1123	0.9611	23.6973
	Predicted TV	0.0019	0.0436	0.9865	1.1506
	DBH and predicted TV	0.0063	0.0431	0.9871	1.3057
	Combined estimator	0.0017	0.0436	0.9865	1.1347
	DBH and Combined estimator	0.0061	0.0431	0.9871	1.2898
Taper and cumulative volume	Unadjusted	0.0137	0.0472	0.9860	2.6288
	DBH	0.1237	0.1242	0.9439	30.0000
	Predicted TV	-0.0011	0.0430	0.9865	1.0156
	DBH and predicted TV	0.0054	0.0419	0.9874	1.0239
	Combined estimator	-0.0013	0.0430	0.9865	1.0315
	DBH and Combined estimator	0.0052	0.0419	0.9874	1.0080
Taper and total volume	Unadjusted	0.0107	0.0470	0.9855	2.4791
	DBH	0.1219	0.1225	0.9463	29.1147
	Predicted TV	-0.0017	0.0435	0.9858	1.2803
	DBH and predicted TV	0.0045	0.0419	0.9870	1.0424
	Combined estimator	-0.0019	0.0435	0.9858	1.2962
	DBH and Combined estimator	0.0044	0.0419	0.9870	1.0345
Taper, cumulative volume, and total volume	Unadjusted	0.0138	0.0476	0.9857	2.7518
	DBH	0.1203	0.1212	0.9472	28.6305
	Predicted TV	-0.0005	0.0445	0.9863	1.1914
	DBH and predicted TV	0.0051	0.0425	0.9872	1.1165
	Combined estimator	-0.0012	0.0443	0.9865	1.1782
	DBH and Combined estimator	0.0045	0.0423	0.9874	1.0000

(1.51). Indeed, the taper optimization method produced the best prediction of both taper and cumulative volume.

Reed and Green (1984) found that simultaneous optimizing for both taper and cumulative volume produced smaller total system squared error, but did not show how the system behaved separately for taper and volume. In this study, the method of optimizing for both taper and cumulative volume (fitting method 3) did not improve but rather worsened predictions for taper and volume, as compared to optimizing for taper only.

TABLE 5 Overall comparisons of optimization and adjustment methods. Bold, italic numbers denote the best method for each criterion, whereas underlined numbers denote the worst method

Optimization	Adjustment	Taper Ranks	Volume Ranks	Overall Rank
Taper	Unadjusted	3.9073	1.5077	2.7983
	DBH	2.8641	29.0472	23.3650
	Predicted TV	3.6802	1.7500	2.8101
	DBH and predicted TV	4.6297	1.1377	3.0719
	Combined estimator	3.7004	1.7844	2.8525
	DBH and Combined estimator	4.6457	1.1297	3.0781
Cumulative volume	Unadjusted	30.0000	3.0734	24.2671
	DBH	16.7619	23.6973	30.0000
	Predicted TV	14.6004	1.1506	10.8212
	DBH and predicted TV	22.1091	1.3057	16.7700
	Combined estimator	14.6662	1.1347	10.8600
	DBH and Combined estimator	22.2665	1.2898	16.8798
Taper and cumulative volume	Unadjusted	11.9781	2.6288	9.9332
	DBH	2.3439	30.0000	23.7008
	Predicted TV	4.2257	1.0156	2.6635
	DBH and predicted TV	6.4519	1.0239	4.3979
	Combined estimator	2.0667	1.0315	1.0000
	DBH and Combined estimator	6.9040	1.0080	4.7365
Taper and Total Volume	Unadjusted	11.0792	2.4791	9.1192
	DBH	2.1567	29.1147	22.8683
	Predicted TV	2.2404	1.2803	1.3279
	DBH and predicted TV	3.8918	1.0424	2.4251
	Combined estimator	2.4652	1.2962	1.5148
	DBH and Combined estimator	4.2757	1.0345	2.7170
Taper, cumulative volume, and total volume	Unadjusted	12.7607	2.7518	10.6361
	DBH	1.0000	28.6305	21.5946
	Predicted TV	9.3875	1.1914	6.8066
	DBH and predicted TV	12.2395	1.1165	8.9622
	Combined estimator	10.0867	1.1782	7.3391
	DBH and Combined estimator	12.8685	1.0000	9.3600

Compared to the unadjusted strategy, the DBH adjustment (adjustment strategy 2) resulted in better evaluation statistics for taper prediction, but worse statistics for prediction of cumulative volume. Adjustment for predicted total volume (from either a total volume model or a combined estimator), in many cases, bettered prediction of both taper and cumulative volume. Adding DBH to the above adjustment actually lowered the overall ranks (Table 5).

The worst overall procedure (rank of 30.00), which is the cumulative volume optimization coupled with DBH adjustment, gave poor prediction for both taper and volume. The best overall rank came from a taper equation optimized for taper and cumulative volume (fitting method 3) which was then adjusted for the combined estimator (adjustment strategy 5). This procedure achieved relative ranks of 2.07 and 1.03 for predicting taper and cumulative volume, respectively.

Finally, the proposed taper and stem volume models for optimization alternatives were refit to the entire data set using all five fitting methods (Table 6). Figure 1 shows the observed data, overlaid with predictions from the taper model of fitting method 5.

TABLE 6 Estimates of parameters (and standard errors) for taper and volume equations of different fitting methods based on all sample data.

Fitting methods	Parameters					
	b_1	b_2	b_3	b_4	a_1	a_2
Taper	0.1060 (0.0115)	1.5561 (0.0642)	-1.7349 (0.0586)	53.2930 (6.2852)	0.2452 (0.0099)	0.9187 (0.0042)
Cumulative volume	0.2139 (0.1341)	1.4019 (0.5544)	-1.9383 (10.087)	1.0310 (10.218)	0.3569 (0.4214)	0.4893 (0.7409)
Taper and cumulative volume	0.0865 (0.0093)	1.9549 (0.0504)	-1.7782 (0.0452)	51.5390 (4.3554)	0.2472 (0.0078)	0.9136 (0.0032)
Taper and total volume	0.0902 (0.0087)	1.9360 (0.0477)	-1.7187 (0.0436)	56.0283 (4.8487)	0.2460 (0.0076)	0.9189 (0.0031)
Taper, cumulative volume, and total volume	0.0856 (0.0085)	1.9613 (0.0469)	-1.7736 (0.0418)	54.9194 (4.4743)	0.2452 (0.0071)	0.9172 (0.0029)

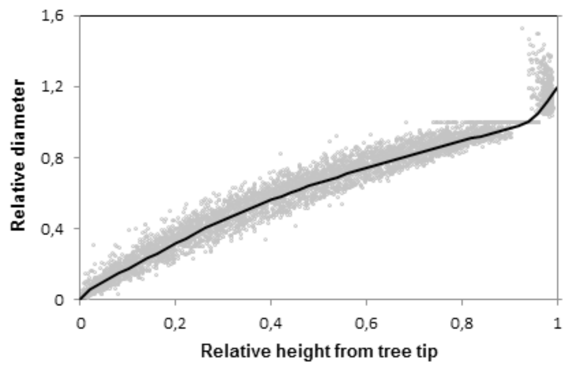

FIGURE 1 Graph of observed data and predictions from the taper model optimized for taper, cumulative volume, and total volume.

CONCLUSIONS

In this study, a simpler form of the Max and Burkhart's (1976) taper model was used to predict taper and stem volume of oriental spruce. A total of thirty procedures was evaluated, including five fitting methods (optimized for taper, cumulative volume, taper and cumulative volume, taper and total volume, and taper and both cumulative and total volumes) and six adjustment strategies (unadjusted, and adjusted to match DBH, predicted total volume predicted from either a total volume model or a combined estimator, and DBH and predicted total volume). Results of this study indicated that, without adjustment, the model with parameters optimized for taper gave good prediction for both taper and cumulative volume. Mixed results were obtained when various adjustment strategies were used on different fitting techniques. The overall best-ranked procedure for estimating both taper and stem volume was the model optimized for taper and cumulative volume and then adjusted to fit the combined estimator.

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