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Volume equations for Scots pine trees in Kastamonu region

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Abstract: The objective of this study is to develop tree volume equations for Scots pine trees in the Kastamonu region and to compare the prediction capability of these equations with existing tree volume equations. For this purpose, stump diameter, diameter at breast height, diameters in each meter up to the top of the tree, and tree height measurements were measured on 127 sample trees from the Kastamonu Forest Enterprise in the Kastamonu Regional Directorate of Forestry. Subsequently, tree volumes were calculated based on these measurements and using the sectional method. This method entailed volumizing the trees in three sections: the stump section, the top section and the one-meter sections between the stump and the top sections. To develop single- and double-entry tree volume equations, the parameters of eight volume equations were estimated. Four statistical criteria were employed to identify the best predictive models. The coefficients of determination for the best predictive single- and double-entry models were found to be 0.972 and 0.975, respectively. Additionally, the results of these models were compared with the volume predictions derived from four models presented in the literature. The results of this study will enhance the accuracy of tree volume estimation for Scots pine stands in the Kastamonu region.
Keywords: *Pinus sylvestris* L., Tree volume tables, Kastamonu

Kastamonu yöresi sarıçam ağaç türü için ağaç hacim denklemleri

Öz: Bu çalışmanın amacı, Kastamonu bölgesindeki sarıçam ağaçları için ağaç hacim denklemleri geliştirmek ve bu denklem tahminlerini mevcut ağaç hacim denklemleri ile karşılaştırmaktır. Bu amaçla Kastamonu Orman Bölge Müdürlüğü'ne bağlı Kastamonu Orman İşletme Müdürlüğü'nden alınan 127 örnek ağaç üzerinde dip kütük çapı, göğüs yüksekliği çapı, göğüs çapından itibaren ağacın tepesine kadar 1'er metre aralıklarla gövde çapları ve ağaç boyu ölçümleri yapılmıştır. Daha sonra bu ölçümler kullanılarak ağaç hacim değerleri hesaplanmıştır. Tek ve çift girişli ağaç hacim denklemlerinin geliştirilmesi amacıyla sekiz adet (4'er adet tek ve çift girişli) denkleme ilişkin parametreler tahmin edilmiştir. En başarılı olan denklemlerin seçilmesinde dört adet istatistiksel ölçüt kullanılmıştır. En başarılı tek ve çift girişli denklemlere ilişkin belirtme katsayıları sırasıyla 0,972 ve 0,975'tir. Aynı zamanda model sonuçları literatürde yer alan dört adet denkleme ilişkin hacim tahminleri ile de karşılaştırılmıştır. Bu çalışmanın bulguları, Kastamonu yöresi sarıçam meşcerelerinde ağaç hacimlerinin güvenilir bir şekilde tahmin edilmesine katkı sağlayacaktır.
Anahtar kelimeler: *Pinus sylvestris* L., Ağaç hacim tabloları, Kastamonu

1. Introduction

In order to prepare ecosystem-based functional management plans and to manage and operate forests sustainably according to these plans, dynamic growth and yield models for each tree species are needed. One of the most fundamental foundations for growth and yield models is the estimation of individual tree and stand volumes. Volume estimates are important stand parameter used to determine individual tree and stand volumes and the distribution of these values to commercial classes, to prepare forest management plans, and to estimate the amount of biomass and carbon storage by using appropriate biomass conversion factors (Dieguez-Aranda et al., 2006; de-Miguel et al., 2012; Castedo-Dorado et al., 2012; Rodríguez et al., 2014). Therefore, there is a need for flexible, practical and reliable volume estimation methods that are compatible with growth models and allow reliable estimation of individual tree and stand volumes in forestry (de-Miguel et al., 2012). Various methods and approaches have been developed to estimate the volumes of trees. The main reason for this is that tree stems do not resemble existing geometric shapes such as cylinders, paraboloids, cones and neiloids, and therefore it is not possible to calculate the volume of the tree directly using geometric formulae or standard methods (Kalıpsız, 1984; Yavuz, 1999).

For a considerable period of time, tree volume equations and tree volume tables utilizing these equations have been the most popular techniques for estimating the volume of standing stems. This is due to the practicality of these methods compared to other tree volume calculation methods (Kalıpsız, 1984). Depending on the number of independent variables used, single-entry (based on diameter at breast height only), double-entry (based on diameter at breast height and tree height) or multiple-entry (a third or more independent variables in addition to diameter at breast height and tree height) tree volume equations are generally used to organize tree volume tables (Burkhart and Tome, 2012). In the studies carried out for the development of tree volume equations, it is seen that a large number and different forms of models are used. Nevertheless, it seems

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unlikely that these volume tables will be able to meet the evolving commercial standards (Özçelik et al., 2018). For this reason, studies on volume estimation are likely to continue.

The fact that the tree species in Türkiye continue to exist in very wide distribution areas and that the growing environmental conditions in these areas vary considerably over short distances makes it necessary to organize tree volume equations or tables locally. Nevertheless, there are limited locally developed tree volume equations, tree volume tables, and stem profile models for our primary tree species with significant economic and ecological benefits, as well as for other tree species (Özçelik et al., 2018). Wiant et al. (1992) and Ducey and Williams (2011) demonstrated in their studies that errors resulting from the inappropriate use of a volume equation or volume table for volume estimation could exceed 30%. Pillsbury et al. (1995) indicated in their study that using a volume table across different ecoregions with varying site characteristics could result in volume estimation errors reaching up to 40%. Therefore, it is emphasized that, to the extent possible, it is crucial to develop tree volume equations that are sensitive to regional variations for each tree species and to organize tree volume tables accordingly (Brooks and Wiant, 2008).

The Scots pine is one of the most economically and ecologically valuable tree species in Türkiye. It forms extensive forests, both in pure stands and in combination with other species. Additionally, Scots pine wood has a broad range of valuable applications. Furthermore, the capacity of the tree to produce well-formed and tall stems increases the potential for utilizing its wood, thereby elevating the Scots pine species to a significant level in the national economy (Alemdağ, 1967).

Examining studies related to Scots pine tree volume estimation covering the relevant region, it is observed that Alemdağ (1967), Pehlivan (2010), and Şenyurt (2011) developed tree volume equations and organized tree volume tables for Scots pine stands. Yavuz et al. (2010) developed tree volume equations for pure and mixed Scots pine stands in the Black Sea Region. Additionally, a stem taper equation for Scots pine was developed by Yavuz (1995) for the Taşköprü Forest Enterprise and by Seki (2023) for Küre, Taşköprü and Yenice Forest Enterprises. There are also ecoregion-based models developed for Scots pine stands in the relevant region (Sağlam and Sakici, 2024a; 2024b). In addition, volume equations and tables for both single- and double-entry tree species have been developed for various tree species in Türkiye (Eraslan, 1954; Gülen, 1959; Alemdağ, 1962; Evcimen, 1963; Alemdağ, 1967; Asan, 1984; Çalışkan and Yeşil, 1996; Bozkuş and Carus, 1997; Sakıcı and Yavuz, 2003; Mısır and Mısır, 2004; Durkaya and Durkaya, 2006; Özçelik, 2010; Carus et al., 2016; Özçelik and Karaer, 2016; Kahriman et al., 2017; Özçelik and Çevlik, 2017; Sakıcı et al., 2018; Şahin et al., 2018; Şenyurt and Ümit, 2019; Özçankaya et al., 2021; Ölmez and Şenyurt, 2022; Baytaş and Seki, 2023; Sönmez et al., 2023; Şahin and Ercanlı, 2023).

This study aims to achieve accurate and reliable tree stem volume predictions for Scots pine, thereby ensuring low inventory costs (with fewer variable measurements) in making these predictions. In order to achieve this, single- and double-entry tree volume equations have been developed that facilitate the practical calculation of both individual tree and stand volumes. These results were then compared with those obtained from tree volume equations in the literature. Accordingly, an effort was made to identify the model that provides the most satisfactory volume predictions for Scots pine stands in the Kastamonu region.

2. Material and method

In the scope of the study, sample trees data were obtained from natural Scots pine stands in the Kastamonu Forest Enterprise in the Kastamonu Regional Directorate of Forestry (Figure 1). In this study, measurements were conducted on 127 sample trees. The sample trees were tried to be selected for measurements to represent a range of diameter and height classes. Furthermore, during the selection of these sample trees, particular attention was paid to ensure that the stems were as well-formed as possible and that the trees were healthy individuals.

The diameter at breast height ($d_{1.30}$, cm) of the sample trees was measured with an accuracy of 0.1 cm using a caliper while the trees were standing. Sample trees were felled from the stump height (0.3 m), the stump diameter was recorded, and the other stem diameters over bark were measured at 1.3, 2.3, 3.3 m and then at 1-meter intervals up to the tree's top. The height of the tree (h) was measured with a tape measure to an accuracy of 0.05 m.

The stem volumes of the sample trees were calculated using the sectional method. In this method, trees were considered into three sections for the purpose of calculating volume. These sections are: (*i*) the stump section, (*ii*) the one-meter sections situated between the stump and the top section, and (*iii*) the top section. The volumes of these sections were calculated separately, with the assumption that the stump section was to be cylindrical, and the top section was to be conical. The volumes of the one-meter sections were calculated using the Smalian equation. The total stem volume (V, m^3) was calculated by summing the volumes of the three stem sections. A total of 127 sample tree data were divided into two groups: a "model dataset" for the development of tree volume equations and a "control dataset" for the validation of the developed tree volume equations (Figure 2). Descriptive statistics for the model, control and total data were presented in Table 1.

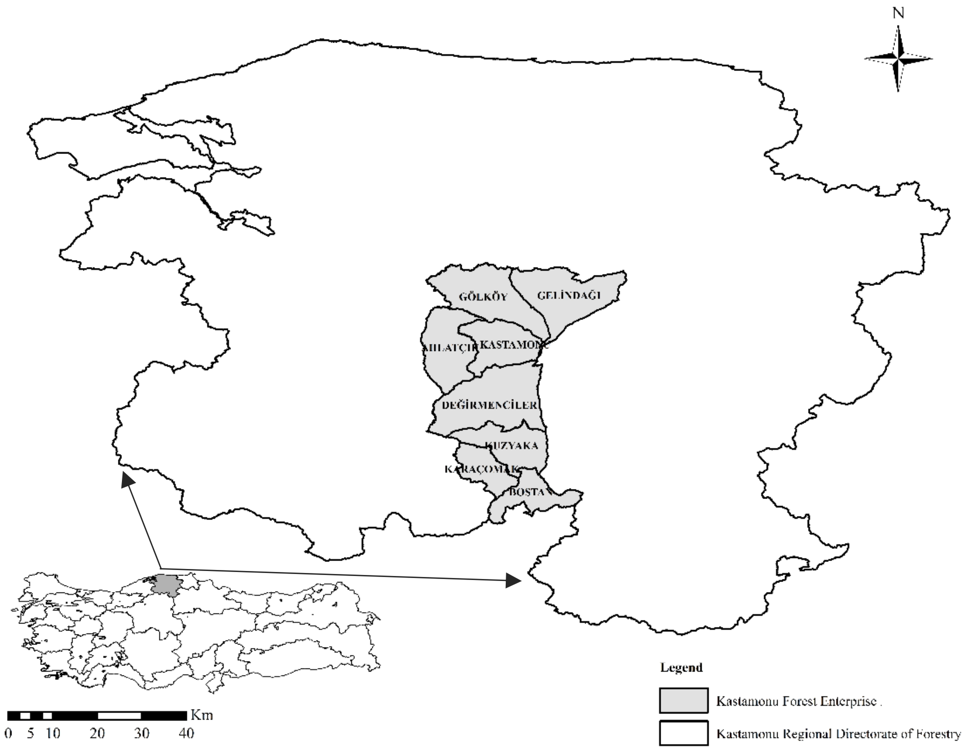

Figure 1. Study area

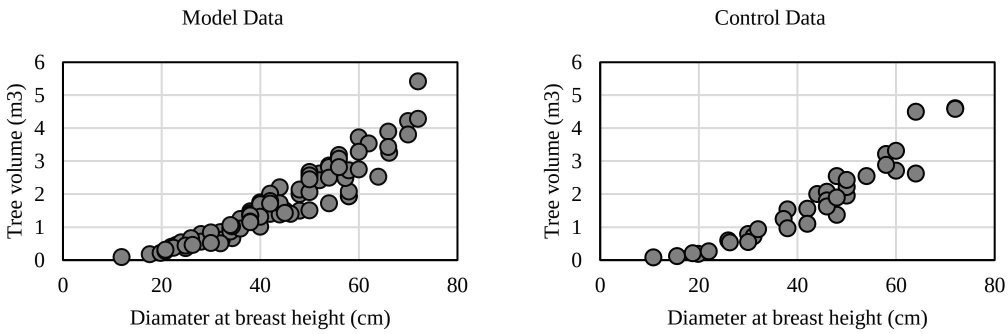

Figure 2. Relationship of tree volume-diameter at breast height for model and control data

Table 1. Descriptive statistics for sample trees

Data	Variables	n	Minimum	Maximum	Mean	Standard deviation
Model Data	$d_{1.30}$, cm	92	11.90	72.00	42.89	13.86
	h, m		8.90	30.00	20.95	4.12
	V, m^3		0.09	5.42	1.72	1.10
Control Data	$d_{1.30}$, cm	35	10.80	72.00	42.79	15.87
	h, m		8.00	29.60	20.01	5.41
	V, m^3		0.08	4.61	1.78	1.26
Total Data	$d_{1.30}$, cm	127	10.80	72.00	42.86	14.38
	h, m		8.00	30.00	20.69	4.51
	V, m^3		0.08	5.42	1.74	1.14

For the purpose of model development, commonly used tree volume equations from the literature were selected. Additionally, new variables were derived from independent variables such as diameter and height, and models were developed that provide successful volume predictions using stepwise regression analysis. The eight models for which parameter estimates were obtained are presented below.

$$V = b_0 d^{b_1} \quad (1)$$
$$V = b_1 d^2 \quad (2)$$
$$V = b_0 lnd^{b_1} \quad (3)$$
$$V = e^{b_0 + \frac{b_1}{lnd}} \quad (4)$$
$$V = b_1\, d^2 h \quad (5)$$
$$V = b_0 (d^2 h)^{b_1} \quad (6)$$
$$V = b_0 * d^{b_1} h^{b_2} \quad (7)$$
$$V = b_1\, d^2 + b_2\, d^2 h \quad (8)$$

Where, V is tree volume (m^3), d is diameter at breast height (cm), h is tree height (m) and b_0, b_1 and b_2 are model parameters.

Four statistical criteria, listed below, were used to select the best predictive model among the developed models. Model predictions were ranked based on coefficient of determination (R^2), root mean square error (*RMSE*), mean error (*ME*) and mean absolute error (*MAE*). To facilitate this ranking, the relative ranking method proposed by Poudel and Cao (2013) was employed. The relative rankings of the tree volume equations were calculated separately for each statistical criterion, and the calculated rankings were summed to determine the total relative ranking and overall ranking values for the equations.

$$R^2 = 1 - \frac{\sum(V_i - \hat{V}_i)^2}{\sum(V_i - \bar{V})^2} \tag{9}$$

$$RMSE = \sqrt{\frac{\sum(\hat{V}_i - V_i)^2}{n-p}} \tag{10}$$

$$ME = \frac{\sum(V_i - \hat{V}_i)}{n} \tag{11}$$

$$MAE = \frac{\sum|\hat{V}_i - V_i|}{n} \tag{12}$$

Where, V_i, $\hat{V}_i$, $\bar{V}$ are observed, predicted and mean values of dependent variable, respectively, p is parameter numbers of model and n is observations numbers.

The applicability of the developed models for Scots pine stands in the Kastamonu region was evaluated through a paired sample t-test, utilizing tree volumes from a control dataset comprising 35 sample trees. The IBM SPSS Statistics 23 software was used for the statistical analyses.

3. Results and discussion

In the scope of the study, parameters for eight tree volume equations (four single-entry and four double-entry) have been estimated and presented in Table 2. All parameters related to the single- and double-entry tree volume equations are statistically significant (p<0.05). The models include diameter at breast height and tree height as independent variables, along with various derived variables based on these factors.

In order to identify the best predictive model from the single- and double-entry tree volume equations, four statistical criteria were employed. The statistical criteria and their relative rankings for the evaluated models were presented in Table 3. Upon examining Table 3, it was observed that Model 2 from the single-entry tree volume equations and Model 8 from the double-entry tree volume equations demonstrated the highest degree of success, as reflected in their relative rankings.

The applicability of the developed tree volume equations for the Scots pine stands in the Kastamonu region was evaluated using the observed volumes of 35 trees designated for model validation. For this purpose, a paired sample *t*-test was employed for the purpose of comparing the observed volumes of the control trees with the estimated volumes obtained from the models. The results of the paired sample *t*-test for the volume models were presented in Table 4. Upon examining the results of the paired sample *t*-test, it is observed that there is no statistically significant difference between the observed and the predicted volumes derived from the models.

Table 2. Parameters for eight models

Model No	R^2	*p*	b_0	b_1	b_2
Model 1	0.941	<0.001	0.000486***	2.140650***	
Model 2	0.972	<0.001		0.000846***	
Model 3	0.943	<0.001	0.000071***	7.556752***	
Model 4	0.941	<0.001	-7.628427***	2.140650***	
Model 5	0.967	<0.001		0.000038***	
Model 6	0.952	<0.001	0.000124***	0.891663***	
Model 7	0.912	<0.001	0.000331*	1.949946***	0.369416**
Model 8	0.975	<0.001		0.000534***	0.000014**

***p<0.001, **p<0.01 and *p<0.05

Table 3. Relative ranking for volume models

Models	R^2	*RMSE*	*ME*	*MAE*	Total	General Ranking
Model 1	0.941 (*4.00*)	0.353 (*4.00*)	0.011 (*2.23*)	0.258 (*4.00*)	14.23	4.00
Model 2	0.972 (***1.00***)	0.343 (***1.00***)	0.002 (***1.00***)	0.251 (*2.09*)	**5.09**	**1.00**
Model 3	0.943 (*3.81*)	0.346 (*1.90*)	0.024 (*4.00*)	0.247 (***1.00***)	10.71	2.84
Model 4	0.941 (*4.00*)	0.353 (*4.00*)	0.009 (*1.95*)	0.258 (*4.00*)	13.95	3.91
Model 5	0.967 (*1.38*)	0.374 (*4.00*)	0.034 (*4.00*)	0.262 (*4.00*)	13.38	4.00
Model 6	0.952 (*2.10*)	0.368 (*3.62*)	0.030 (*3.67*)	0.244 (*2.36*)	11.74	3.35
Model 7	0.912 (*4.00*)	0.328 (*1.06*)	-0.002 (***1.00***)	0.229 (***1.00***)	7.06	1.48
Model 8	0.975 (***1.00***)	0.327 (***1.00***)	0.015 (*2.42*)	0.234 (*1.45*)	**5.87**	**1.00**

The values in brackets in the table are rank values for the relevant statistical criterion.

Table 4. Paired sample *t*-test results for volume models

Models	Mean	Standard deviation	*t*	*p*
Model 1	0.027	0.324	0.488	0.629*
Model 2	0.025	0.330	0.446	0.658*
Model 3	0.052	0.339	0.913	0.368*
Model 4	0.025	0.324	0.457	0.650*
Model 5	0.036	0.362	0.581	0.565*
Model 6	0.050	0.359	0.823	0.416*
Model 7	0.017	0.310	0.332	0.742*
Model 8	0.030	0.308	0.566	0.575*

*p>0.05

The graphs of volume prediction and residuals distribution, illustrated in Figure 3, are presented for the volume models identified as successful in the relative ranking based on statistical criteria. The models were also validated by the paired sample *t*-test. An examination of the figure reveals that as the predicted volumes increase, the prediction errors also tend to increase. Apart from that, the results demonstrate no evidence of bias in the volume predictions.

Double-entry tree volume models provide more reliable estimates compared to single-entry tree volume models (Kahriman et al., 2017; Sakıcı et al., 2018; Yavuz et al., 2010). Moreover, due to their superior performance in terms of statistical criteria and the successful outcomes reported in the literature for double-entry models, comparisons have been conducted for these models. In the study, volumes were estimated using the best predictive double-entry Model 8, based on statistical criteria, in relation to varying diameters and heights of the steps. Subsequently, volume estimates were obtained using the double-entry volume equations developed from the studies conducted by Alemdağ (1967), Pehlivan (2010), Yavuz et al. (2010), and Şenyurt (2011). The variation in volumes predicted using the equations developed in the previous studies compared to the volumes obtained from Model 8 in this study, with respect to diameter at breast height, is shown in Figure 4.

The error distributions of the single- and double-entry models developed in this study, with those of models presented in the literature, are examined in Figure 5. It can be seen that the model developed in this study produce lower prediction errors than those produced by existing studies, which serves to highlight their significance in providing reliable predictions.

When examining Figures 4 and 5, it is seen that the predictions made by Model 8 differ from those of existing studies. Specifically, predictions made by Model 8 for diameters up to approximately 50 cm are higher than those from existing models, whereas for diameters greater than 50 cm, the predictions are lower. Furthermore, it is observed that the prediction errors associated with Model 8 are lower. This disparity may be attributed to the localized focus of the present study, in contrast to the more general and regional focus of other works, as well as potential differences in site conditions and data structures contributing to this variation.

The validity of the existing equations was tested using a dataset obtained from field studies with the aid of a paired sample *t*-test, and the analysis investigated whether there were statistically significant differences between the observed volumes of sample trees and the predicted volumes calculated using the equations (Table 5).

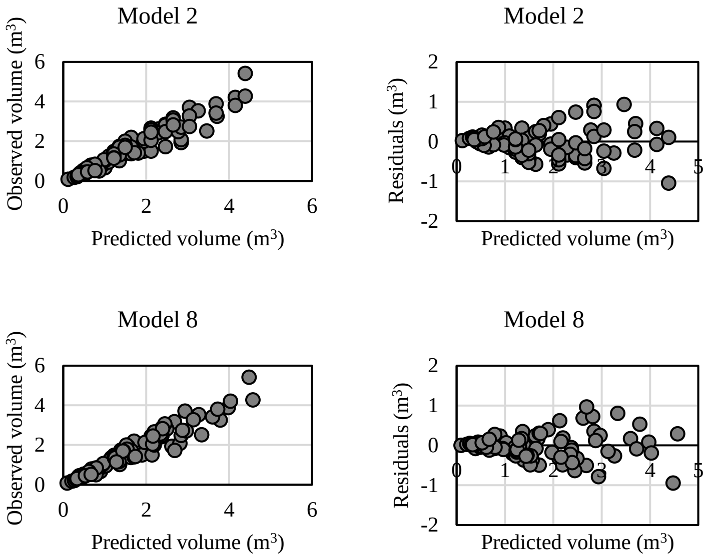

Figure 3. Observed vs. predicted volumes and residuals for best models

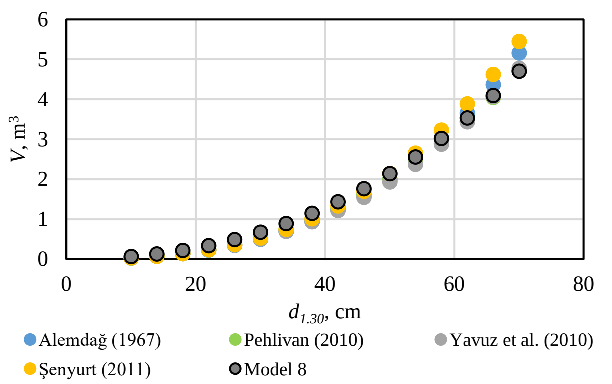

Figure 4. The variation of volumes with respect to diameter

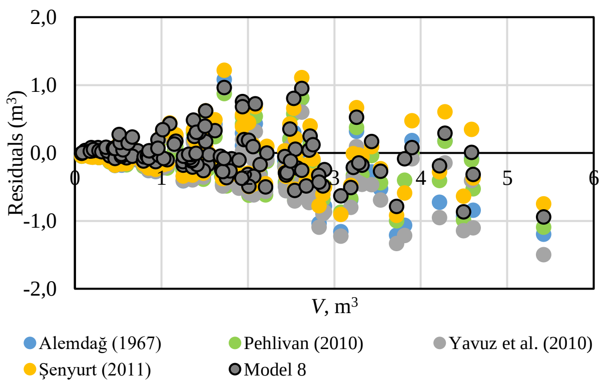

Figure 5. Residuals for models

Table 5. The results of the *t*-test for the models used for volume estimation

Equations	Mean	Standard deviation	*t*	*p*
Alemdağ (1967)	0.174	0.364	5.399	<0.001
Pehlivan (2010)	0.158	0.324	5.506	<0.001
Yavuz et al. (2010)	0.227	0.381	6.719	<0.001
Şenyurt (2011)	0.054	0.346	1.773	0.079*
Model 8 (in this study)	0.030	0.308	0.566	0.575*

*p>0.05

Examination of Table 5 reveals that the volume predictions obtained using the equations developed by Alemdağ (1967), Pehlivan (2010), and Yavuz et al. (2010) exhibit statistically significant differences ($p < 0.05$) in comparison to the observed volume values. It has been observed that the volume predictions derived from the equation developed by Şenyurt (2011) do not exhibit a statistically significant difference from the observed volumes at a 95% confidence level ($p > 0.05$).

The single- and double-entry models developed in this study can be reliably used for volume estimation in the Scots pine stands of the Kastamonu region. Furthermore, it has been demonstrated through a paired sample *t*-test that the models developed by Şenyurt (2011) can also be used for volume estimation. However, when examining the residual distributions of the predictions from both the models developed in this study and those by Şenyurt (2011), it is evident that the models tailored for the region provide more reliable predictions. The tree volume equations developed in this study are valid for volume estimations in Scots pine stands of the Kastamonu region. However, in cases where these equations are to be used for volume estimations of Scots pine in different areas, it is necessary to further assess their suitability for those regions.

4. Conclusion

In this study, single- and double-entry tree volume equations were developed to estimate the stem volume of Scots pine trees in the Kastamonu region. To achieve this object, diameter at breast height and tree height measurements were taken from 127 sample trees obtained from the Kastamonu Forest Enterprise. The volumes of the sample trees were calculated using the sectional method. The developed single- and double-entry models have high coefficients of determination. According to relative ranking, the best predictive single-entry tree volume equation is Model 4, while the best predictive double-entry tree volume equation is Model 8.

According to the information obtained from management plans, the site productivity values of the sampled Scots pine stand in the study area are relatively similar. Consequently, the performance of single- and double-entry tree volume equations are not significantly different from each other. Nevertheless, the error statistics have been relatively calculated to be lower for double-entry equations. While double-entry tree volume equations are recommended for scientific studies requiring reliable volume estimates, it appears that single-entry tree volume equations may be utilized in practical applications where time and cost are of great importance. The developed double-entry model was also compared with existing tree volume equations, and it was observed that the Model 8 presented lower estimation errors. Furthermore, it was determined that the predictions from tree volume equation developed by Şenyurt (2011) did not show a significant difference from the observed volume values. The results of this study will contribute to the reliable estimation of stem volumes for Scots pine trees in the Kastamonu region.

Continuing studies on the development and comparison of tree volume equations, which are one of the essential tools for establishing projections related to forest stands, for the native forest tree species found in Türkiye under different ecological conditions will provide significant contributions to the forestry of Türkiye.

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