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Research Article / Araştırma Makalesi

Individual taper models for natural cedar and Taurus fir mixed stands of Bucak Region, Turkey

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Abstract: In this study, we assessed the performance of different types of taper equations for predicting tree diameters at specific heights and total stem volumes for mixed stands of Taurus cedar (*Cedrus libani* A. Rich.) and Taurus fir (*Abies cilicica* Carr.). We used data from mixed stands containing a total of 131 cedar and 124 Taurus fir trees. We evaluated six commonly used and well-known forestry taper functions developed by a variety of researchers (Biging (1984), Zakrzewski (1999), Muhairwe (1999), Fang et al. (2000), Kozak (2004), and Sharma and Zhang (2004)). To address problems related to autocorrelation and multicollinearity in the hierarchical data associated with the construction of taper models, we used appropriate statistical procedures for the model fitting. We compared model performances based on the analysis of three goodness-of-fit statistics and found the compatible segmented model of Fang et al. (2000) to be superior in describing the stem profile and stem volume of both tree species in mixed stands. The equation used by Zakrzewski (1999) exhibited the poorest fitting results of the three taper equations. In general, we found segmented taper equations to provide more accurate predictions than variable-form models for both tree species. Results from the non-linear extra sum of squares method indicate that stem tapers differ among tree species in mixed stands. Therefore, a different taper function should be used for each tree species in mixed stands in the Bucak district. Using individual-specific taper equations yields more robust estimations and, therefore, will enhance the prediction accuracy of diameters at different heights and volumes in mixed stands.

Keywords: Segmented model, compatible equation, stem form, merchantable volume, autocorrelation, *F*- test

Bucak Yöresi doğal sedir ve Toros göknarı karışık meşcereleri için gövde çapı modelleri

Özet: Çalışmada, Bucak Yöresi doğal karışık sedir (*Cedrus libani* A. Rich.) ve Toros göknarı (*Abies cilicica* Carr.) meşcereleri için gövde çapı modelleri geliştirilmiştir. Bu amaçla sedir ve Toros göknarı karışık meşcerelerinden, 131 adet sedir 124 adet Toros göknarı ölçülmüştür. Çalışmada, ormancılıkta yaygın olarak kullanılan Biging (1984), Zakrzewski (1999), Muhairwe (1999), Fang ve ark. (2000), Sharma ve Zhang (2004) ve Kozak (2004)'ın modelleri test edilmiştir. Modellerinin geliştirilmesinde, hiyerarşik verilerdeki çoklu bağıntı ve otokorelasyon problemlerini de dikkate alan uygun istatistiksel yöntemler kullanılmıştır. Geliştirilen gövde çapı denklemlerinin tahmin performanslarının değerlendirilmesinde, üç farklı ölçüt kullanılmıştır. Karışımdaki her iki tür için de, Fang ve ark. (2000) tarafından geliştirilen uyumlu gövde çapı modelinin, çap, ticari boy, ticari hacim ve toplam gövde hacmi tahminlerinde, diğer modellerden daha başarılı olduğu görülmüştür. Zakrzewski (1999)'nin modeli ise diğer modellerle karşılaştırıldığında, her iki tür için de en başarısız modeldir. Karışımı oluşturan sedir ve göknar türleri için ayrı gövde çapı ve hacim modeline ihtiyaç olup olmadığı *F-testi* ile ortaya konmuştur. Yapılan değerlendirmelerde, sedir ve göknar türleri için farklı çap ve hacim denklemlerinin kullanılması gerektiği ortaya çıkmıştır. Geliştirilen gövde çapı modelleri ile Bucak Yöresi karışık sedir ve göknar meşcerelerindeki ağaç türleri için daha doğru çap ve hacim tahminleri yapılabilmesi mümkündür.

Anahtar Kelimeler: Parçalı model, uyumlu denklem, gövde formu, ticari hacim, otokorelasyon, *F* testi

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1. INTRODUCTION

Turkey's forest cover is about 21.68 million ha according to the recent forest inventories. 41 percent of these forests are considered to be mixed forests (GDF, 2012). The total tree growing stock of Turkey is about 1.3 billion m^3 according to the forest inventory information of 2006. 707 million m^3 (55%) of this growing stock is consist of the mixed stand forests (GDF, 2006). Thus, mixed stands and mixed forest have an important role on Turkey's forestry. As stated by Kapucu (1988) mixed stands are formed when a tree species find proper growth conditions in another species' habitat.

Many studies showed that mixed stands have some advantages such as ecological-biological superiority, ecosystem diversity, aesthetic visuals, resistance to the biotic and abiotic factors and high efficiency on light and water resources when compared to the pure stands (Kapucu, 1988; Knoke et al., 2005; Griess and Knoke, 2011; Bielak et al., 2014; Sterba et al., 2014; Pretzsch and Schütze, 2014). Because of the advantages of mixed stands explained above, the approach of preservation of current mixed stands and creating the new ones are strongly suggested on all around the world.

As indicated by Weiskittel et al. (2016), growth and yield models have an important role for forest management practices. However, a relatively limited growth and yield studies exist about growth characteristics and managements principles of mixed stands in Turkey. The most comprehensive work was studied by Kapucu (1988) for mixed stands in Eastern Black sea region. Other than this, some studies have been carried out by Çalışkan (1989) about growth relationships of mixed stands in Büyükdüz Research Forests of Karabük, Sönmez and Şahin (2008) developed diameter increment models for mixed stands of oriental spruce, Özdemir (2011) presented simulation of growth and development for mixed stands in Büyükdüz Region of Karabük, Kahriman (2011) developed growth models for oriental spruce and scots pine in Black Sea Region, Durkaya et al. (2012) presented biomass estimation in mixed stands of Bartın Region and Kaya (2016) developed merchantable volume systems for mixed stands in Devrek Region of Zonguldak. However, most of the growth and yield studies have been carried out on same or differed aged pure stands in Turkey. As indicated by Yavuz et al. (2010) mixed stands show diversity in terms of number of species, mix ratio, habitat conditions and structure. Thus, growth characteristics and management principles that belongs to pure stands are not suitable and applicable for mixed stands. Therefore, more studies should be carried out about growth and development characteristics of mixed stands.

The information obtained with the growth and yield models will provide useful information for decision makers about forest management applications, updating the forest inventory information, future yield prediction, and obtaining different methods and techniques (Castedo-Dorado et al., 2012). Volume estimation is one of the most components of growth and yield models. Volume estimation is an important tool to predicting upper stem diameter and volume to different merchantable height (Dieguez-Aranda et al., 2006; Crecente-Campo et al., 2009), to forest management and planning (de-Miguel et al., 2012; Rodríguez et al., 2015), to projecting regarding future of forest products industry (Fang et al., 2000; de-Miguel et al., 2012), to monitoring forest health and productivity and to estimating biomass and carbon stocks (Castedo-Dorado et al., 2012; Gomez-Garcia et al., 2015). Stem taper models are one of the most accurate and efficient procedures to estimate tree volume (Jiang et al., 2005).

Many stem diameter models have been presented over the past 100 years for describe the tree stem shape. Two major groups of taper model form are used in forestry practice with success today (Fang et al., 2000). The one express variable exponent taper equation assumes that tree form varies continuously along the bole. In these models, the regression exponent varies from the ground to the top in order to compensate for the neiloid, paraboloid, and conic forms within a tree bole (Newnham, 1992; Kozak, 1988; Kozak 2004). However, variable form models have some disadvantages. These models cannot be integrated directly to calculate volume and volume must be calculated by numerical integration from as estimated diameter. The other expresses segmented taper models assume that the tree bole is divisible into three geometric shapes: a neiloid frustum at the base, a paraboloid frustum in the middle portion, and a cone frustum at the top. These three segments are fitted with different equations, and later mathematically joined to generate an overall taper function. This approach requires the proper specification of inflection and other joining points to ensure smooth connections of the segments. These form taper models can be integrated directly to calculate volume and can be rearrangement algebraically to directly estimate merchantable height for a given top dimeter (Fang et al., 2000).

Although many studies have been carried out about taper and volume equations for more than ten decades, there are only a few studies present in Turkey. In these studies, parameters have been estimated for the models developed in different countries that can be applied to some tree species on regional level in Turkey (Sakıcı et al., 2008; Brooks et al., 2008; Özçelik and Brooks, 2012; Özçelik and Yaşar, 2015; Özçelik and Crecente-Campo, 2016; Gomez-Garcia et al., 2016). Nevertheless, taper and stem volume equations for the mixed stands are developed by Kaya (2016) only for the mixed stands of black pine and scots pine in Devrek Region of Zonguldak. In that study, only two models were tested and total volume estimations has not been obtained.

In this study, we aimed to find the best taper model among different equation forms (simple, variable-exponent, and segmented) for stem diameter, merchantable height and volume, and total stem volume estimations for the mixed stands of cedar and Taurus fir in Bucak Region of Turkey. For this purpose, six commonly used and well-known taper equations were chosen and applied separately for each tree species in mix. On the second stage of this study, we evaluated whether the taper models vary among tree species in mix using nonlinear extra sum of squares procedure.

2. MATERIALS AND METHODS

2.1 Materials

Turkey's forest management regulations indicated that a second tree species should be mixed at least 10% in terms of volume to be able to define a stand as a mixed stand (GDF, 2008). Therefore, cedar and Taurus fir mixed stands which met criteria explained above have been selected as a study area in Isparta Forest Directorate, Uğurlu Forest Management Unit of Bucak Forest Region. Necessary tree sampling data is collected from these areas to develop stem taper and volume equations. 255 trees which 131 of them is cedar and 124 of them is Taurus fir, have been measured on field for this purpose. Trees were selected to ensure a representative distribution by diameter and height classes. Trees possessing multiple stems, broken tops, obvious cankers or crooked boles were not included in the sample. Diameter at breast height (*D,* cm) was measured and recorded to nearest 0.1 cm. The trees were later felled, a tape stretched along the stem from base to tree tip for measuring the total height (*H*, m) of individual tree, which recorded to the nearest 0.01 m. Stem diameters over bark were measured at 0.3 (stump height), 2.3, 3.3 and 4.3 and every 1 m up to the tree tip. Estimation of the log volumes was performed in cubic meters with the help of Smalian's formula. The top section of the stem was assumed as a cone. The sum of over bark log and the top of the tree volumes gave us the over bark total stem volume.

Developing stem taper and stem volume models for both tree species were not tested with an independent data in this study. Model validation is usually desired with an independent data (Kozak and Kozak, 2003). Because of obtaining an independent data set is extremely difficult, some alternative techniques like cross validations and double cross validation have been suggested for validating the models. However, these validation procedures do not assure extra information compared with the respective statistics obtained directly from models built from the all data sets. The relative height-relative diameter relationship for both tree species is shown in Figure 1. Descriptive statistics for both tree species are presented in Table 1.

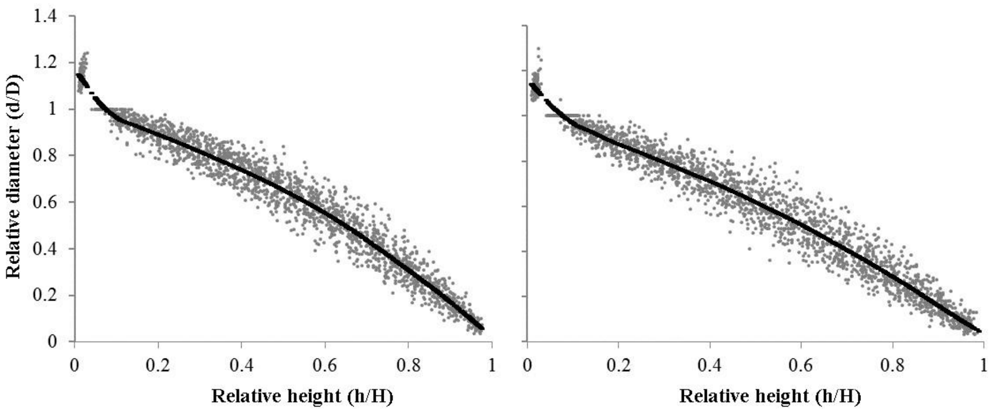

Figure 1. Relative height-relative diameter relationship for cedar (a) and Taurus fir (b)

Şekil 1. Sedir (a) ve Toros göknarı (b) için nisbi boy-nisbi çap ilişkileri

Table 1. Descriptive statistics for cedar and Taurus fir trees
Tablo 1. Sedir ve Toros göknarı için nitelendirici istatistikler

Species	***Variable***	**Average**	**S.D.**	**Minimum**	**Maximum**
Cedar (*n=131*)	*D* (cm)	28.70	7.21	14.00	51.00
	H (m)	20.38	3.63	10.00	31.50
	d (cm)	18.20	9.53	1.00	55.00
	h (m)	9.77	6.13	0.30	30.30
	v (m^3)	0.48	0.39	0.02	3.04
	V (m^3)	0.66	0.45	0.08	3.04
Taurus Fir (*n=124*)	*D* (cm)	32.50	10.88	12.00	64.00
	H (m)	18.73	4.52	9.70	31.40
	d (cm)	19.68	11.78	1.00	70.00
	h (m)	9.05	5.93	0.30	30.30
	v (m^3)	0.60	0.67	0.02	4.18
	V (m^3)	0.80	0.80	0.06	4.18

D: diameter at breast height over bark (cm, 1.3 m); *H*: total tree height (m); *d*: diameter over bark at height *h* (m); *h:* height of i^{th} point from ground (m); *v*: merchantable volume with bark (m^3); *V*: stem volume with bark (m^3).

2.2 Methods

2.2.1 Stem taper models

Many taper models have been developed for the last 10 decades (Max and Burkhart, 1976; Clark et al., 1991; Fang et al., 2000; Kozak 2004, etc.,). Sharma and Zhang (2004) stated that the main limitation of taper equations is that they are species specific, thus the model accuracy depends on the species being analyzed. Furthermore, the model choice will rely on stem forms characteristics of each species such as thinning, density, soil type, and site conditions (Muhairwe et al., 1999). In this study, some of the most used stem taper models were tested.

These models are Biging (1984), Zakrzewski (1999), Muhairwe et al. (1999), Fang et al., (2000), Sharma and Zhang (2004), and Kozak (2004), respectively. Among them, the Fang et al., (2000) and Kozak (2004) models are used to estimate upper stem diameter and stem volume for various species in many studies. Zakrzewski (1999) and Muhairwe et al. (1999) were used in only a few studies in order to develop taper equations in Turkey (Özçelik et al. 2016; Özçelik and Crecente-Campo, 2016). Table 2 shows the formulas and explanations of these models.

Table 2. Taper models and compatible volume systems analyzed in study
Tablo 2. Çalışmada kullanılan gövde çapı modelleri ve uyumlu hacim sistemleri

Model	Equation	
Biging (1984)	$d = D\left[b_1 + b_2 \ln\left\{1-\left(1-\exp(\frac{-b_1}{b_2})\right)\left(\frac{h}{H}\right)^{1/3}\right\}\right]$	(1)
Zakrzewski (1999)	$ca_z = \left(\frac{C(Z_0 - s))}{Z_0^2 + b_1 Z_0^3 + b_2 Z_0^4}\right)\left(\frac{Z_1^2 + b_1 Z_1^3 + b_2 Z_1^4}{Z_1 - s}\right)$ where: $Z_0 = \frac{H-1.30}{H}$, $Z_1 = \frac{H-h}{H}$,	(2)
Muhairwe et al. (1999)	$d = b_1 D^{b2} b_3^D \left[1-\sqrt{Z}\right]^{\left(b_3 Z + b_4 Z^2 + \frac{b_5}{Z} + b_6 Z^3 + b_7 D + b_8 (D/H)\right)}$	(3)
Fang et al. (2000)	$d = c_1 \sqrt{H^{(k-b_4)/b_4} (1-Z)^{(k-b)/b} \alpha_1^{I_1+I_2} \alpha_2^{I_2}}$ where: $k = \pi/40{,}000$, $Z = h/H$, $\begin{cases} I_1 = 1 \text{ if } p_1 \le Z \le p_2; 0 \; otherwise \\ I_2 = 1 \text{ if } p_2 < Z \le 1; 0 \; otherwise \end{cases}$, $p_1 = h_1/H$ and $p_2 = h_2/H$ (h_1 and h_2 are the heights from ground level where the two inflection points assumed in the model occur), $b = b_4^{1-(I_1+I_2)} b_5^{I_1} b_6^{I_2}$, $\alpha_1 = (1-p_1)^{(b_5-b_4)k/b_4 b_5}$, $\alpha_2 = (1-p_2)^{(b_6-b_5)k/b_5 b_6}$, $r_0 = ((1-h_{st})/H)^{k/b_4}$, $r_1 = (1-p_1)^{k/b_4}$, $r_2 = (1-p_2)^{k/b_5}$, $c_1 = \sqrt{\frac{b_1 D^{b_2} H^{b_3 - k/b_4}}{b_4(r_0 - r_1) + b_5(r_1 - \alpha_1 r_2) + b_6 \alpha_1 r_2}}$, The compatible models for merchantable (v) and total volume (V) from stump height are: $v = c_1^2 H^{k/b_4} \left(b_4 r_0 + (I_1 + I_2)(b_5 - b_4) r_1 + I_2 (b_6 - b_5) \alpha_1 r_2 - \beta (1-Z)^{k/\beta} \alpha_1^{I_1+I_2} \alpha_2^{I_2}\right)$ $V = b_1 D^{b_2} H^{b_3}$	(4)
Kozak (2004)	$d = b_1 D^{b_2} H^{b_3} x^{b_4 Z^4 + b_5 (1/e^{D/H}) + b_6 x^{0.1} + b_7 (1/D) + b_8 H^w + b_9 x}$ where: $x = w/\left(1-(1.3/H)^{1/3}\right)$, $w = 1 - Z^{1/3}$, $Z = h/H$	(5)
Sharma and Zhang (2004)	$d = D\left(b_1 \left(\frac{H-h}{H-1.3}\right)\left(\frac{h}{1.3}\right)^{2-(b_2 + b_3 Z + b_4 Z^2)}\right)^{0.5}$ where: $Z = \frac{h}{H}$	(6)

D, diameter at breast height (cm); *H*, total tree height (m); *d*, diameter outside bark at height *h* (m), b_i and p_i are the parameters to be estimated

2.2.2 Statistical Analysis

Multicollinearity is a problem when using regression analysis in empirical forest modeling especially in overcomplicated taper equations with several polynomial terms (Kozak 1997). At high levels of multicollinearity, minor changes in the data may result in large differences in parameter estimates, and high standard errors of the estimates. Thus, appropriate statistical procedures should be applied to refrain problems of autocorrelated errors and models with low multicollinearity should be selected whenever possible (Kozak, 1997). The presence of multicollinearity is assessed using the condition number (CN-the square root of the largest eigenvalue divided by the smallest eigenvalue of the correlation ratios) in this study. If the CN is given by the interval 5-10 collinearity is not a problem, if it is in between 30-100, there are associated problems of collinearity, and if it is in between 100 and 3000 there are serious problems associated with the collinearity of variables (Belsey, 1991). Myers (1990) stated that if the CN is larger than 32, it is an indicative of serious multicollinearity. According to Guangyi et al., (2015) collinearity is strongly correlated with the number of parameters of the model developed, thus, an increase at the number of parameters causes the increase of probability of the problems associated with the collinearity.

Because the data contains multiple observations for each tree, it is possible to expect that the measurements within each tree are spatially correlated. This situation disrupts the presumption of independent error terms. A continuous-time autoregressive error structure CAR(x) was used to account for the inherent autocorrelation of the data. To test for the level of autocorrelation and the order of the CAR(x) to be used, plots representing residuals versus residuals from previous observations (lag-residuals) within each tree were examined visually (Dieguez-Aranda et al., 2000). Appropriate fits for the models with correlated errors were done by including the CAR(x) error structure in the MODEL procedure of SAS system (SAS Institute, 2010).

2.2.3 Evaluation statistics for judging the model performance

For evaluation of practical differences, evaluation statistics explained below were used to assess the goodness of fit for the models analyzed in this study. They included coefficient of determination (R^2), root mean square error (RMSE), and Akaike's information criterion (AIC). These statistics are defined as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{i=n}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{i=n}\left(Y_i - \overline{Y}_i\right)^2} \quad (7)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{i=n}\left(y_i - \hat{y}_i\right)^2}{n-p}} \quad (8)$$

$$\text{AIC} = n\log\left(\sum_{i=1}^{i=n}\left(y_i - \hat{y}_i\right)^2 / n\right) + 2p \quad (9)$$

Where y_i , $\hat{y}_i$ and $\overline{y}$ are the observed, predicted and mean value of the measured variables, respectively; n is observations number in the dataset; and p is the number of estimated parameters.

For the analyzed models, estimates of the height at which each commercial diameter happens were also obtained. Since most of the models cannot be inversed to obtain an explicit mathematical solution for height estimation depending on diameter (d), numerical solutions were obtained through an iterative method. For this aim, we used the bisection method. In addition, merchantable tree volume (v) was computed for each diameter (d) by means of the QUAD subroutine of the SAS statistical package, which performs numerical integration of a scalar function in one dimension over a finite interval (SAS Institute 2010). The above mentioned statistics were also calculated using the h and v "predicted" values.

2.2.4. Relative Rankings of Models

As indicated by Poudel and Cao (2013), when comparing different fitting procedures, the traditional standard or ordinal ranks for m methods are 1, 2, …, m. They show the order of the methods, but fail to depict the exact positions of the methods compared with one another. The same may be argued for the comparison of some models using fitting statistics. In this study, we used the method of ranking presented by Poudel and Cao (2013) to display the relative position of the different models, and to depict the exact position of each model compared with the others. The relative rank of model i is defined as:

$$R_i = 1 + \frac{(m-1)(S_i - S_{min})}{S_{max} - S_{min}} \tag{10}$$

Where, R_i is the relative rank of model i (i=1, 2, …, m), S_i is the goodness-of-fit statistics produced by model i, S_{min} is the minimum value of S_i, and S_{max} is the maximum value of S_i.

The best and the worst models have relative ranks of 1 and 6 in this ranking system, respectively, while ranks of the remaining methods are expressed as real numbers between 1 and 6. Because the magnitude and not only the order of evaluation statistics is taken into consideration, the relative ranking system should provide more information than the traditional ordinal ranks. It can be used to make groups for similar models (e.g., Poudel and Cao, 2013).

We applied this ranking system using the R^2, RMSE, and AIC statistics for each variable (i.e., diameter, height, merchantable volume, and total volume), and we calculate an average rank value. Then we calculate an overall rank value by using evaluation statistics for all variables.

The nonlinear extra sum of squares procedure was used to determine whether differences in the analyzed taper functions among different species (Bates and Watts, 1988). This method has been used to evaluate whether separate taper models are necessary for different species (Corral-Rivas et al., 2007), different geographic regions (Crecente-Campo et al., 2009) or different ecoregions (Huang et al., 1999). This method requires the fitting of reduced and full models. If there is no significant difference between the parameters of taper equations developed for different tree species, it can be assumed that a common taper equation can be used for all these tree species. Thus, forest inventory costs can be reduced significantly. *F*-test given by Bates and Watt (1988) can be written in following form:

$$F = \frac{(SSE_R - SSE_F)/(df_R - df_F)}{SSE_F / df_F} \tag{11}$$

where,

SSE_R = error sum of squares of the reduced model,

SSE_F = error sum of squares of the full model,

df_R = degree of freedom of the reduced model,

df_F = degree of freedom of the full model.

Generally, when a significant *F*-value ($P<0.05$) is obtained, should the taper function for these species be considered different.

3. RESULTS AND DISCUSSION

Firstly, the models were fitted by ordinary nonlinear least squares (ONLS) without expanding the error terms to account for autocorrelation. However, presence of a strong autocorrelation was observed. A trend in residuals as a function of lag1- and lag2-residuals within the same tree was apparent in all the models analyzed, as expected because of the longitudinal nature of the data used for model fitting. Figure 2 (first row) provides an example of this with the model of Fang et al. (2000) for Taurus fir. Firstly, CAR (1) structure was used to correct autocorrelation, but the trends in residuals was not able to been disappeared completely (Figure 2, second row). After inclusion of CAR (2) structure, the trends in residuals cleared out (Figure 3, third row).

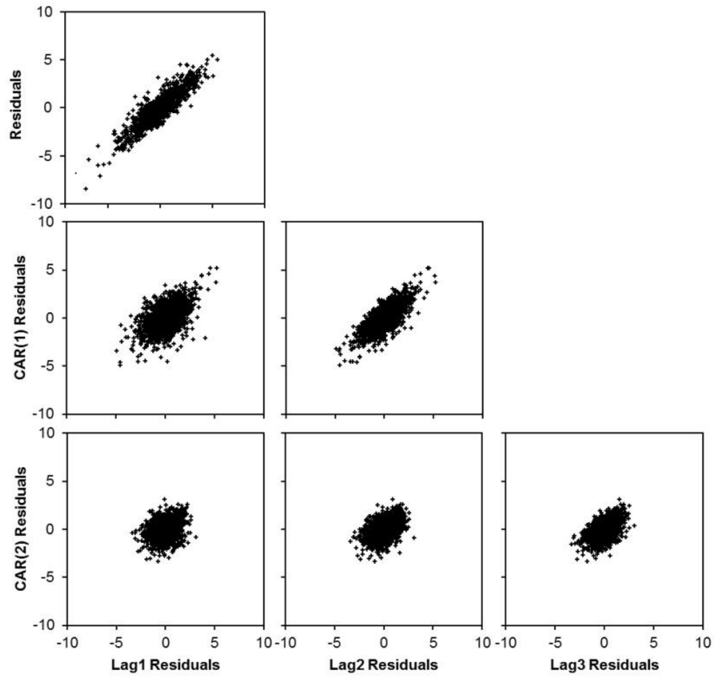

Figure 2. *d* residuals plotted against: Lag1-residuals (left column), Lag2-residuals (middle column), and Lag3-residuals (right column) for the Fang et al. (2000) fitted without considering the autocorrelation parameters (first row), and with continuous autoregressive error structures of first and second order (second and third rows) for Taurus fir

Şekil 2. Toros göknarında çap tahmininde ortaya çıkan hatalar için, Fang et al. (2000) modelinin parametreleri arasında otokorelasyon olmadığı (ilk satır) ve otoregresive hata yapıları CAR (1) ve CAR(2) ile testi (sırasıyla ikinci ve üçüncü satırlar)

The level of multicollinearity of the equations tested was determined by calculating condition number (CN). It can be said all of the models developed for each tree species in cedar-Taurus fir mixed stands in Bucak Region of Burdur have the multicollinearity problem on an intermediate level. The condition number for Taurus fir changes in the range of 3-625, while these values changes in the range of 3-641 for the cedar. While Biging (1984) model has the lowest value in terms of condition number for both tree species, Muhairwe et al. (1999) model has the highest value for both tree species as well. Biging (1984) model which has the lowest condition number value, has only two parameters. On the other hand, Muhairwe et al. (1999) model has the highest condition number value and has eight parameters. Furthermore, intermediate level multicollinearity which all these models have no important effect in terms of practical usage of the models.

Estimated parameter of fitted models and their approximate standard errors for cedar and Taurus fir species are presented in Table 3. All the parameters were significant at $P<0.0001$ for six taper equations for both tree species. The models tested in this study reasonably good data fits (Table 4) and explained for more than 99%, 96%, 98%, and 97% of the total variance of *d* (stem diameter), *h* (merchantable height), *v* (merchantable volume), *V* (toplam gövde hacmi) for both tree species, except for Zakrzewski (1999) taper model, respectively. RMSE values ranged from 0.82-1.07, 1.03-1.41, 0.05-0.09, and 0.07-0.10 cm for *d*, *h*, *v* and *V* depending on tree species, respectively. The taper model of Fang et al. (2000) provided slightly better results than the other models for the both tree species for diameter along the stem, merchantable height, merchantable volume and total volume predictions. These results show similarities with both local and international literatures (Dieguez-Aranda et al. 2006; Crecente-Campo et al. 2009; Li and Weiskittel 2010; Menendez-Miguelez et al. 2014; Özçelik and Karaer 2016 and Özçelik and Crecente-Campo, 2016). The model of Zakrzewski (1999) had lower performance compared to other stem diameter models for both tree species in mix (Table 4).

In this study, merchantable height, merchantable volume and total volume estimates were obtained by using coefficients for taper equations. Fit statistics were computed to evaluate stem diameter, merchantable diameter at any height, merchantable volume and total volume predictions and are shown in Table 4. The relative ranks were computed from the means of the statistics for each estimation (stem diameter, merchantable height, merchantable volume, and total volume) based on the method presented in section 2.2.4 and results are presented in Table 4. Overall relative rank for all estimations based on relative ranks of each estimation computed to find the best method for each tree species in mix. However, all the models are supposed to be successful according to the relative rankings, expect Zakrzewski (1999) for cedar and Zakrzewski (1999) and Biging (1984) for Taurus fir.

Segmented taper functions use inflection points to describe the stem profile by combining the different parts of the stem. The first inflection point of Fang et al. (2000) model was at around 6.4% and 5.9% of total height for cedar and Taurus fir, respectively. The second inflection point was at around 58.3% and 45.8% of total height for cedar and Taurus fir, respectively. It can be assumed that the p_1 inflection point is near to the diameter breast height for both tree species. The second inflection point, p_2, is a little bit higher of the half of the total height for cedar; and is a little bit lower of the half of the total tree height for Taurus fir. However, this second inflection point is near to the beginning of the crown for both tree species. These results suggest that two inflection points should be used to more accurate stem diameter and tree volume predictions in mixed stands of cedar and Taurus fir in Bucak region.

Similar results were obtained earlier studies by Fang et al. (2000), Crecente-Campo et al. (2009) and Quinonoz-Barraza et al. (2014). The form factor values for the tree species are 0.166, 0.433 and 0.369 for cedar, 0.178, 0.382 and 0.369 for Taurus fir, respectively. Both show that form factor values are low at bottom, high at the top, and moderate in the middle for both tree species. These form factor values almost similar to 0.250, 0.500, and 333 for neiloid, paraboloid, and cone, respectively. According to these results, it can be said the lover part of the stem is similar to neiloid, the middle part is similar to paraboloid and the upper part is similar to cone for both tree species. Considering the inflection points that were obtained with the model Fang et al. (2000) for both tree species, first inflection point of cedar is located lower and the second one is located higher when compared with the Taurus fir. Thus, it can be said cedar stem is more cylindrical than the Taurus firs. This situation makes cedar more valuable in terms of merchantable volume.

The plots of d, h, v, V residuals against relative height classes, relative diameter, and diameter classes are shown in Figure 3 and 4 for both tree species, respectively. These values were obtained with the help of the models of Fang et al. (2000) and Zakrzewski (1999), respectively. As shown on the Figure 3, when predicting the stem diameter for cedar, there is no significant difference for relative heights between the models. However, Fang et al. (2000) s model variance gives lower values for relative height classes. Although the model of Fang et al. (2000) produced positive residuals for all relative height classes, the model of Zakrzewski (1999) produced positive residuals for the first half of the relative height classes and negative residuals for the second part of the relative height classes. Residuals for relative height classes are lower at the first part of the stem, especially when compared to the second part for both models. The most valuable parts of a tree are the lower and middle parts of the stem in terms of high quality timber production. Thus, producing high residuals on the upper parts of the stem by the models developed is not a considerable problem in practical applications (Jiang et al., 2005; Li and Weiskittel, 2010; Schröder et al., 2014).

According to the plots of merchantable height prediction against diameter classes for cedar, all analyzed models showed variances for different diameter classes. The models showed larger variance values for diameter classes over 65% for both tree species. However, Fang et al. (2000) model good results with lower bias than Zakrzewski (1999) model for merchantable height predictions.

Table 3. Estimated parameters (and standard errors) for taper models
Tablo 3. Gövde çapı modelleri için tahmin edilen parametreler ve bunlara ilişkin standart hatalar

Models	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	p_1	p_2
Cedar											
Biging (1984)	1.2618 (0.0033)	0.4677 (0.0044)									
Muhairwe et al. (1999)	39726.56 (13020)	0.9170 (0.0092)	-12.7757 (0.8411)	14.9044 (1.5966)	20.2764 (0.6386)	-3.5922 (0.9689)	-0.0065 (0.0022)	-0.0046 (0.0634)			
Zakrzewski (1999)	-1.8285 (0.0119)	0.9698 (0.0109)									
Fang et al. (2000)	0.000054 ($32x10^{-7}$)	1.9159 (0.0208)	0.9496 (0.0288)	0.000013 ($26x10^{-8}$)	0.000034 ($26x10^{-8}$)	0.000029 ($31x10^{-8}$)				0.0642 (0.0016)	0.5829 (0.0117)
Kozak (2004)	1.2001 (0.0488)	0.9546 (0.0112)	-0.0035 (0.0177)	0.4401 (0.0223)	-0.2920 (0.0790)	0.3941 (0.0172)	3.4560 (0.6120)	0.0290 (0.0053)	-0.1997 (0.0435)		
Sharma and Zhang (2004)	0.9926 (0.0062)	2.1457 (0.0037)	-0.6019 (0.0359)	1.0315 (0.0440)							
Taurus fir											
Biging (1984)	1.2667 (0.0035)	0.5148 (0.0053)									
Muhairwe et al. (1999)	2015.257 (958.9)	0.9354 (0.0068)	-9.3228 (0.8557)	10.5188 (1.6417)	14.4537 (0.6417)	-1.7692 (1.0031)	-0.0021 (0.0014)	0.4026 (0.0541)			
Zakrzewski (1999)	-1.6724 (0.0149)	0.8403 (0.0133)									
Fang et al. (2000)	0.000050 ($23x10^{-7}$)	1.7985 (0.0213)	1.0936 (0.0287)	0.000014 ($40x10^{-8}$)	0.000030 ($32x10^{-8}$)	0.000029 ($36x10^{-8}$)				0.0593 (0.0023)	0.4581 (0.0363)
Kozak (2004)	1.0394 (0.0327)	0.9161 (0.0110)	0.0933 (0.0167)	0.4283 (0.0229)	-0.5865 (0.0865)	0.6154 (0.0159)	1.8137 (0.6155)	0.0041 (0.0044)	-0.1579 (0.0361)		
Sharma and Zhang (2004)	0.9873 (0.0066)	2.1235 (0.0039)	-0.3278 (0.0401)	0.8733 (0.0503)							

Table 4. Evaluation statistics and CN of models analyzed
Tablo 4. Test edilen modeller için ölçüt değerleri ve koşul sayıları

Models	Diameter				Height*				Merchantable volume**				Total volume				General relative ranking	CN
	R^2	RMSE	AIC	Rel. rank	R^2	RMSE	AIC	Rel. rank	R^2	RMSE	AIC	Rel. rank	R^2	RMSE	AIC	Rel. rank		
Cedar																		
Biging (1984)	0.9911	0.8981	-449	3.2513	0.9618	1.1474	554	1.7005	0.9836	0.0503	-12613	1.2526	0.9747	0.0656	-595	1.0000	1.2614	3
Muhairwe et al. (1999)	0.9916	0.8766	-546	2.5397	0.9611	1.1589	600	1.8910	0.9840	0.0480	-12649	1.0000	0.9741	0.0684	-580	1.7345	1.2488	641
Kozak (2004)	0.9923	0.8405	-720	1.3919	0.9620	1.1457	555	1.6785	0.9804	0.0550	-12223	2.3755	0.9704	0.0710	-578	2.3705	1.5472	86
Fang et al. (2000)	0.9925	0.8279	-787	1.0000	0.9647	1.1035	404	1.0000	0.9821	0.0526	-12415	1.8035	0.9714	0.0718	-570	2.5761	1.0000	66
Sharma and Zhang (2004)	0.9922	0.8418	-721	1.4555	0.9637	1.1190	456	1.2440	0.9828	0.0515	-12512	1.5392	0.9721	0.0696	-580	2.0292	1.0543	13
Zakrzewski (1999)	0.9893	0.9847	-61	6.0000	0.9419	1.4145	1391	6.0000	0.9678	0.0705	-11190	6.0000	0.9574	0.0852	-538	6.0000	6.0000	16
Taurus fir																		
Biging (1984)	0.9918	1.0667	277	5.3528	0.9581	1.1661	615	6.0000	0.9868	0.0766	-10836	2.2548	0.9806	0.0941	-568	4.6471	3.1718	3
Muhairwe et al. (1999)	0.9927	1.0066	38	2.0376	0.9677	1.0256	111	1.0000	0.9890	0.0699	-11218	1.0957	0.9845	0.0862	-584	1.3958	1.0539	625
Kozak (2004)	0.9929	0.9923	-20	1.2603	0.9668	1.0394	165	1.4985	0.9877	0.0740	-10975	1.7953	0.9836	0.0863	-589	1.3849	1.3468	75
Fang et al. (2000)	0.9930	0.9890	-37	1.0000	0.9670	1.0361	151	1.3784	0.9892	0.0694	-11251	1.0000	0.9849	0.0851	-586	1.0000	1.0000	67
Sharma and Zhang (2004)	0.9926	1.0170	77	2.5339	0.9638	1.0833	324	3.0659	0.9889	0.0702	-11203	1.1476	0.9839	0.0878	-574	2.3992	1.6657	12
Zakrzewski (1999)	0.9916	1.0778	320	6.0000	0.9601	1.1373	516	4.9838	0.9822	0.0887	-20	6.0000	0.9792	0.0973	-560	6.0000	6.0000	16

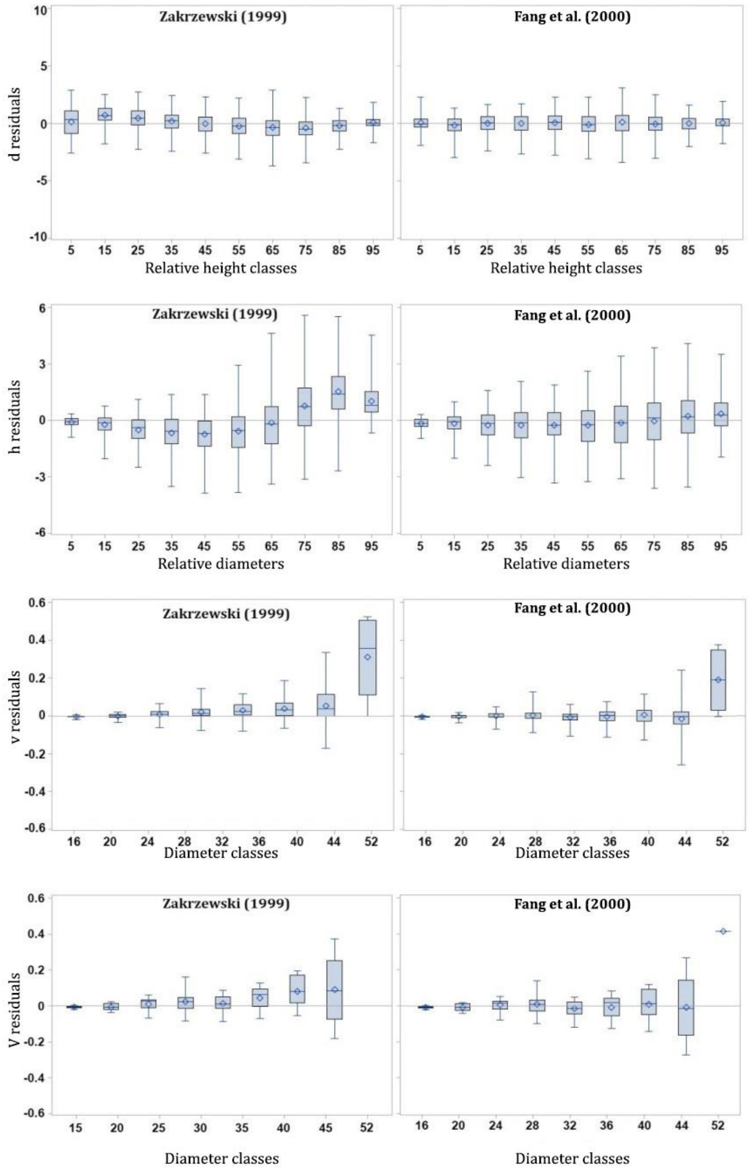

Figure 3. Box plots of d, h, v, and V residuals (Y-axis, cm) against relative height classes, relative diameter classes, and diameter classes (X-axis, in percent) for the Fang et al. (2000) and Zakrzewski (1999)'s taper models for cedar. The plus signs represent the mean of prediction errors for the corresponding relative height classes. The boxes represent the interquartile range. The maximum and minimum diameter over bark prediction errors are represented respectively by the upper and lower small horizontal lines crossing the vertical lines

Şekil 3. Sedir için Fang et al. (2000 ve Zakrzewski (1999) modellerin d, h, v_i ve V tahminlerinde ortaya çıkan artıkların nisbi boy, nisbi çap ve çap sınıflarına dağılım grafiği. Kare işareti, çap sınıfına ilişkin tahmin hatalarının ortalamasını temsil etmektedir. Kutular hataların yayılma alanını temsil etmektedir. Yukarı ve aşağı uzanan dikey çizgiler ise, maksimum ve minimum çap, boy ve hacim tahmin hatalarını temsil etmektedir

Fang et al. (2000) and Zakrzewski (1999) taper models showed similar bias trends for al stem sections for cedar. The both models showed higher error variances in larger diameter classes. But these variance is relatively lower in Fang et al. (2000) model than the Zakrzewski (1999) model. Generally, all the models produced positive residuals on lower diameter classes and negative on higher diameter classes expect some of models. The Fang et al. (2000) model has lower residual variance for all diameter classes when predicting merchantable volume.

All the models compared in terms of total volume prediction for both tree species. While all the models predict more reliable results on lower and moderate diameter classes, with the larger diameter classes (>40 cm), they produce relatively higher variances. All the models produced negative residuals for predicting above 40 cm expect the model of Zakrzewski (1999).

The error distribution to the relative heights, relative diameters, and diameter classes for the model developed for Taurus fir to predict stem diameter, merchantable height, merchantable and total volume are presented in Figure 4. Error distributions to relative height classes for all six models analyzed, showed similarities with each other. The error distributions of the Fang et al. (2000) and Zakrzewski (1999) models showed differences in different relative height classes as shown in Figure 4. It can be said that all the models produced larger bias especially of the 45-55 percent of the total tree height. This may be depend from branching begins at that height for Taurus fir.

Residuals on predicting the tree height by the relative diameter classes are presented in Figure 4. Both two models showed larger bias for relative diameters between 65-95%. All the models analyzed produced positive residuals for the larger relative diameters. All the models showed significant fluctuations on predicting tree height for all the relative diameters, expect the Fang et al. (2000) model.

When compared the bias of the best and the worst models for predicting merchantable volume, both model produced lower bias for diameter classes between 12-36 cm and relatively larger bias for diameter classes between 40 and 64 cm. The Fang et al. (2000)'s taper model showed good results with lower bias than Zakrzewski (1999) model for predicting merchantable volume. None of the models analyzed in this study produced systematic residuals for diameter classes.

In terms of the distribution of residuals for predicting the total volume, all the models produced lower residuals for lower and moderate diameter classes and relatively higher residuals for larger diameter classes. This situation may be related with the insufficient number of the trees at that diameter classes. The clearance between quarters (50% of the values in the middle) are quite lower on the model of Fang et al. (2000) when compared with the rest of the models for cedar and as well as Taurus fir. All the models expect Biging (1984), produced positive residuals for the larger diameter classes. The Fang et al. (2000) model was to be found superior to the others for predicting the total tree volume. Especially the models of Muhairwe et al. (1999), Sharma and Zhang (2004), and Kozak (2004) are quite unsuccessful for predicting merchantable and total volume when compared to the Fang et al. (2000) model. This may be related with the fact that these models are variable form taper models. This group of models cannot be converted to the volume equation by getting the integral of it for two diameter values. An iteration is required in order to estimate volume with these models.

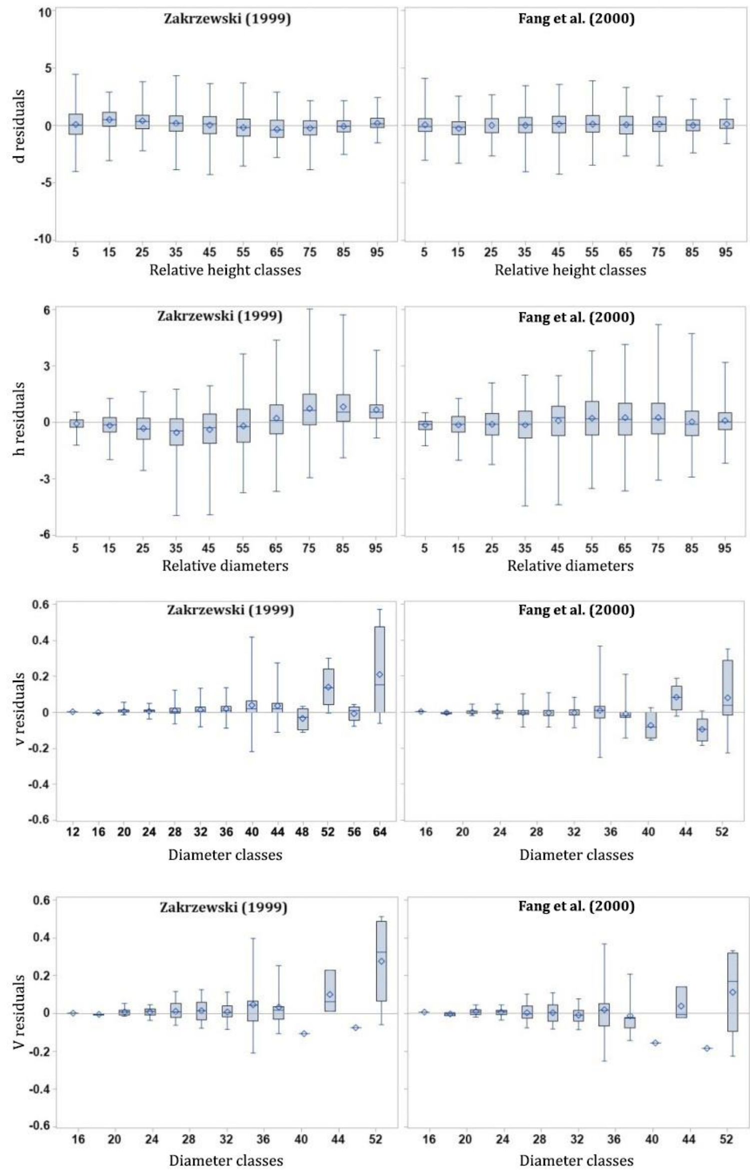

Figure 4. Box plots of *d* residuals (*Y*-axis, cm) against relative height classes, relative diameter classes, and diameter classes (*X*-axis, in percent) for the Fang et al. (2000) and Zakrzewski (1999)'s taper models for Taurus fir

Şekil 4. Toros göknarı için başarılı (Fang et al. (2000) ve başarısız (Zakrzewski (1999) modellerin gövde çapı (*d*), ticari boy (*h*), ticari hacim (v_i) ve topla hacim (*V*) tahminlerinde ortaya çıkan artıkların nisbi boy, nisbi çap ve çap sınıflarına dağılım grafiği

Comparison of the predicted stem taper in cedar and Taurus fir according to the fitted Fang et al. (2000) model, that gave the best results for both tree species with dbh 40 cm and total tree height 20 m is presented in Figure 5.

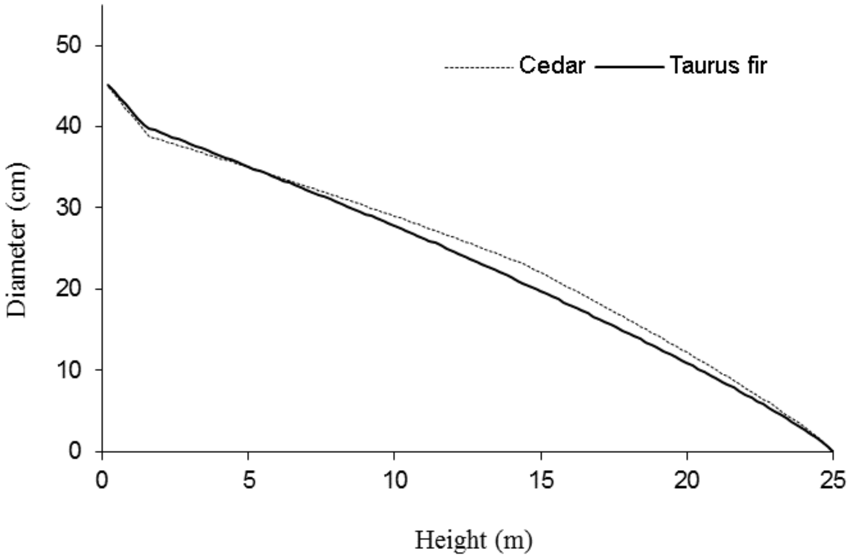

Figure 5. Comparison of the predicted stem taper in cedar and Taurus fir according to the fitted Fang et al. (2000) model with dbh 40 cm and total height 20 m

Şekil 5. Sedir ve Toros göknarı için 40 cm çap ve 25 m boya sahip bir ağaç için Fang et al. (2000) için tahmin edilen gövde çapı tahminlerinin karşılaştırılması

Of the two species, cedar has a more cylindrical stem form than Taurus fir. The comparison in Figure 5 stresses out the importance of developing separate taper functions for different species. Considering the inflection points that were obtained with the model Fang et al. (2000) for both tree species, first inflection point of cedar is located lower and the second one is located higher when compared with the Taurus fir.

Moreover, by using the Fang et al. (2000) model which gave the best results for both tree species, further analyzes were performed to assess whether separate models are necessary for different species. The nonlinear extra sum of squares method was used for this purpose (Neter et al. 1990). The results of *F*-test are presented in Table 5. The analysis indicates that there are differences among taper models from different species. Different model parameters should be predicted and used for each tree species. These results were supported by the results presented in Figure 5.

Table 5. *F*-test for the differences between tree species based on Fang et al. (2000) taper model

Tablo 5. Fang ve ark. (2000) gövde çapı modeli için türler arasındaki farklar için *F*-testi

Equation	Full Model		Reduced Model		*N*	*F-value*	*p*-value
	df_F	SSE_F	df_R	SSE_R			
Fang et al. (2000)	*4200*	*3496.90*	*4210*	*3643.80*	*4220*	17.644**	*<0.0000*

n is observation number, SSE_F, df_F, SSE_R and df_R are the sum of squared errors and the degrees of freedom associated with the full and reduced models, respectively.

4. CONCLUSIONS

Individual merchantable volume systems are developed for tree species of natural cedar and Taurus fir mixed stands in Bucak Region by using six different taper equations. Models developed by Biging (1984), Zakrzewski (1999), Muhairwe (1999), Fang et al. (2000), Sharma and Zhang (2004) and Kozak (2004) were chosen for this purpose. The reason for choosing the models explained above is some of these models have not been used in Turkey before. Furthermore, these models are more likely superior to the others.

Appropriate approaches are used to correct autocorrelation and multicollinearity. CN was used to evaluate the existence multicollinearity. CAR (2) structure was used to account for the inherent autocorrelation of the hierarchical structure of the data. The inclusion of CAR (2) structure minimized the problem with autocorrelation of models analyzed.

Models tested in this study were not only evaluated in terms of predicting stem diameter, but also were evaluated in point of merchantable height, merchantable volume and total volume. As stated by Schröder et al. (2016), a taper model should estimate stem form well, and also provide accurate predictions of stem volume as well. The obtained results showed that the taper models provided reliable and accurate predictions for the merchantable and total tree volume, as well. The RMSE values are lower than 1 cm for diameter estimation, 1.4 m for merchantable height estimation and 0.09 m^3 for merchantable and total volume estimation.

According to the relative rankings obtained from three different criteria, Fang et al. (2000) model gave best results in terms of diameter, merchantable height, merchantable and total volume for both tree species in mix. The model of Zakrzewski (1999) was to be found the most unsuccessful model in terms of the predictions explained above. However, there was no significant difference between the models of Fang et al. (2000), Muhairwe et al. (1999) and Sharma and Zhang (2004) in accordance with relative ranking. Along with that, being of a segmented model and can easily be converted into a merchantable or total volume equation, the model Fang et al. (2000) is a reason for preference.

Of the two species, cedar has a more cylindrical stem shape than Taurus fir. The comparison in Figure 5 show the importance of developing separate taper functions for different species. Considering the inflection points that were obtained with the Fang et al. (2000) model for both tree species, first inflection point of cedar is located lower and the second one is located higher when compared with the Taurus fir.

The nonlinear extra sum of squares method was used to assess the differences in the taper equations among different species. The results showed that different taper equations whereby different volume equations should be used for both tree species in cedar-Taurus fir mixed stands in Bucak Region.

Considering the results of this study as well as the previous studies, the Fang et al. (2000) model was to be found the most superior taper equation for cedar-Taurus fir mixed stands in Bucak region. Volume prediction success has also an important role beside diameter prediction success when it comes to be preferred as taper equation. Because predicting the volume is way more important than diameter prediction in practically. However, when it comes to prefer a taper equation as a model for any region, it is strongly suggested that the models should be applicable practically by the decision makers.

The results of this study are valid for cedar-Taurus fir mixed stands in Bucak Region of Burdur. Stem taper as well as stem volume varies depending many factors such as ecoregion, stand density and silvicultural applications. Thus, these factors should be considered when developing a taper model for any region. In another word, separate taper models should be developed for each region to be able to get the best results.

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