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Development of ecoregion-based height–diameter models for 3 economically important tree species of southern Turkey

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Abstract: Seven different nonlinear height (*h*)–diameter (*d*) models were developed and compared for brutian pine (*Pinus brutia* Ten.), black pine (*Pinus nigra* Arnold), and Taurus cedar (*Cedrus libani* A.Rich.) in southern Turkey. Residual analysis was conducted to identify the error structure. A weighting factor of $w_i = 1/d$ was found to be appropriate for achieving the equal error variance assumption. The performance of the models was compared and evaluated based on 6 statistical criteria and residual analysis. Results suggested that the Gompertz model was superior to the other models in terms of its predictive ability. These tree species were located throughout the Mediterranean region, covering a wide range of topographic and climatic conditions. It is well known that height–diameter relationships depend heavily on local environmental conditions. Differences in the height–diameter relationship among and between ecoregions were tested using the nonlinear extra sum of squares method. Test results suggested that height–diameter models significantly differed between ecoregions, indicating that ecoregion-based height–diameter models are needed for prediction purposes. The ecoregion-based height–diameter models developed in this study may provide more accurate information for developing forest growth and yield models.

Key words: Height–diameter model, ecoregion, Gompertz model, forest management

1. Introduction

Accurate estimation of tree height (*h*) is of critical importance to forest managers and practitioners for decision making, since tree diameter (*d*) and height allow the indirect estimation of individual tree volume, biomass, and site index and the description of stand growth dynamics and succession over time (Curtis, 1967). Parresol (1992) identified height–diameter (*h*–*d*) models as important components in yield estimation, stand description, and damage appraisal. The *h*–*d* relationship is also used to characterize the vertical structure of forest stands (Gadow et al., 2001) and to predict the height of individual trees in numerous forest growth simulators (e.g., Burkhart and Strub, 1974; Wykoff et al., 1982). Height/diameter ratios, which are an important measure of stand stability (Vospernik et al., 2010), and dominant height and competition indices can also be easily calculated by using the *h*–*d* relationship, without investing large amounts of money in height measurement (Calama and Montero, 2004). Furthermore, *h*–*d* models are needed to help forest managers better understand the nature of various relationships that characterize, differentiate, and influence the development of forest ecosystems (Peng et al., 2001).

Brutian pine (*Pinus brutia* Ten.), black pine (*Pinus nigra* Arnold), and Taurus cedar (*Cedrus libani* A.Rich.) are the most widespread and economically important tree species in Turkey. Black pine forests cover an area of about 4.2×10^6 ha, brutian pine forests cover an area of about 5.4×10^6 ha, and Taurus cedar forests cover an area of about 417,000 ha (GDF, 2006).

Forest ecosystems containing these tree species occur over a large geographic area. As a result, site conditions (climate, soil type, etc.) vary greatly throughout their range. The ability to predict the growth and yield of forest stands growing in various site conditions is critical in the development of ecologically based management plans and strategies (Klos et al., 2007). A number of model forms have been used to evaluate *h*–*d* relationships by species (Huang et al., 1992; Huang, 1999; Peng et al., 2001; Castedo-Dorado et al., 2005; Brooks and Wiant, 2007). Regional differences in *h*–*d* models were the result of different geographical and climate conditions (Huang et al., 2000; Zhang et al., 2002; Peng et al., 2004). In recent years, Turkey has adopted the

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principles of multipurpose and ecologically based forest management. Therefore, the General Directorate of Forests needs to develop and evaluate tree *h–d* models and growth and yield prediction models for management of forest resources. One of the essential building blocks in forest growth and yield modeling is the model for describing *h–d* relationships of different tree species. However, the available information regarding *h–d* relationships between forest productivity and climate and site variables concerning the above species is very limited. The existing *h–d* models in the Mediterranean region do not account for differences in climate and soil features. Since *h–d* relationships depend heavily on local environmental conditions and vary within a large geographic region (Peng et al., 2004), the development of an *h–d* model should account for the effects of soil and physiographic features, which are influenced by climate, topography, and geology. This can be accomplished with use of the ecoregion classification system developed by Kantarcı (1991) for the Mediterranean region. This classification system differentiates maritime (ME), interior (IE), and lakes (LE) ecoregions based on both soil and physiographic features. The data were grouped into the Mediterranean region in order to study differences in *h–d* relationships for the main ecoregions where these species occurs in southern Turkey (Figure 1).

The objective of this study was the development and comparison of *h–d* models for major commercial tree species growing in 3 different ecoregions.

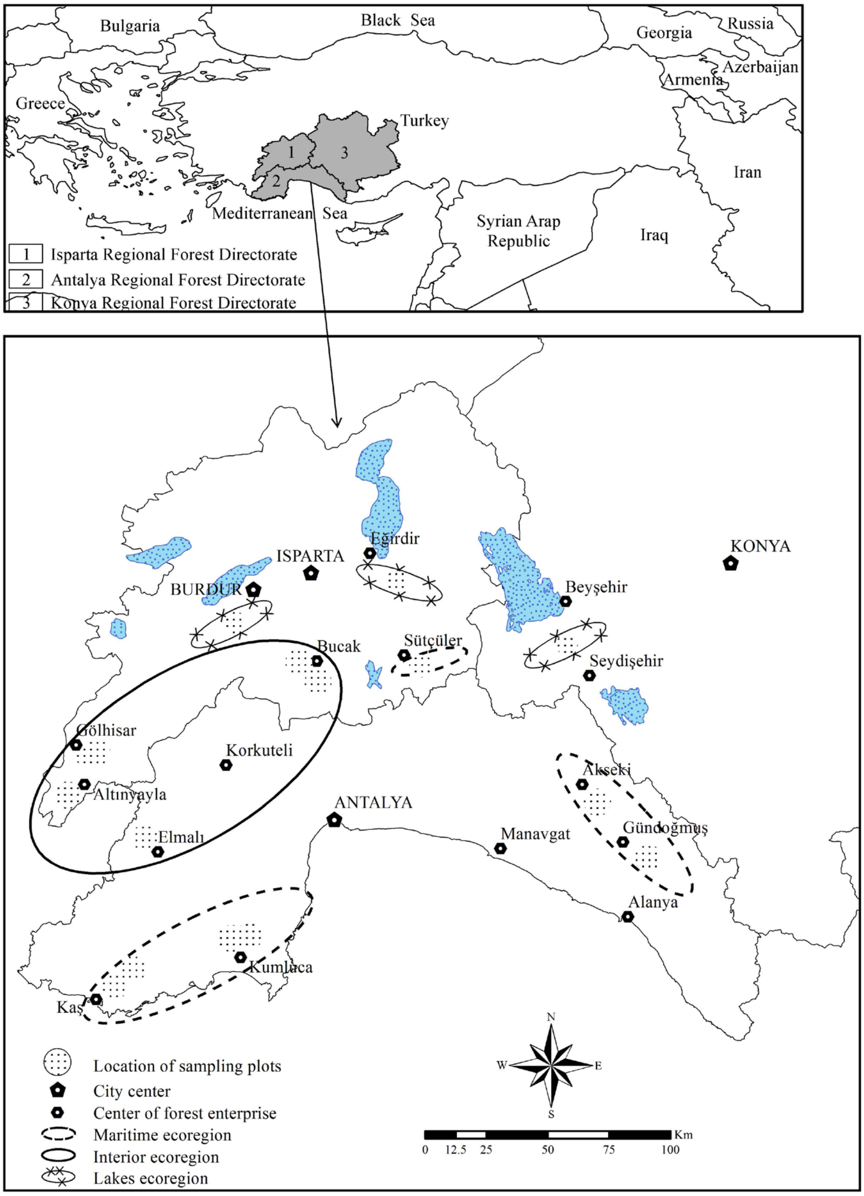

Figure 1. Simple map of ecoregion classification in Mediterranean region.

2. Materials and methods

2.1. Study sites

The Mediterranean region of Turkey is a southern coastal region, which extends from the Mediterranean Sea in the south to the central Anatolian plateau in the north. It is a mountainous area with variable physiographic characteristics, differentiated by land form, elevation, aspect, slope, position against the Mediterranean Sea and other water bodies, parent rock, and soil type (Kantarcı, 1991). The variable physiographic features result in highly diverse ecological conditions and very rich species diversity. The most common and economically important forest tree species of this region are *Pinus brutia*, *Pinus nigra*, and *Cedrus libani*, the subject species of this study. The study areas are located between 237 and 1865 m in elevation. Kantarcı (1991) divided this region into 4 major subregions, including the ME, the IE, the LE, and the backside of the Mediterranean ecoregion. The first 3 of these ecoregions are found within the geographic region encompassed by this study (Figure 1).

The ME faces the Mediterranean Sea and is under the influence of warm and humid air coming from the sea. Mean annual precipitation ranges from 882 to 1351 mm and mean annual temperature ranges from 12.2 to 18.7 °C in this ecoregion. The IE is mainly surrounded by masses of mountains and receives little or no direct effects of maritime weather. Here, mean annual precipitation ranges from 604 to 1241 mm and mean annual temperature ranges from 7.7 to 13.9 °C. The LE is located between the interiors of the Mediterranean and central Anatolia and is characterized by many small and large lakes, which affect the vegetation of the surrounding forests. Mean annual precipitation in this ecoregion ranges from 437 to 1605 mm and mean annual temperature ranges from 9.9 to 12.6 °C (Kantarcı, 1991).

Individual tree *h–d* data from 3 conifer species were collected from even-aged managed stands in the 3 different ecoregions of the Mediterranean region of Turkey. A total of 5398 destructively sampled brutian pine, black pine, and Taurus cedar trees were used in this study. These trees were felled throughout clear-cutting areas and all sampled trees were subjectively chosen to ensure a representative distribution among diameter and height classes within stands varying in density, height, stand structure, age, and site condition. On each sampled tree, 2 perpendicular diameters on the outside bark (1.3 m above ground level) were measured to the nearest 0.1 cm using electronic calipers and were then arithmetically averaged. The trees were later felled, leaving a stump with an average height of 0.30 m, and total bole length was measured to the nearest 0.05 m. The available tree *h–d* data were split into 2 sets: the majority (75%) of the data was used for model development while the remaining data (25%) in each diameter class for each species were randomly selected and reserved for model evaluation. The summary statistics for the 2 variables by species for each ecoregion are provided in Table 1.

2.2. Methods

The 7 candidate models were selected from previous studies based on their appropriate mathematical features, possible biological interpretation of parameters, and satisfactory prediction for tree *h–d* relationship in the literature (Fang and Bailey, 1998; Huang et al., 2000; Peng et al., 2001; Yuancai and Parresol, 2001; Diamantopoulou and Özçelik, 2012). These models include the most flexible equations for *h–d* relationships (Zhang, 1997; Peng et al., 2001), the Bertalanffy–Richards (Bertalanffy, 1949; Richards, 1959), Weibull (Yang et al., 1978), and Schnute (Schnute, 1981) models:

Bertalanffy–Richards (Model 1)

$$h = 1.3 + a_0 \cdot \left(1 - \exp\left(-a_1 \cdot d\right)\right)^{a_2} , \tag{1}$$

Weibull (Model 2)

$$h = 1.3 + a_0 \cdot \left(1 - \exp\left(-a_1 \cdot d^{a_2}\right)\right) , \tag{2}$$

Exponential (Model 3)

$$h = 1.3 + a_0 \cdot \exp\left(\frac{a_1}{d + a_2}\right) , \tag{3}$$

Modified-logistic (Model 4)

$$h = 1.3 + \frac{a_0}{\left(1 + a_1^{-1} . d^{-a_2}\right)} , \tag{4}$$

Korf–Lundqvist (Model 5)

$$h = 1.3 + a_0 \cdot \exp\left(-a_1 \cdot d^{-a_2}\right) , \tag{5}$$

Gompertz (Model 6)

$$h = 1.3 + a_0 \cdot \exp\left(-a_1 \cdot \exp\left(-a_2 \cdot d\right)\right) , \tag{6}$$

Schnute (Model 7)

$$h = \left(1.3^{a_0} + \left(a_1^{a_0} - 1.3^{a_0}\right)\frac{1 - \exp\left(-a_2 \cdot d\right)}{1 - \exp\left(-a_2 \cdot 100\right)}\right)^{\frac{1}{a_0}} , \tag{7}$$

where *h* is tree total height (m), *d* is tree diameter at breast height (cm), and a_0, a_1, and a_2 are the parameters to be estimated.

A fundamental assumption of least squares regression is that errors are independent and normally distributed with a mean of zero and constant variance. However, in

Table 1. Summary statistics for different ecoregions and tree species.

Ecoregions	Tree species*	Variables	Model development data					Evaluation data				
			n	Mean	Std. dev.	Min.	Max.	n	Mean	Std. dev.	Min.	Max.
Maritime ecoregion (ME)	BRM	*d* (cm)	487	36.09	12.99	9.00	72.00	190	38.40	16.69	8.00	76.00
		h (m)	487	18.31	4.98	7.60	30.40	190	20.11	5.37	8.60	31.20
	BLM	*d* (cm)	439	33.97	12.27	8.00	78.00	144	33.44	13.80	63.00	8.50
		h (m)	439	18.44	4.44	5.00	29.00	144	17.86	5.04	4.60	27.50
	CM	*d* (cm)	551	42.94	12.57	15.00	69.00	162	40.68	16.30	7.90	94.30
		h (m)	551	19.20	4.28	7.90	29.40	162	18.66	4.92	5.70	32.40
Interior ecoregion (IE)	BRI	*d* (cm)	405	40.65	13.81	9.00	72.00	128	39.03	14.47	9.00	66.00
		h (m)	405	19.44	4.58	7.00	28.00	128	19.23	4.46	7.00	28.00
	BLI	*d* (cm)	343	41.78	15.01	8.50	86.00	147	42.05	17.16	10.50	98.00
		h (m)	343	20.72	4.96	7.70	30.20	147	19.95	5.20	8.00	30.00
	CI	*d* (cm)	445	37.33	12.86	10.00	76.00	122	40.02	14.04	12.00	71.00
		h (m)	445	18.50	4.65	7.30	28.40	122	18.64	4.79	8.30	29.10
Lakes ecoregion (LE)	BRL	*d* (cm)	465	35.36	11.57	9.00	61.00	156	35.06	12.52	9.00	62.00
		h (m)	465	16.31	3.90	7.60	26.20	156	17.04	3.86	24.40	7.60
	BLL	*d* (cm)	480	34.72	12.08	11.00	65.00	153	34.16	13.66	9.00	65.00
		h (m)	480	15.94	3.80	6.70	24.60	153	15.88	4.02	6.80	25.10
	CL	*d* (cm)	420	35.66	12.60	14.60	65.60	161	30.94	11.51	9.00	55.00
		h (m)	420	17.09	4.12	6.90	29.50	161	16.23	4.77	6.30	26.70

*BRM: brutian pine in ME; BLM: black pine in ME; CM: Taurus cedar in ME; BRI: brutian pine in IE; BLI: black pine in IE; CI: Taurus cedar in IE; BRL: brutian pine in LE; BLL: black pine in LE; CL: Taurus cedar in LE.

many forest modeling situations, there is a common pattern whereby the error variation increases as the values of the dependent variable increase (Huang et al., 1992; Parresol, 1993). Because this trend was apparent within this dataset (Figure 2), weighted least squares (WLS) estimation was applied to correct this shortcoming. Based on the residuals analysis (Figure 2), a weight factor of *l*/*d* was found to be the most suitable, resulting in residual plots with a homogeneous band, and was subsequently applied in all regressions. Final parameter values were estimated using weighted nonlinear regression, using the PROC NLIN procedure within SAS (SAS Institute Inc., 2002).

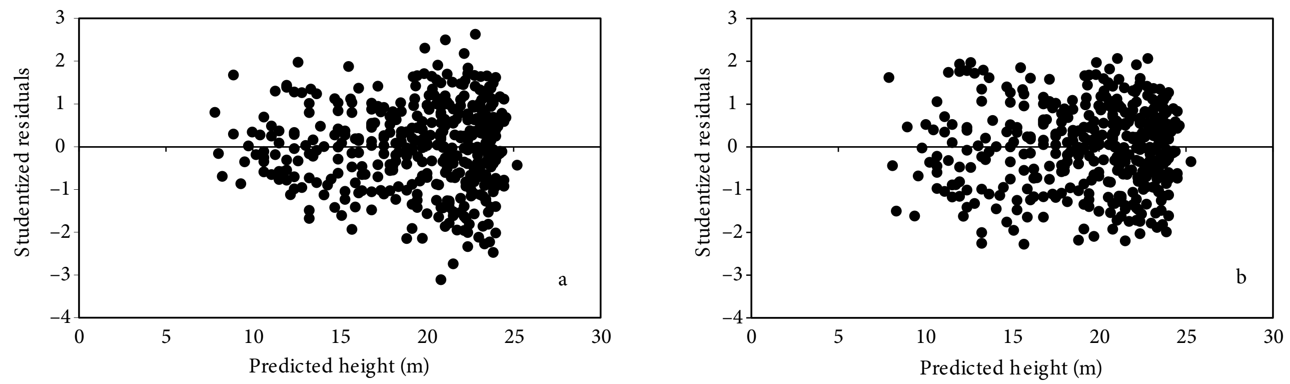

Figure 2. a) Plot of studentized residuals against the predicted height from the ordinary nonlinear least squares fit of Eq. (6) and b) plot of studentized residuals against the predicted height from WLS fit of Eq. (6), with weight $w_i=1/d$ for brutian pine in the interior ecoregion.

To simplify the evaluations of statistics such as average absolute error (AAE), maximum absolute error (MAE), root mean square error (RMSE), correlation coefficient (R), mean bias (E), and Akaike information criterion (AIC), a ranking procedure was employed for fit data. Rank 1 corresponded to the best value (lowest) for each statistic and a rank 7 to the poorest value (highest), except for R. Overall ranking was based on a sum of the individual ranks. When the values for 2 or more models were equal, the same rank was assigned (Kozak and Smith, 1993).

The nonlinear extra sum of squares procedure as demonstrated by Bates and Watts (1988) and Peng et al. (2004) was used to determine whether differences of *h–d* models existed between ecoregions. This method was recently developed and used to detect differences among geographic regions (Bates and Watts, 1998; Zhang et al., 2002). The method requires the fitting of a full model and reduced model. For the *h–d* analysis, the full model corresponds to completely different sets of parameter estimates for each of the 3 ecoregions, and the reduced model uses the same parameter estimates for all 3 ecoregions (Huang et al., 1999).

Using the dummy variable approach as indicated by Huang et al. (2000), the following full model of the Gompertz *h–d* equation for 3 ecoregions can be written as:

$$h_{ij} = 1.3 + \left(a_0 + \sum_{i=1}^{2} a_{0i} z_{0i}\right) \cdot \left[\exp\left(-\left(a_1 + \sum_{i=1}^{2} a_{1i} z_{1i}\right) \cdot \exp\left(-\left(a_2 + \sum_{i=1}^{2} a_{2i} z_{2i}\right) \cdot d_i\right)\right)\right], \quad (8)$$

where z_0, z_1, and z_2 are dummy variables for specific ecoregions, whose values equal 1 if the tree is located in that region and 0 if not. This model has 9 estimable parameters. The reduced model for this test takes the form of Eq. (7) with 3 parameters.

The appropriate test statistics for comparing the full and reduced models is an F-test:

$$F = \frac{(SSE_R - SSE_F)/(df_R - df_F)}{SSE_F / df_F}, \quad (9)$$

where SSE_R is the error sum of squares associated with the reduced model and its degrees of freedom are written as df_R. SSE_F is the error sum of squares associated with the full model and its degrees of freedom are written as df_F. Generally, the F-test is significant if the P-value for the test is less than α = 0.05.

2.3. Model performance criteria

Six statistical criteria obtained from the residuals were examined to compare the performance of the developed models: AAE; MAE; RMSE, which indicates the accuracy of the estimates; R, which is a measure used to determine the relative correlation and the goodness of fit between the estimated and the measured data (Castano-Santamaria et al., 2013); E, which indicates the precision of the model; and the AIC, which is an index used to select the best model from a group of candidate models (Akaike, 1974), all summarized as follows:

$$AAE = \frac{\sum_{i=1}^{i=n} |y_i - \hat{y}_i|}{n}, \quad (10)$$

$$MAE = \max\left(|y_i - \hat{y}_i|\right), \quad (11)$$

$$R = \frac{\sum_{i=1}^{i=n} \left[(y_i - \bar{y}) \cdot (\hat{y}_i - \bar{y}_{est})\right]}{\sqrt{\sum_{i=1}^{i=n} (y_i - \bar{y})^2} \cdot \sqrt{\sum_{i=1}^{i=n} (\hat{y}_i - \bar{y}_{est})^2}}, \quad (12)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{i=n} (y_i - \hat{y}_i)^2}{n - p}}, \quad (13)$$

$$E = \frac{\sum_{i=1}^{i=n} (y_i - \hat{y}_i)}{n}, \quad (14)$$

$$\mathrm{AIC} = n \ln(RMSE) + 2p, \quad (14)$$

where y_i, $\hat{y}_i$, and $\bar{y}$ are the measured, estimated, and average values of the dependent variable, respectively; $\bar{y}_{est}$ is the average value of the estimated values; *n* is the total number of observations used for fitting the model; *p* is the number of model parameters that have to be estimated; and ln is the natural logarithm.

3. Results

H–d models were developed for black pine, brutian pine, and Taurus cedar using 7 nonlinear growth functions. It is apparent from the model performance criteria that each growth function fits the tree *h–d* data of the 3 species equally well. The fitted nonlinear least squares estimates of parameters RMSE, AIC, E, AAE, MAE, and R are shown in Tables 2–4 for the 3 species and ecoregions. All model coefficients were significant at the significance level of 0.0001. Based on the model fitting statistics, the model in Eq. (6) performed best in the ME, IE, and LE for brutian

Table 2. Parameter estimates and fit statistics for 3 tree species in the maritime ecoregion.

Models	Parameters			Goodness-of-fit statistics					
	a_0	a_1	a_2	AAE	MAE	RMSE	E	R	AIC
Brutian pine									
Bertalanffy–Richards	23.559	0.042	0.995	0.328	1.362	0.415	0.000	0.737	–730.94
Weibull	23.486	0.042	1.004	0.328	1.361	0.415	0.000	0.737	–730.94
Exponential	29.706	–19.975	5.481	0.329	1.373	0.416	0.000	0.735	–729.04
Mod-logistic	27.957	0.025	1.212	0.328	1.367	0.416	0.000	0.736	–729.33
Korf–Lundqvist	34.583	6.512	0.649	0.329	1.374	0.417	0.000	0.734	–727.72
Gompertz	22.527	1.823	0.062	0.328	1.356	0.414	0.000	0.738	–732.23
Schnute	1.000	24.501	0.043	0.328	1.362	0.415	0.000	0.737	–730.94
Black pine									
Bertalanffy–Richards	24.713	0.047	1.370	0.372	1.380	0.469	0.000	0.816	–344.95
Weibull	24.164	0.019	1.216	0.372	1.379	0.469	0.000	0.816	–344.96
Exponential	32.648	–22.039	3.356	0.372	1.393	0.469	0.000	0.815	–344.51
Mod-Logistic	28.748	0.010	1.466	0.372	1.386	0.469	0.000	0.816	–344.71
Korf–Lundqvist	36.530	10.216	0.759	0.372	1.397	0.469	0.000	0.815	–344.34
Gompertz	23.494	2.397	0.067	0.372	1.380	0.469	0.000	0.816	–344.95
Schnute	0.583	25.566	0.050	0.372	1.379	0.469	0.000	0.816	–344.90
Taurus cedar									
Bertalanffy–Richards	22.583	0.046	1.270	0.338	1.636	0.422	0.000	0.707	–616.12
Weibull	22.240	0.023	1.160	0.337	1.633	0.422	0.000	0.707	–616.33
Exponential	28.544	–19.495	2.267	0.339	1.651	0.424	0.000	0.705	–614.30
Mod-Logistic	25.432	0.010	1.498	0.338	1.641	0.423	0.000	0.706	–615.12
Korf–Lundgvist	28.759	13.998	0.921	0.339	1.648	0.424	0.000	0.705	–614.07
Gompertz	22.047	1.994	0.058	0.337	1.633	0.422	0.000	0.708	–617.13
Schnute	0.674	23.510	0.048	0.337	1.634	0.422	0.000	0.707	–616.22

pine and in the ME and LE for Taurus cedar; the model in Eq. (2) performed the best in the ME for black pine; the model in Eq. (1) performed the best in the IE for black pine; and the model in Eq. (3) performed the best in the LE for black pine. The R values for all 7 models, 3 tree species, and 3 ecoregions were 0.71 or greater in each case. According to the nonlinear regression models, the highest R-value of 0.885 was reached for brutian pine trees in the IE (Table 3). The bias ranged from –0.0004 to 0.0004, and MAE values ranged from 1.031 to 1.651, for all species. Differences in bias among the 7 nonlinear models for each species were not significant. Comparing the RMSEs of the models, the Gompertz, Schnute, Weibull, and Bertalanffy–Richards models had the smallest RMSE values for black pine, Taurus cedar, and brutian pine trees, respectively. The AAE value ranged from 0.337 to 0.339 for Taurus cedar trees, was 0.372 for black pine trees, and ranged from 0.328 to 0.329 for the brutian pine trees in the ME; was 0.358–0.361 for Taurus cedar trees, 0.332 for black pine trees, and 0.282–0.284 for brutian pine trees in the IE; and was 0.321–0.322 for Taurus cedar trees, 0.285 for black pine trees, and 0.294–0.295 for brutian pine trees in the LE. Residual analysis showed that there were no detectable trends in the plots of residuals versus predicted tree heights and indicated that the assumptions of least squares regression were met adequately (Figure 3). Although the 7 growth functions were fitted to the same datasets, they resulted in different asymptote coefficients for different tree species and ecoregions (coefficient a_0 in Tables 2–4). In general, the Gompertz function yielded the smallest asymptote coefficients for all tree species, with the exception of the Schnute model, in which the asymptotic

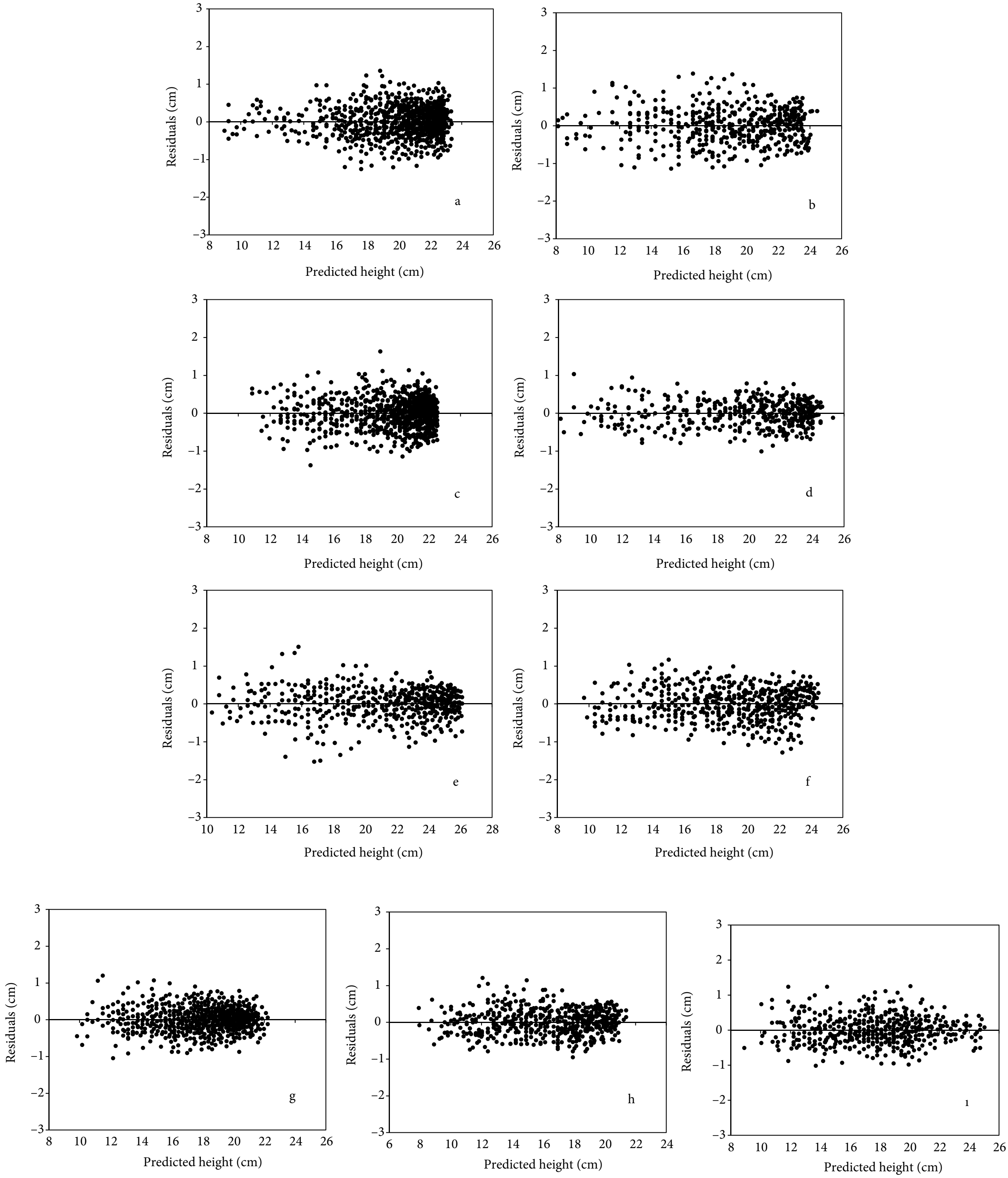

Figure 3. The plots of residuals against the predicted height for the development dataset for all weighted nonlinear least squares fits of the Gompertz model and tree species: a, b, and c are brutian pine, black pine, and Taurus cedar in the maritime ecoregion; d, e, and f are brutian pine, black pine, and Taurus cedar in the interior ecoregion; g, h, and i are brutian pine, black pine, and Taurus cedar in the lakes ecoregion, respectively.

Table 3. Parameter estimates and fit statistics for 3 tree species in the interior ecoregion.

Models	Parameters			Goodness-of-fit statistics					
	a_0	a_1	a_2	AAE	MAE	RMSE	E	R	AIC
Brutian pine									
Bertalanffy–Richards	30.957	0.021	0.912	0.282	1.120	0.349	0.000	0.885	–420.70
Weibull	31.265	0.028	0.939	0.282	1.128	0.349	0.000	0.885	–420.61
Exponential	41.362	–43.942	14.802	0.282	1.075	0.348	0.000	0.885	–421.28
Mod-logistic	44.817	0.018	0.988	0.283	1.123	0.349	0.000	0.884	–420.09
Korf–Lundqvist	134.742	5.865	0.293	0.284	1.116	0.350	0.000	0.884	–418.99
Gompertz	25.911	2.004	0.045	0.280	1.031	0.346	0.000	0.886	–423.39
Schnute	1.122	28.796	0.021	0.282	1.130	0.349	0.000	0.885	–420.61
Black pine									
Bertalanffy–Richards	30.005	0.024	0.859	0.332	1.551	0.432	0.000	0.838	–374.35
Weibull	30.588	0.038	0.899	0.332	1.553	0.432	0.000	0.838	–374.31
Exponential	38.461	–34.288	12.053	0.332	1.551	0.432	0.000	0.837	–374.17
Mod-logistic	40.299	0.025	0.996	0.332	1.556	0.432	0.000	0.837	–374.07
Korf–Lundqvist	69.670	5.501	0.400	0.332	1.560	0.432	0.000	0.837	–373.73
Gompertz	26.677	1.790	0.046	0.332	1.528	0.432	0.000	0.838	–374.28
Schnute	1.219	29.049	0.024	0.332	1.552	0.432	0.000	0.838	–374.33
Taurus cedar									
Bertalanffy–Richards	27.195	0.035	1.295	0.359	1.282	0.439	0.000	0.806	–398.54
Weibull	27.189	0.017	1.148	0.360	1.285	0.439	0.000	0.806	–398.24
Exponential	34.721	–26.735	3.179	0.358	1.271	0.437	0.000	0.807	–400.14
Mod-logistic	31874	0.007	1.423	0.359	1.277	0.438	0.000	0.807	–399.40
Korf–Lundqvist	40.400	12.402	0.753	0.358	1.274	0.437	0.000	0.808	–400.53
Gompertz	24.955	2.352	0.053	0.361	1.284	0.438	0.000	0.807	–398.30
Schnute	0.698	27.484	0.035	0.360	1.283	0.439	0.000	0.806	–398.33

coefficient was approximately equal to coefficient a_2; the Bertalanffy–Richards and Weibull models had similar asymptotes (Tables 2–4).

Using this ranking system and results from Tables 2–4 for 7 nonlinear growth functions, the rank sums were created by ranking the performance by 6 attributes in Table 5. Overall ranking was based on a sum of the individual ranks. The Gompertz model gave the best results with the lowest sum of ranks, while the Korf–Lundqvist model ranked the poorest with the highest sum of ranks. For predicting height, similar results were obtained. The Bertalanffy–Richards, Weibull, exponential, and Schnute models exhibited relatively low sums of ranks and were very similar in their ability to predict height. From the ranking results, the predictive ability of each model can be easily evaluated by different species and ecoregions (Table 5).

In order to evaluate the predictive ability of the best 2 models, the performance criteria, i.e. Eqs. (10), (11), (13), and (14), were calculated using the predictions obtained with the 2 weighted models and the evaluation dataset (Table 6). Both models produced low values of E, AAE, MAE, and RMSE for all tree species and ecoregions. The measured total height values of the 3 tree species in different ecoregions were graphically compared to the corresponding values estimated by the Gompertz *h–d*

Table 4. Parameter estimates and fit statistics for 3 tree species in the lakes ecoregion.

Models	Parameters			Goodness-of-fit statistics					
	a_0	a_1	a_2	AAE	MAE	RMSE	E	R	AIC
Brutian pine									
Bertalanffy–Richards	41.631	0.006	0.551	0.295	1.207	0.371	0.000	0.793	–507.97
Weibull	63.930	0.038	0.578	0.295	1.205	0.371	0.000	0.793	–507.95
Exponential	37.664	–48.389	23.013	0.294	1.205	0.371	0.000	0.793	–507.92
Mod-logistic	110.401	0.022	0.583	0.295	1.205	0.371	0.000	0.793	–507.95
Korf–Lundqvist	127.242	7.276	0.437	0.295	1.211	0.371	0.000	0.793	–507.90
Gompertz	24.207	1.465	0.038	0.294	1.198	0.371	0.000	0.793	–507.90
Schnute	1.049	27.993	0.003	0.295	1.206	0.371	0.000	0.793	–507.95
Black pine									
Bertalanffy–Richards	24.193	0.030	1.057	0.285	1.188	0.356	0.000	0.846	–518.38
Weibull	24.154	0.026	1.033	0.285	1.188	0.356	0.000	0.846	–518.36
Exponential	31.915	–31.964	8.551	0.285	1.184	0.356	0.000	0.847	–518.75
Mod-logistic	30.526	0.015	1.186	0.285	1.184	0.356	0.000	0.846	–518.66
Korf–Lundqvist	48.019	7.068	0.512	0.285	1.177	0.356	0.000	0.847	–518.66
Gompertz	21.585	2.078	0.052	0.285	1.204	0.357	0.000	0.846	–518.44
Schnute	0.925	24.211	0.030	0.285	1.188	0.356	0.000	0.846	–518.37
Taurus cedar									
Bertalanffy–Richards	33.380	0.015	0.783	0.322	1.268	0.408	0.000	0.818	–395.73
Weibull	35.574	0.032	0.825	0.322	1.269	0.408	0.000	0.818	–395.65
Exponential	42.055	–52.292	19.839	0.322	1.266	0.408	0.000	0.818	–395.94
Mod-logistic	53.655	0.021	0.856	0.322	1.271	0.408	0.000	0.818	–395.51
Korf–Lundqvist	222.053	5.856	0.226	0.322	1.275	0.408	0.000	0.817	–395.24
Gompertz	26.342	1.795	0.037	0.321	1.251	0.407	0.000	0.819	–396.63
Schnute	1.370	28.422	0.014	0.322	1.269	0.408	0.000	0.818	–395.66

model for the evaluation dataset (Figure 4). As suggested by Yang et al. (2004), a simple linear model, Actual H = a + b × Predicted H, was fitted on the data in Figure 4. If significant prediction errors are present, the intercept of this model will not equal 0 ($a \neq 0$) and the slope will not equal 1 ($b \neq 0$). For this aim, predicted values were regressed against observed values to look for possible bias in the model. Confidence intervals for the model intercept and slope were produced. As a result, the model showed slightly biased estimation for both the smaller and the greater diameters for all tree species and ecoregions. For example, using the data from cedar in the ME, the model intercept confidence interval ranged from –1.446 to –1.034, indicating that the intercept was significantly different from 0. The model slope confidence interval ranged from 1.057 to 1.079, indicating that the slope was significantly different from 1. Similar results were found for all tree species and ecoregions.

The F-test results for ecoregion differences are shown in Table 7. Based on the testing results, ecoregional differences were explored for black pine, brutian pine, and Taurus cedar using the Gompertz model. For example, the F-statistic calculated using the Gompertz model is 22.846, which is greater than the critical F-value. This implies that stem taper differed between the ecoregions and ecoregion-specific h–d models are required for brutian pine. The h–d

Table 5. Sum of the ranks, and ranks based on the rank sums (in brackets), of the 7 height–diameter estimating systems.

Description	Estimating system						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
BRM	12 (3)	10 (2)	21 (6)	25 (7)	25 (7)	6 (1)	13 (4)
BLM	8 (2)	6 (1)	15 (4)	17 (5)	18 (6)	8 (2)	8 (2)
CM	13 (4)	8 (2)	23 (6)	23 (7)	23 (6)	6 (1)	10 (3)
BRI	18 (3)	22 (4)	12 (2)	28 (7)	32 (8)	7 (1)	25 (5)
BLI	7 (1)	11 (3)	12 (4)	18 (6)	18 (6)	9 (2)	9 (2)
CI	17 (5)	22 (7)	8 (2)	7 (1)	7 (1)	16 (4)	20 (6)
BRL	11 (2)	10 (1)	13 (4)	12 (3)	18 (5)	10 (1)	12 (3)
BLL	13 (4)	15 (6)	7 (1)	8 (2)	8 (2)	13 (4)	14 (5)
CL	13 (3)	17 (5)	11 (2)	22 (7)	22 (7)	6 (1)	15 (4)
Total	112 (27)	121 (31)	122 (31)	160 (45)	171 (48)	81 (17)	126 (34)

Table 6. The fit statistics for evaluation dataset.

Model	Ecoregions	Tree species	AAE	MAE	RMSE	E	R	AIC
Gompertz	Maritime	BR1	0.384	1.472	0.489	0.180	0.861	−130.023
		BL1	0.386	1.336	0.490	−0.049	0.852	−96.672
		C1	0.369	1.446	0.457	0.047	0.847	−120.698
	Interior	BR2	0.256	0.967	0.329	0.058	0.911	−136.415
		BL2	0.363	1.069	0.442	−0.135	0.867	−114.090
		C2	0.343	1.240	0.413	−0.056	0.843	−101.806
	Lakes	BR3	0.349	1.017	0.440	−0.044	0.766	−122.051
		BL3	0.299	0.780	0.355	0.043	0.862	−152.639
		C3	0.362	1.251	0.449	0.039	0.873	−123.012
Chapman–Richards	Maritime	BR1	0.386	1.442	0.487	0.174	0.862	−130.558
		BL1	0.382	1.302	0.486	−0.050	0.854	−98.050
		C1	0.364	1.448	0.451	0.053	0.847	−122.851
	Interior	BR2	0.252	0.931	0.325	0.056	0.913	−137.961
		BL2	0.364	1.052	0.443	−0.140	0.865	−113.548
		C2	0.321	1.264	0.413	−0.057	0.845	−101.783
	Lakes	BR3	0.349	1.015	0.440	−0.043	0.764	−122.090
		BL3	0.299	0.783	0.354	0.045	0.865	−152.777
		C3	0.357	1.236	0.443	0.051	0.874	−125.171

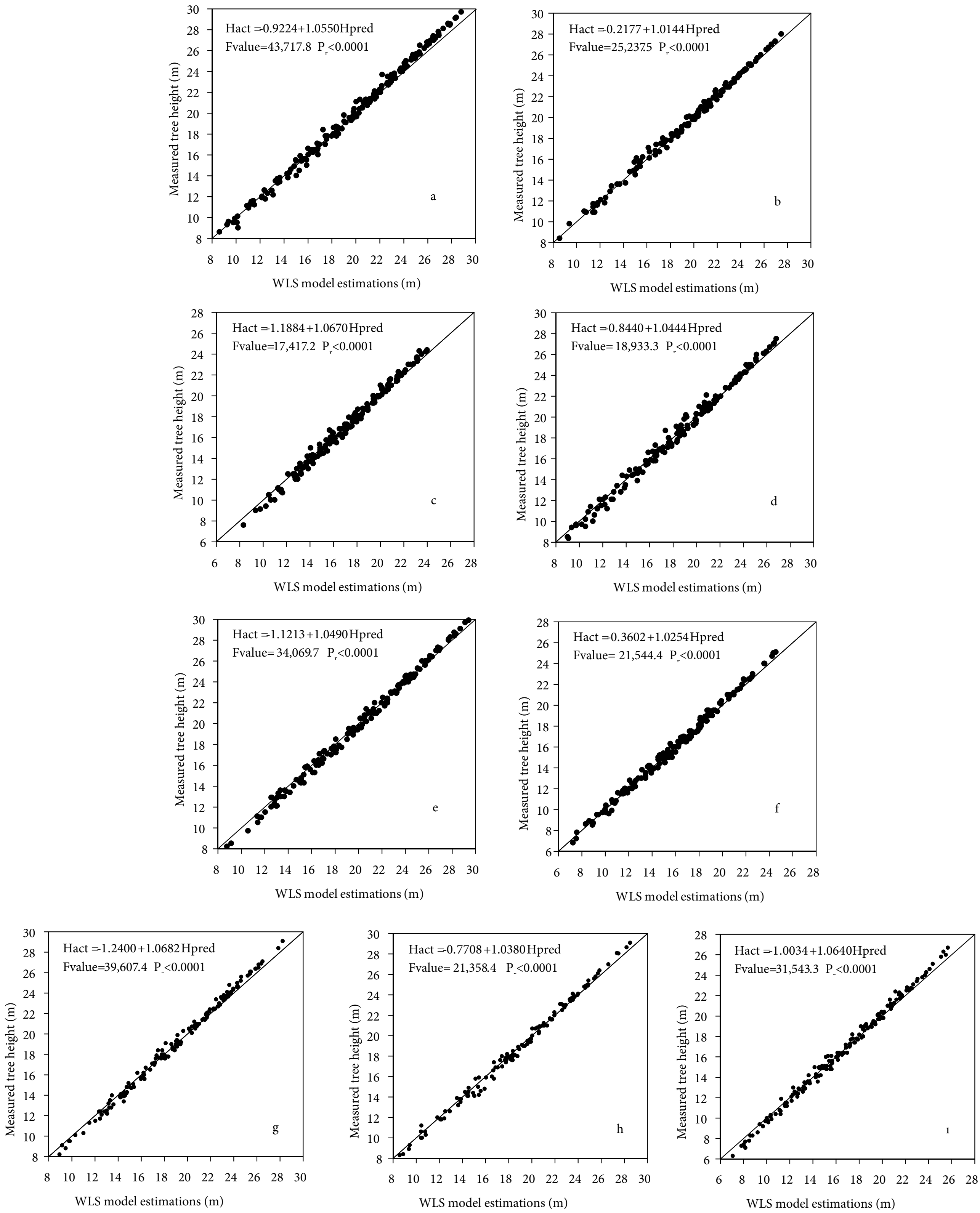

Figure 4. The 45° line plots for evaluation dataset for the Gompertz model and tree species: a, b, and c are brutian pine, black pine, and Taurus cedar in the maritime ecoregion; d, e, and f are brutian pine, black pine, and Taurus cedar in the interior ecoregion; g, h, and i are brutian pine, black pine, and Taurus cedar in the lakes ecoregion, respectively.

relationships of 3 species for 15 possible pairs of ecoregion groups are statistically significant in Table 7. F-values suggest that different models (the Gompertz model) are required for 3 ecoregions. Among the regions, the greatest differences were between the LE and the ME and IE.

4. Discussion

As indicated by Diamantopoulou and Özçelik (2012), knowledge of tree heights, such as total height, is fundamental for developing growth and yield models in forest stands. Precise tree height estimations are needed because height is an important variable in volume estimation and biomass calculation. Based on their appropriate mathematical features and possible biological interpretation of parameters, 7 nonlinear growth functions were fitted to 3 tree species and 3 ecoregions of southern Turkey. Development and analysis of 7 nonlinear *h–d* models fitted to tree species and different ecoregions in southern Turkey show that most concave and sigmoidal models are able to accurately describe tree *h–d* relationships. These results support the recent findings reported by Diamantopoulou and Özçelik (2012) for 3 species in the Mediterranean region of Turkey, by Zhang (1997) for major tree species in United States, and by Peng et al. (2004) for 9 tree species in Canada.

Based on the development data, the best-fitting model was the Gompertz model, which provides the most precise estimates with RMSE values from 0.346 to 0.469 for all species and ecoregions. The Gompertz and Chapman–Richards models were further analyzed by evaluating their predictive abilities using an independent dataset. Evaluation of these models indicated that both produced satisfactory results for each ecoregion, although a very slight bias was observed for smaller and greater heights.

Based on the fitting statistics, evaluation statistics, and graphical examinations, the model in Eq. (6) is the best model to quantify *h–d* relationship for brutian pine, black pine, and Taurus cedar. Considering the model mathematical features, biological interpretation of parameters, and accurate prediction, we recommend the Gompertz model as the best. However, the performance of other models, such as the Schnute model or the

Table 7. F-test for *h–d* models for different ecoregions.

Model pairs*	Full model		Reduced model			
	df_F	SSE_F	df_R	SSE_R	F-value	P-value
Between ecoregions						
BR1-BR2-BR3	1348	263.5	1354	292.9	25.067	<0.0001
BL1-BL2-BL3	1253	249.0	1259	339.7	76.069	<0.0001
C1-C2-C3	1407	296.3	1413	307.6	8.943	<0.0001
BR1-BR2	886	192.7	889	204.5	18.238	<0.0001
BR1-BR3	864	119.7	867	127.3	18.285	<0.0001
BR2-BR3	946	214.6	949	236.7	32.474	<0.0001
BL1-BL2	776	184.9	779	191.7	9.513	<0.0001
BL1-BL3	817	148.0	820	217.0	126.966	<0.0001
BL2-BL3	913	165.1	916	223.4	107.466	<0.0001
C1-C2	990	222.2	993	228.8	9.802	<0.0001
C1-C3	859	168.0	862	172.9	8.351	<0.0002
C2-C3	965	202.4	968	209.2	10.807	<0.0001
Inside ecoregions						
BR1-BL1-C1	1468	373.2	1474	397.9	16.193	<0.0001
BR2-BL2-C2	1356	226.7	1362	246.4	19.639	<0.0001
BR3-BL3-C3	1184	208.9	1190	229.4	19.364	<0.0001

*1: Maritime ecoregion; 2: interior ecoregion; 3: lakes ecoregion.

Bertalanffy–Richards model, was also very good. These models have been shown to be very flexible and have been used extensively in growth and yield studies for describing height–age, diameter–age, and volume–age relationships (Somers and Farrar, 1991).

However, *h–d* relationship varies within a region, depending on local environmental conditions, and also varies within a geographic region. The 4 ecoregions described by Kantarcı (1991) within the Mediterranean region are characterized by broad climatic patterns and topography. The results of the F-test showed significant differences between the 3 ecoregions for the 3 tree species (Table 7). F-test results in Table 7 justify the use of a separate *h–d* model for tree species in these ecoregions. As suggested by Xu (2004), because the differences among ecoregions may be caused by only 2 or all of the ecoregions involved, it is often desirable to apply the indicator variable approach to each possible pair of ecoregions so that the source of the differences can be identified and data from similar ecoregions can be combined. Results of the F-test are given in Table 7, which reveals significant differences in the *h–d* models between any 2 ecoregions for all trees. These results are not surprising, given that different ecoregions have very different biogeoclimatic conditions. Note that an unusually large estimate for the asymptotic parameter occurred in the IE. Trees in the IE are typically bigger and taller than those from other ecoregions. Applying the combined *h–d* model to each ecoregion resulted in unacceptable errors in height prediction. For brutian pine, the ME *h–d* model overestimated (negative bias %) the tree heights by about 2.79% in the IE and 6.46% in the LE. For black pine, the ME *h–d* model overestimated the tree heights by about 15.14% in the IE and 1.35% in the LE. For Taurus cedar, the ME *h–d* model underestimated (positive bias %) the tree heights by about 4.86% in the IE and overestimated the tree heights by about 7.76% in the LE. The accuracy test (Gribko and Wiant, 1992) indicated that the mean prediction bias significantly differed from 0 at the $\alpha = 0.05$ level. Therefore, existing *h–d* models from other ecoregions or tree species should be avoided whenever possible. Each ecoregion appeared to need a unique *h–d* relationship so as to ensure a proper fit to the data. These results support the findings reported by Huang (1999), by Peng et al. (2004) in Alberta, and by Zhang et al. (2002) in Ontario. They attributed the differences in height growth patterns to the differences in climate between the ecoregions.

Development of ecoregion-based growth and yield relationships, such as *h–d* models, is an essential step toward the implementation of ecosystem-based forest management. Often, growth and yield relationships are different among different ecoregions, so wherever data permit, it is preferable to develop ecoregion-specific models. These localized models allow for the uniqueness of each individual ecoregion to be captured. Consequently, ecoregion-based models are able to provide more reliable predictions (Xu, 2004). Moreover, as indicated by Huang (1999), they are also able to provide more reliable predictions on a regional basis and avoid the potential errors that may be incurred when such models are applied outside their areas.

In conclusion, the Gompertz model is recommended for all 3 species, both for its good behavior in fitting and the biological interpretability of its parameters. In addition, our results suggest that ecologically based *h–d* models should be fitted by ecoregion to reflect the regional differences. These ecoregion-based *h–d* models provide useful tools to forest resource managers in forest management practices and decision making.

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