SITE INDEX CURVES FOR EUROPEAN CHESTNUT (*CASTANEA SATIVA* MILL.) IN BELASITSA MOUNTAIN

KRIVULJE INDEKSA STANIŠTA ZA PITOMI KESTEN (*CASTANEA SATIVA* MILL.) NA PLANINI BELASICI

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Abstract

Richards, Lundqvist-Korf and Hossfeld growth functions were fitted to age-height data of European chestnut (*Castanea sativa* Mill.) dominant trees on the northern slopes of Belasitsa mountain, Southwest Bulgaria. The model prediction performance was evaluated using quantitative as well as qualitative examinations. Goodness of fit of each model was estimated by the coefficient of determination, *F*-test for significance of the regression and *t*-tests for significance of the coefficients of the model. Models were further compared by the evaluation of the standard error of the model and Akaike's Information Criteria. Site index curves were constructed following the "guide curve method" procedure. In accordance with the evaluation tests, the Richards function was chosen as most adequate to express the age-dominant height relationship. Accordingly, it was further employed as a guide function to derive site index curves for studied chestnut population. It was recommended that the growth model and the site index curves elaborated in the current study are used within the data range 10–110 years.

KEY WORDS: *Castanea sativa*, height growth, site index curves, Guide curve method, Richards function

Introduction
Uvod

European chestnut (*Castanea sativa* Mill.) represents one of the most important broad-leaved plants in South Europe, even though both socio-economic changes and pathologies reduced the importance it had till the first decades of the last century (Haltofová, et al. 2005). The ecological and economical relevance of chestnut has been related to its multipurpose character and presence across different domestication forms: mixed forests, coppices and orchards (Lauteri et al. 2009). Until recently there were uncertainties with respect to the origin of chestnut in Belasitsa mountain. It was reckoned to be either artificial, the species having been introduced from its southern localities (Dobrev 1914; Stoyanov 1921), or related to its broader relict distribution (Bratanova-Doncheva et al. 2005). Zlatanov et al. (2011) revealed genetic congruence between studied chestnut population and those located in Northern Greece, and found (by pollen analyses and C14 dating of samples) that chestnut was present in the mountain as early as 8000 years BP. These findings support the theories that Belasitsa mountain is most likely a refugium area of chestnut, hence the importance of this species in the mountain. For many centuries chestnut dominated stands in Belasitsa mountain used to be intensively managed for nut and firewood production, and grazing. Human impact over chestnut stands diminished after nationalization of forests in 1948. Only the interest of the local people in collection of chestnut fruits remained though it became more unorganized and uncontrolled (Kostov 1979). The consistent increase of the demand for wood and the subsequent outbreaks of the exotic pathogen *Cryphonectria parasitica* (Murrill) Barr. during the last 15 to 20 years brought about interest of targeted management of chestnut stands.

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One of the most widely used methods for assessing the growth of a tree species is based on the dominant height-age relationship and is termed the site index (Savill et al. 1997; Avery and Burkhart 2002; Fontes et al. 2003). The dominant height of a tree species on a given site is insignificantly influenced by the thinning intensity (Hamilton 1981) hence being good indicator of the species potential productivity on that particular site (Cailliez and Alder 1980). Based on Eichhorn's hypothesis (Eichhorn 1904) the total production from a fully stocked stand, which is the volume of currently standing trees plus anything removed in previous thinnings, is a function of its dominant height (Savill et al. 1997). One of the major needs in forest management planning is to predict forest stand development under various treatment alternatives. In this respect, a thorough knowledge of tree growth on different sites is critical, and an aid to successful forest management and silviculture. Hence, construction of site index curves is a fundamental task.

No literature data has been found to suggest that site index curves have been developed in the region of South East Europe in order to determine the growth of European chestnut (*Castanea sativa* Mill.) along the site gradients in regions where it grows. Accordingly, the objective of the study is (*i*) to model the age – dominant height growth relationship and (*ii*) to elaborate site index curves for chestnut population on the northern slopes of Belasitsa mountain, Southwest Bulgaria.

Materials and methods
Materijali i metode

Study area – Područje istraživanja

Currently, chestnut dominated and codominated stands in Bulgarian part of Belasitsa mountain occupy an area of 1700 ha which is approximately 20 % of the total forested area in the mountain. Chestnut dominated forest alone cover 648 ha, 93 % of them located between 176 000 and 186 000 meridians (Velichkov et al. 2010). Chestnut forests grow at elevation between 350 to 950 m a.s.l., on often steep slopes with predominantly northern exposures. The total growing stock of chestnut is 96 000 m^3 out of the total of 1 850 000 m^3 (PFEMP 2010). Currently, blight disease caused by *Cryphonectria parasitica* has spread into most chestnut stands, disease incidence ranging from 18% to 100% of the trees in the stands, and mortality caused by the fungus ranging from 2 % to 80 % (Zlatanov et al. 2011). The current spatial and age structure of chestnut dominated forests in the mountain is considered to be a result of the management regime alteration (land abandonment) since the first half of the last century. The spatial structure of the stands is generally horizontal (simple). Most stands are composed of two age classes. The first class/cohort includes rarely spaced overmatured chestnut trees (density 20–40 trees/ha; age close to 100 and above). The second cohort originated shortly after the land abandonment (40–60^s of the last century) under the sparse chestnut canopy at that time. It is composed of chestnut with participation of European beach (*Fagus sylvatica* L.) and/or sessile oak (*Quercus petraea* Liebl) in most plots. As a light demanding species, chestnut discontinued its further recruitment in the study area after canopy closure of the stands. Management trials, were initiated again since (80^s) 90^s of the last century in the form of clearcuts on small areas (less than 1 ha).

Due to the latitudinal position of Belasitsa mountain the climate on its northern slopes is not as strongly influenced by the Mediterranean as the climate of the surrounding territories. The average annual precipitation of the nearest climatic station (climatic station Petrich, 200 m a.s.l.) for the years 1965–2010 is 580 mm, predominantly occurring in the period November – February (240 mm). The driest period is June – September (150 mm). The altitudinal increase in precipitation and decrease in temperature in Belasitsa mountain average 30 mm and 0,7 °C per each 100 m respectively (Galabov et al. 1973). The soil is loamy-sand Eutric Cambisols with depth mostly varying between 40 and 80 cm (PFEMP 2010).

Data collection – Prikupljanje podataka

Data for the construction of the chestnut age – dominant height relationship and site index curves was collected from a systematic network of temporary sample plots in 2010. As a part of the systematic sampling approach, a grid was drawn between the 176 000 and 186 000 meridian lines (coordinate system: UTM 35 North, WGS 1984) across the most recently updated forestry map of Belasitsa mountain, Southwest Bulgaria (PFEM 2010). The interval between grid lines was set to 250 *m* in both longitudinal and latitudinal direction. A total of 67 grid intersections fell within the boundaries of chestnut dominated stands as depicted in the Petrich Forest Enterprise Management Plan (PFEMP 2010). Grid intersections were positioned on the field by GPS (Trimble Juno SB) navigation. Accordingly, 67 temporary sample plots sized 0.125 ha (40 m in diameter) were installed, plot centres coinciding with the grid intersection points. The plots extended over the altitudinal belt from 400 to 900 m a.s.l.

Two steps procedure was applied in order to select dominant chestnut trees for analyses. At the first step the three tallest chestnut trees per a plot were selected. The total number of dominant trees selected at this stage was 201. At the second step all selected dominant trees characterized by presence of blight disease symptoms were removed from the selection. Accordingly, 97 trees were finally selected from the systematic network of temporary plots. The lack of dominant chestnut trees aged less than 35 in the representative network of sample plots was an important restriction in the initial data set of the study. In order to achieve better coherence of the sample along the age gradient, and following the same approach for selection of dominant trees, 32 dominant chestnut trees aged 10 to 33 were selected in younger stands at various altitudes. Finally, a total of 129 dominant trees were chosen for further analyses. The height of the trees was measured by Vertex IV heightmeter with accuracy of 0.1 m. Increment core samples were extracted at *dbh* (1.3 m) to obtain the age. The tree rings were counted using a WILD M3Z binocular with polarized light source.

Data analyses – Obrada podataka

The following equations which have been widely used in modelling biological growth phenomena were used as candidate functions to model dominant height (*H*) of studied chestnut population: (*i*) Richards, Eq. 1 (Richards 1959; Pienaar and Turnbull 1973; Zeide 1993; Rennolls 1995; Rojo and Montero 1996; Amaro et al. 1998); (*ii*) Lundqvist-Korf Eq. 2 (Stage, 1963; Tome 1988; Zeide 1993); and (*iii*) Hossfeld, Eq. 3 (Pita 1964; Elfving and Kiviste 1997; Palahí et al. 2004)

$$H = a\,[1 - \exp(-kA)]^c \qquad (1)$$

$$H = a\exp(-kA^{-c}) \qquad (2)$$

$$H = \frac{a}{1 + \dfrac{k}{Ac}} \qquad (3)$$

where *A* is the age, *a* is the asymptote of *H*, *k* is a growth rate related parameter, and *c* is a shape parameter.

The procedure used to evaluate the models incorporated qualitative as well as quantitative examinations. The goodness of fit of all regression models was assessed through the coefficient of determination (R^2), *F*-test for significance of the regression and *t*-tests for significance of the coefficients of the models. Plots of the predictor variables against the residuals and the predicted values against the residuals were examined to check for model deficiencies (Draper and Smith 1981). Cook's distance, Leverage and DFFit residual statistics were employed to identify potential influence cases.

Models were further compared by the evaluation of the standard error of the model S_y (Eq. 4) and Akaike's Information Criteria (*AIC*, Eq. 5)

$$Sy = \sqrt{\frac{S}{M - m}} \qquad (4)$$

$$AIC = M\ln(S/M) + 2m \qquad (5)$$

where *M* is the sample size, *S* is the residual sum of squares, and *m* is the number of coefficients of the regression. *AIC* is measure of the relative goodness of fit of a statistical model. For chosen set of models for fitting the data, the one with minimum *AIC* value is the preferred one. Unlike R^2, *AIC* is a relative measure, and cannot tell us how well a model fits the data in an absolute sense, but can be used as a mean of comparison among models (Stankova *et al.* 2006; Field 2009). At this stage, the residual plots of the models were further examined in order to check for violation of the assumptions of linearity and homoscedasticity. Biological realism and graphical appearance of the models were also considered.

The elaboration of Site Index Curves (*SIC*) for studied chestnut population followed the "guide curve method" procedure as suggested by Clutter at al. (1983).

Results
Rezultati

It is apparent from the model statistics shown in Table 1 that each growth function was well fitted to the tree age/height data. The overall fit of the models was significant at $a < 0.01$ and they accounted for at least 60 % of the total variation in dominant height, which according to Cohen (1986) is a large effect. Richards function performed marginally better compared to the others with R2 = 0.62. The Richards function had the smallest values of Standard error of the model (Sy) and AIC coefficients: Sy = 3.12 and AIC = 296.3. The Richards function was the only one with all model coefficients being statistically significant at $a < 0.01$. Although the three growth functions were fitted to the same data set, they resulted in different asymptote coefficients. The asymptote of the height was greatest for the Lundqvist-Korf function (28.91) and lowest for the Richards function (23.26) (Table 1). The three growth functions used in the current study similarly predicted the tree dominant heights for most age classes with exception for the older trees (Figure 1). The Lundqvist-Korf function predicted larger tree heights, followed by the Hossfeld and Richards functions. Furthermore, at older ages the Lundqvist-Korf and Hossfeld equations produced a less-asymptotic trend than the Richards one, hence the latter being considered as more biologically realistic. The residuals for the three models showed a random manner of distribution (Figure 2), which suggested that there were no violations of the assumptions about the errors. No potentially influential cases were detected.

In accordance with the evaluation tests, the Richards function (Eq. 1) was chosen as most adequate to express the age-dominant height relationship and further employed as a guide function to derive site index curves for studied chestnut population.

Table 1. Results from the statistical tests examining the goodness of fit of the regression models for the age-dominant height relationship

Tablica 1. Rezultati statističkih testova analiziranih regresijskih modela ovisnosti dominantne visine o starosti

Model	R2	Sig. F	Coefficients				Sy	AIC
				B	Std. error	Sig.		
Richards	0.62	<0.01	a	23.27	0.94	<0.01	3.12	296.35
			k	0.041	0.01	<0.01		
			c	1.03	0.25	<0.01		
Lundqvist-Korf	0.60	<0.01	a	28.91	4.6	<0.01	3.18	301.04
			k	8.85	4.71	0.06		
			c	0.81	0.23	<0.01		
Hossfeld	0.61	<0.01	a	25.89	2.14	<0.01	3.15	299.00
			k	54.04	36.15	0.14		
			c	1.34	0.26	<0.01		

The total number of trees used in fitting the models was n=129; a is an asymptote of height; k is a growth rate related parameter; and c is a shape parameter

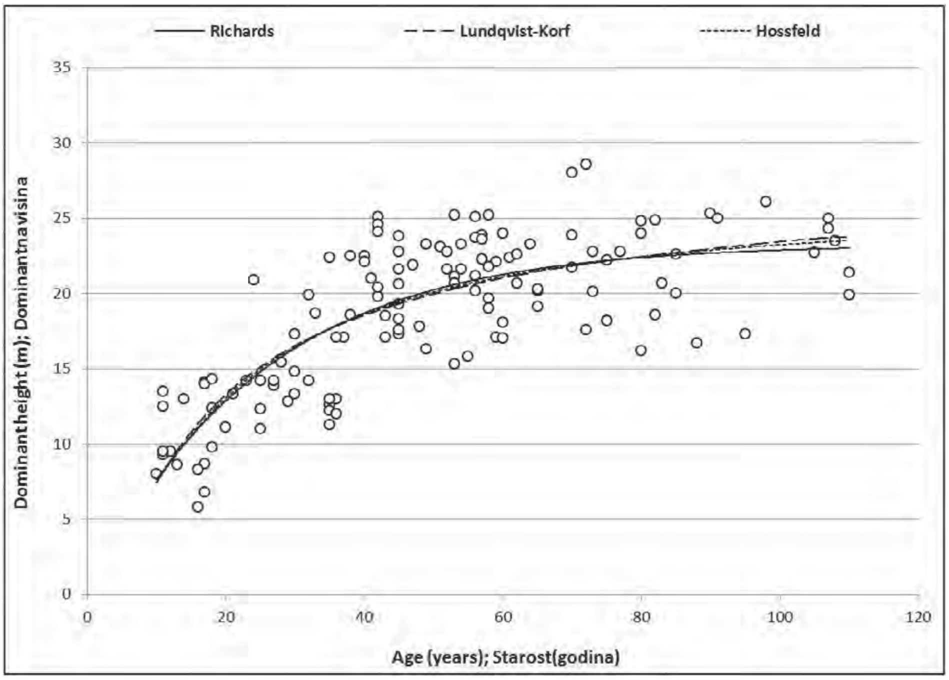

Figure 1. Age-dominant height curves based on Richards, Lundqvist-Kort and Hossfeld growth functions

Slika 1. Krivulje ovisnosti dominantne visine o starosti dobivene jednadžbama rasta Richardsa, Lundquist-Korfa i Hossfelda

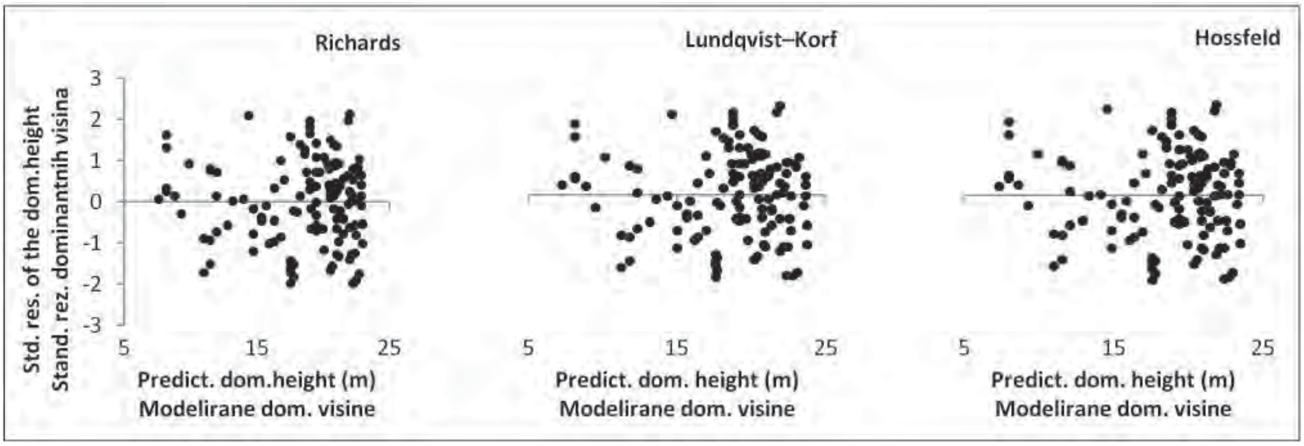

Figure 2. Predicted values against standardized residuals for the age-dominant height curves based on Richards, Lundqvist-Kort and Hossfeld growth functions

Slika 2. Grafički prikaz standardiziranih reziduala u ovisnosti o dominantnim visinama dobivenim pomoću krivulja baziranih na jednadžbama rasta Richardsa, Lundqvist -Korfa i Hossfelda

When A = 50, the calculated H value is

$$H = 23.26\,[1 - \exp(-0.041 \times 50)]^{1.03} = 22.39m \qquad (6)$$

The curve from Eq. 6 is the site index curve for a site index value of 22.39 *m* and index age of 50 years. Curves for other site index values were obtained from the guide curve equation by holding the shape parameters *k* and *c* constant and varying the asymptote parameter *a* as necessary to achieve the required *H* value when *A* (the index age) equals 50. The equation of the curve for site index *SI* was therefore

$$SI = a_i\,[1 - \exp(-0.041 \times 50)]^{1.03} \qquad (7)$$

so that

$$a_i = SI\,[1 - \exp(-0.041 \times 50)]^{-1.03} \qquad (8)$$

and

$$H = SI\left[\frac{1-\exp(-0.041A)}{1-\exp(-0.041\times 50)}\right]^{1.03} \qquad (9)$$

or, for prediction of site index from dominant height and age

$$SI = H\left[\frac{1-\exp(-0.041\times 50)}{1-\exp(-0.041A)}\right]^{1.03} \qquad (10)$$

For given age and dominant height, site index can also be derived from the graphical representation of the site index curves fitted for the Richards guide curve at index age of 50 years (Figure 3)

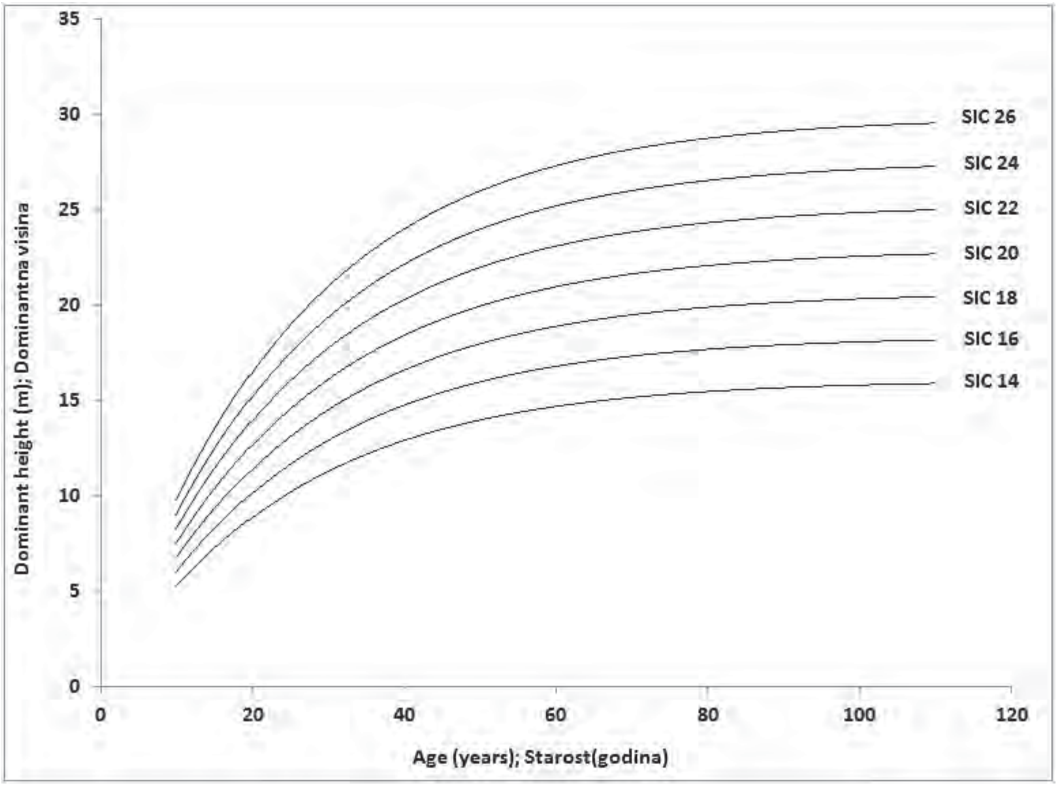

Figure 3. Castanea sativa site index curves fitted by the Richards guide curve at index age of 50 years
Slika 3. Krivulje indeksa staništa dobivene pomoću Richardsovog modela za indeksnu starost 50 godina

Discussion
Rasprava

The lack of sample plots measured at young ages was an important restriction in the initial data set of the study. Accordingly, the inclusion of additional dominant trees selected in younger stands at various altitudes was crucial to develop a model that could predict accurately dominant height development at young ages. Some authors (Rojo and Montero 1996; Palahi et al. 2004) recommend the inclusion of tree stem analysis data instead. It is emphasized that models based on temporary plots and stem analyses data deliver higher dominant heights at young ages than models based only on temporary plots which supports the conclusion that the analysed sample trees were dominant at young ages as well. Stem analyses data was not used in the current study due to the uneven-aged structure of *Castanea sativa* dominated stands on the Northern slopes on Belasitsa mountain and to avoid the risk of violation of the assumption of the independence of the error term. According to West (1995), the violation of this assumption is likely to produce an estimator of the covariance matrix of the parameter estimates that is negatively biased, leading to the invalidation of the normal statistical hypothesis test about the fitted equation.

The relatively large difference between the asymptotic coefficients of the three functions used in the current study is in accordance with the relevant literature. Zhang (1997) reports on greater asymptotic height predicted by Lundqvist-Korf function in comparison with the Richards one. According to Ratkowsky (1983), the asymptotic coefficient is the least stable parameter in non-linear growth functions and the least-squares fit often results in biologically unreasonable upper asymptotes, especially when there are few data observations near the asymptote. In such cases, overestimation or underestimation of the height of the large-sized trees might be expected, regardless the function fitted.

Top height growth for chestnut has been modelled in other European countries where the species is present. Examples are: the curves of Everard and Christie (1995) for chestnut plantations in Great Britan, the curves of Manetti et al. (2001) for chestnut coppice and high forests based on aggregated data from different regions of Europe and the curves of Alvares et al. (2010) for chestnut plantations in Northern Spain aged up to 20 years. In comparison, current study data set is characterized by more balanced and extended age distribution than data used in the other studies attempting to derive representative height growth curves for *Castanea sativa*. Despite the fewer observations in the older age classes (e.g. more than 70–80 years) current study data set covers the range of 10–110 years whereas data sets of all other studies do not comprised trees over than 70 years of age. Accordingly the *SIC* elaborated in the current study provide basis for best up to now *SIC* estimation for mature (over than 80 years of age) chestnut stands as well: although most of the non-linear growth functions can adequately predict height growth, they may produce large errors when applied beyond the range of model development data (Zhang et al. 1996).

According to Clutter et al. (1983), most techniques for site index curve construction can be viewed as special cases of three general methods: (*1*) the guide curve method; (*2*) the parameter prediction method; and (*3*) the difference equation method. One-time (single) measurement of stand height and age on temporary plots is sufficient for the guide curve method whereas the implementation of the others require either measurement of height and age over time with monumental trees or plots (the parameter prediction method), or reconstruction of height/age development patterns for individual trees through stem analyses (the difference equation method). Shortcomings of using stem analyses data in the case of the current study has already been discussed. Measurement over time was also avoided due to the mass occurring of chestnut dieback in Belasita mountain caused by the ascomycete fungus *Cryphonectria parasitica* (Murrill) Barr. According to Zlatanov et al. (2011), each year many trees are infected by the fungus in a rather chaotic manner. The guide curve method assumes that the full range of site indices is comparatively well presented in all age classes within the sample (Clutter et al. 1983), which is the case with respect to the current study data set. Still, we are aware that the guide curve method derives anamorphic site index curves, only asymptote coefficient is changed while the shape of the curves stays constant. Most studies (Garcia Abejon 1981; Alemdag 1988) suggest that the shape of the curves might also vary from site to site.

It can be generalized from the results of the current study that the growth model based on the Richards growth function best fitted the age – dominant height relationship for the studied *Castanea sativa* dominated stands (Figure 1, Table 1), hence the Richards guide curve (Eq. 7) being employed for the construction of the population site index curves. It is recommended that the growth model and the site index curves elaborated in the current study are used within the data range 10–110 years.

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Zahvala

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Sažetak:

U ovome su radu jednadžbe rasta koje su razvili Richards (jednadžba 1), Lundqvist-Korf (jednadžba 2) i Hossfeld (jednadžba 3) upotrijebljene za modeliranje dominantne visine populacije stabala pitomoga kestena (*Castanea sativa* Mill.) sa sjevernih ekspozicija planine Belasitsa u jugozapadnoj Bugarskoj. Mogućnost predikcije dominantnih visina pomoću izrađenih modela procijenjena je koristeći kvantitativne i kvalitativne kriterije. Uklapanje linije izjednačenja svakoga modela procijenjena je pomoću koeficijenta determinacije R^2, F-testa značajnosti regresije i t-testa značajnosti parametara modela. Nadalje, modeli su međusobno uspoređeni kroz evaluaciju standardne pogreške modela (S_y) i *AIC* kriterija (Akaike's Information Criteria). Linije svih upotrijebljenih funkcija rasta zadovoljavajuće naliježu na podatke ovisnosti visine o starosti. Uklapanje linija izjednačenja za sve je modele statistički značajno na razini $\alpha < 0.01$, pri čemu se objašnjava najmanje 60 % cjelokupne varijabilnosti dominantne visine stabala pitomoga kestena. Funkcija Richardsa pokazala je marginalno bolje rezultate od ostala dva modela s koeficijentom determinacije od R2 = 0.62 (tablica 1). Ovaj je model također imao i najmanje vrijednosti standardne pogreške (S_y) i *AIC* kriterija. Nadalje, funkcije Lundqvist-Korfa i Hossfelda daju krivulju koja odstupa od asimptotskoga trenda u većoj mjeri nego krivulja Richardsa (slika 1), pri čemu se ova zadnja smatra bližom biološkim zakonitostima rasta. U skladu s provedenim analizama, funkcija Richardsa odabrana je kao najpovoljniji model ovisnosti dominantne visine o starosti, te je dalje upotrijebljena za izradu krivulja indeksa staništa za istraživanu populaciju pitomoga kestena (slika 3). Za određenu starost i dominantnu visinu, indeks staništa može se izraditi i pomoću jednadžbe 10. Dobiveni model visinskoga rasta kao i krivulje indeksa staništa mogu se koristiti u starosnom rasponu od 10 do 110 godina.

KLJUČNE RIJEČI: *Castanea sativa*, visinski rast, krivulje indeksa staništa