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Testing non-linear height-diameter functions for three native trees of Greece on ICP forests Level II plots

Entwicklung nichtlinearer Höhen-Durchmesser-Funktionen für drei einheimische Baumarten Griechenlands in ICP Forests Level II Plots

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Schlüsselbegriffe: *Nichtlineare Regression, Dauerbeobachtungsflächen, Sigmoidal-Chapman-Modell, Griechenland*

Abstract

Many height-diameter functions have been developed for various tree species in order to be used as a component in estimations necessary in forest management activities. This study aims to evaluate diameter and height functions for three native tree species of Greece and validate the best fitting model. Tree diameter and height data were obtained from three permanent ICP-Forests plots (Level II) corresponding to Bulgarian fir, European beech and Hungarian oak stands, located in Timfristos and Ossa mountains, respectively. The evaluation of the diameter and height nonlinear models was based on adjusted coefficient of determination, the root mean square error, the predicted residual error sum of squares and the homogenous distribution of studentized residuals of the selected function. The final stage of the analysis, sho-

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wed that the Sigmoidal-Chapman model provided the most accurate estimations for diameter and height growth. In addition, the model showed satisfying results after its implementation in the coming years. These specific models are flexible and can be used successfully as a tool by foresters and researchers for forest management activities. Furthermore, their satisfying performance at specific sample plots could be considered as a first step for extended testing conserving forest inventory preparation. In general, their contribution to future monitoring is traditionally significant, considering that future challenges require more effort to get appropriate and valuable information from Mediterranean forest resources.

Zusammenfassung

Schätzfunktionen wie Baumhöhen-Durchmesser-Funktionen werden in der Forstwirtschaft häufig verwendet. Ziel dieser Studie ist es Durchmesser- und Höhenfunktionen für drei einheimische Baumarten Griechenlands zu entwickeln und das am besten geeignete Modell zu validieren. Baumdurchmesser- und Höhendaten wurden auf drei permanenten ICP Forests Level II Dauerversuchsflächen erhoben. Die Versuchsflächen liegen in den Bergen Timfristos und Ossa in bulgarischen Tannen-, europäischen Rotbuchen- und ungarischen Eichenbeständen. Die Bewertung der nichtlinearen Durchmesser-Höhe-Modelle basiert auf angepassten Bestimmtheitsmaßen, dem mittleren Quadratwurzelfehler, der vorhergesagten Restfehlersumme der Quadrate und der homogenen Verteilung der studierten Restwerte der ausgewählten Funktion. Die Ergebnisse unserer Studie zeigen, dass das Sigmoidal-Chapman-Modell für alle drei Beständen die genauesten Schätzungen liefert. Darüber hinaus zeigte sich, dass dieses Modell auch in den nach folgenden Jahren zufriedenstellende Ergebnisse liefert. Die getesteten Modelle sind flexibel und können nun von Forstleuten und Forschern als Werkzeug für die Forstwirtschaft und forstliche Planung eingesetzt werden. Darüber sind die Ergebnisse dieser Studie hilfreich für die Vorbereitung der Griechischen Waldinventur. Im Diese Studie liefert somit einen Beitrag zu der Herausforderung des künftigen Monitoring und hilft dabei verlässliche Informationen für die Waldbestände des Mittelmeerraums zu erhalten.

1. Introduction

Calculating total tree height, based on observed diameter at breast height (bark included), is a common practice in practical management activities. Total height together with breast diameter allow us to estimate total tree volume, tree growth or to find the dominant trees and combining with age to estimate the site index (Peng 1999). Also it is an important component in yield estimation, stand description and damage appraisals (Parresol 1992). One relative aspect of tree height-diameter estimation is its usage to determine tree growth and tree vitality (i.e. Dobbertin 2005). More specifically, those relationships are used to compare the effect of an imposed stress on a tree. For example, the effect on tree vitality of planting depth on *Platanus occidentialis* (American sycamore) and *Taxodium distichum* (bald cypress) or the effect of drought stress on *Acer platanoides* (Norway maple) and Tilia spp. (linden) (Bryan et al., 2010; Fini et al., 2009). Many references can be found in literature and some of them are summarized by Johnstone et al. (2013).

Furthermore, those estimations could also be used for carbon stock estimation. Reliable estimates of tree height are essential for assessing above ground biomass (Kearsley et al., 2013). However, in many situations, the sample size needed is too large for practical purposes and a lot of time and resources are required.

According to Fotheringham et al. (2002) global and local regression models have traditionally been used for studying spatially heterogeneous data. For this reason, several methods for solving the heterogeneity problem are proposed using heteroscedasticity specification, generalized additive models, classification and regression trees, linear mixed models (LMM) or geographically weighted regression (GWR) (Quiros-Segovia et al., 2016).

Worldwide, the nature of height-diameter relationship has been examined many times in the past using mostly non-linear functions. Most of these models use a representative sample of height sample trees from the target stand (Curtis 1967, Arabatzis & Burkhart 1992, Huang et al., 1992, Lynch & Murphy 1995, Fang & Bailey 1998). The main focus in these studies was to find the best functional form of the model. Petras et al. (2014) presented generalized height-diameter models for mixed-species forest stands consisting of Norway spruce (*Picea abies* Karst.), Silver fir (*Abies alba* L.), and European beech (*Fagus sylvatica* L.) from Slovakia. In addition, they summarized some of them giving more attention to the type of function that was used across several areas in Europe. Suggestively, in all these cases, polynomial functions, fractional polynomials, exponential functions, or transformed nonlinear to linear models have been used across plots and species. Kennel (1972) tested functions in beech stands in Bavaria and Switzerland. Meanwhile, Sterba & Marschall (1976) tested eight functions using data from the National Forest Inventory in Austria, followed by quite satisfactory results. More recently, Mehtätalo (2005) estimated height-diameter models for pine and birch in Finland from longitudinal data. Globally, Huang et al. (1992) evaluated the relative performance of a variety of potential height-diameter functions on a large regional data set regarding many Alberta tree species and determined the most appropriate. Six commonly used non-linear growth functions to tree height-diameter data of ten major US tree species were statistically tested by Zhang (1997). Sumida et al. (2013) examined patterns of height growth and diameter growth along a stem, using a 20-year record of an even-aged hinoki cypress (*Chamaecyparis obtusa* Endl.) stand.

Regarding some Greek tree species, similar types of functions were proposed in the past. Total height and diameter at breast height relationships models were used for oak, beech and fir which were: $H = a + b\ln d$, $H = ae^{b/d}$, $H = 1.3 + bd + cd^2$ (Apatsidis & Sifakis 1999). Chatziphilipidis & Spyroglou (2006) applied the simulator MOSES for modelling the growth of Oak in Greece using diameter and height increment, crown recession and mortality models. They made the assumption that the observed diameter increment depended on the potential one as it resulted from open grown trees.

This study aims to evaluate the statistical performance of a variety of potential height-diameter common functions on biometrical data of samples from three different study areas in Greece (ICP-Forests Level II plots) (International Co-operative Programme on Assessment and Monitoring of Air Pollution effects on forests, ICP-forests.net 2017) located in stands of Bulgarian fir, European beech and Hungarian oak and to identify the most suitable function.

2. Methodology and data

Abies borissi-regis Mattf. (Bulgarian Fir) is an endemic tree species to the Balkan Peninsula Minor distributing is found in Greece, Albania, Bulgaria and FYROM (Caudullo & Tinner 2016). *Fagus sylvatica* L. (European beech) forests are distributed from Western and Central Europe to Asia Minor and finally *Quercus frainetto* Ten. (Hungarian or Italian oak) is distributed in the Balkan Peninsula, spreading from Central Europe to Asia Minor (Euro+Med 2006).

According to De Vries et al. (2003), growth measurements of the above mentioned species, took place within ICP-Forests Level II plots (plot characteristics from Greece are presented in Table 1). Oak and beech plots belong to habitat types which ranked at high level of importance for monitoring (Dimopoulos et al., 2006). Both plots are placed on a N-NE aspect, at an altitude of 740 and 890 m a.s.l. for oak and beech respectively. They are situated on the Mt Ossa, a mountain included in Natura 2000 Network (GR 1420003), located in the East Central floristic region of Greece (Strid & Tan, 1997). The above area is also characterized, at national level, as an "aesthetic" forest. In the oak plot, ground vegetation consists of *Sorbus torminalis* (L.) Crantz, *Pteridium aquilinum* (L.) Kuhn, *Melittis melissophyllum* L., *Hieracium bracteolatum* Sm., and *Galium laconicum* Boiss. & Heldr. Dominant plant species for beech plot were *Galium rotundifolium* L., *Doronicum orientale* Hoffm. and *Cyclamen graecum* Link, respectively. Soil at both plots was developed on mica schist, was well drained, deep and classified as Haplic Calsisol for the beech plot and Dystric Cambisol for the oak plot (Michopoulos et al., 2008). Soil of the beech plot was silty loam and that of the oak plot is loam (FAO 1988); soil under the beech plot was more acidic than that of the oak one. Specifically, the average pH of the FH horizon was found 5.43 and 5.76 for the beech and oak plots, respectively, whereas in the mineral horizons the values ranged from 4.09-4.68 in the beech plot and 4.70-4.67 in the oak plot. The average base saturation values were 15% for the beech and 30% for the oak plot.

In the fir plot that was placed on a N aspect at 1175 m a.s.l. the ground vegetation consists mainly of ferns (*Pteridium aquilinum* (L.) Kuhn.), shrubs (*Rubus hirtus* W. & K.), herbs (*Sanicula europaea* L., *Geranium lucidum* L., *Geranium rotundifolium* L., *Luzula forsteri* (Sm.) DC.) and several Gramineae taxa, e.g. *Melica uniflora* Retz. and *Brachypodium sylvaticum* (Huds.) P. Beauv. H. (Michopoulos et al., 2015). Soil was developed on sandy flysch, it was drained, deep and classified as Humic Alisols (FAO, 1988). It is a clay loam with an average base saturation of 35%. The average pH value of the FH soil horizon was found 6.48, whereas the pH values of the mineral soil layers ranged from 5.32-6.07 (determined in a mixture of soil and water at a ratio of 1:5 per volume).

The mean annual temperature was 12.1 °C and the yearly precipitation 1302 mm in the meteorological station of Mt Ossa derived from period 1997-2010. In the MS of Mt Timfristos and for the period 1995-2010, the corresponding values were 10.3 °C and 1413 mm, respectively. The above three plots correspond to habitat types as described in Table 1.

Table 1: Plot characteristics of the three ICP-Level II representative forest ecosystems in Greece

Tabelle 1: Standorts- und Bestandesmerkmale der drei ICP Forests Level II Plots in Griechenland

Level II plot	**Mountain / Regional unit**	**Latitude**	**Longitude**	**Altitude (m)**	**Exposure**	**Surface (m^2)**	**Mean age (yrs)**	**Dominant tree species**	**Habitat type Directive 92/43 EC (Annex I)**
2	Mt Ossa Larissa / Thessaly	39° 47' 10''	22° 47' 40''	740	NE	2.624	61	*Quercus frainetto* Ten. (Hungarian oak)	9280: Mediterranean deciduous forests: *Quercus frainetto* woods)
3	Mt Ossa Larissa / Thessaly	39° 47' 52''	22° 46' 37''	890	N-NE	2.733	120	*Fagus sylvatica* L. (European beech)	9110:Forests of Temperate Europe: Luzulo-Fagetum beech forests
4	Mt Timfristos Evrytania / Central Greece	38° 52' 29''	21° 52' 02''	1175	N	2.990	110	*Abies borisii-regis* Mattf. (Bulgarian fir)	9270: Mediterranean deciduous forests: Hellenic beech forests with *Abies borisii regis*

Following the harmonized methods for sampling and analysis manual aiming at the relevant monitoring (Dobbertin & Neumann 2010), the basic periodic measurements (DBH, tree height, height to crown base, removals and mortality) were carried out approximately every 5th year. All trees were marked (with labels and numbers) so that surveys could be repeated in the future using the same trees. Particularly, for

DBH (tree diameter-outside bark at 1.3 m from ground level) measurements, a caliper of 0.1 cm accuracy or a diameter tape was used; forked trees, with the fork below 1.3 m, were treated as two separate trees. Tree height measurements were made using Blume-Leiss and/or Haga altimeters (0.1 m). The first measurement survey within the ICP-Forests Programme was carried out during the winter of 1995-1996 and subsequently every 5th year later, until the winter of 2009-2010. Overall, four growth data inventories (1996, 2000, 2006 and 2009) were implemented for oak and beech plot, except for fir plot, where five inventories (1996, 2000, 2003, 2006 and 2009) were carried out. Tree summary statistics regarding the DBH and height are described in table 2.

Four common nonlinear functions were used for the determination of the appropriate tree growth model for the fir, oak and beech plots. More specifically, logarithm, polynomial-quadratic, power (3 parameter) and finally Sigmoidal-Chapman (4 parameter) were tested (Table 3). Their selection was based mostly on the examination of the height-diameter relationship as observed by plotting tree height against DBH for the three species but on the literature as well. The evaluation of the diameter and height growth models was based on the adjusted coefficient of determination (R_{adj}), Root Mean Square Error (RMSE), and the significance ($p<0.005$). Also the equality of error variance was tested, using the studentized residuals. The homogeneity of the studentized residuals was also examined in order to avoid overestimations. The model construction was based on the data of 1996 regarding all the tree species. Analysis also included testing the models using height and diameter data received the following years.

Table 2: Summary statistics of stand properties of the three plots

Tabelle 2: Zusammenfassung der Bestandesmerkmale der drei Plots

		Number sampled trees	Diameter at breast height (cm)			Tree height (m)		
			Mean	Min	Max	Mean	Min	Max
Abies borisii-regis (Bulgarian fir)	1996	95	38.2	7.4	72.4	20.6	4.0	32.6
	2000	92	39.4	8.8	74.9	21.9	5.0	32.8
	2003	89	41.1	9.5	76.7	23	5.2	34.8
	2006	89	41.6	9.5	78.0	23.8	5.7	35.0
	2009	86	42.5	9.5	80.6	24.3	5.9	37.3
Fagus sylvatica (European beech)	1996	137	32.6	7.6	67.7	22.7	5.2	30.2
	2000	128	33.6	7.7	69.1	24.9	5.2	31.1
	2006	110	35.9	9.9	70.4	25.9	7.00	32.2
	2009	106	37	10.0	72.6	26.6	8.0	33.6
Quercus frainetto (Hungarian oak)	1996	214	19.3	4.4	45.4	12.9	2.3	19.8
	2000	208	20.8	5.4	46.0	13.9	2.3	21.0
	2006	197	22.4	5.7	47.4	15.2	3.0	22.3
	2009	191	23.2	6.1	47.5	16.4	3.4	23.3

Forked or top damaged and dead trees were excluded from the analysis across all the measurements (Peng 1999; Dobbertin & Neumann 2010). That was determined by giving a unique number to each tree at every plot.

Table 3: Height-Diameter functions selected for comparison

Tabelle 3: Getestete Höhe - Durchmesserfunktionen

Function No	Function type	Function format	References
[1]	Logarithm	$H = H_0 + a \ln D$	Apatsidis & Sifakis 1999
[2]	Polynomial- Quadratic	$H = H_0 + a\, D + b\, D^2$	Huang et al., 1992; Schreuder et al., 1979
[3]	Power-3 Parameter	$H = H_0 + aD^b$	Huang et al., 1992; Schreuder et al., 1979
[4]	Sigmoidal, Chapman-Richards- 4 parameter	$H = H_0 + a(1 - e^{-bD})^c$	Huang et al., 1992; Richards 1959

note: Where D is diameter at breast height (DBH), a, b, c parameters to be estimated, e the base of the natural logarithm (~2.718), H_0 is 1.3 and used to account that DBH is measured at 1.3 m above ground.

3. Results and discussion

Several different criteria were selected for evaluating the performance of the height-diameter functions; Tables 4, 5 and 6 show the results of the evaluation. The adjusted coefficient of determination in all the cases based on 1996 data was acceptable and ranged from 0.57 to 0.87 for fir, 0.55 to 0.68 for oak and 0.67 to 0.84 for beech. Simultaneously, the sigmoidal and the polynomial functions had the most desirable values across all the species, when all the parameters of the functions were significant ($p < 0.005$). In addition, RMSE values varied from 2.59 to 4.83 for fir, 1.83 to 2.58 for oak and 5.54 to 2.94 for beech. The smallest errors were observed across all the species on [2] and [4] structures. Based on the above results and at the first stage of the analysis, sigmoidal-4 parameter Chapman function together with the polynomial-quadratic function could be characterized as best fitted. The Sigmoidal-Chapman is more flexible and has been used extensively in the past to describe this kind of relationships (Huang et al., 1992). In our case, it is also well suited for modelling height-diameter relationships. At the same time, at the literature it is mentioned that the quadratic height diameter function often leads to unrealistic height predictions (e.g. Watts 1983; Huang et al., 1992). In our study, the smallest RMSE values were observed in all cases. Firstly, in the Chapman function and then in the quadratic function. Based on these findings, Chapman's function seemed to be the most optimum first choice for predicting and fitting performance. Further analysis that included testing of the selected functions is presented on Table 7. Due to the static character of these models (the H-D relationship of a stand is not stable but develops over time) it is interesting to test their performance over time. Testing the functions using measurements of the same trees during the following years indicated that Chapman's sigmoidal function fitted better with acceptable RMSE and R^2_{adj} values. The quadratic function also fitted very well but with slight higher values on the examined tests. In all these occasions, the significance of the coefficient of H_0 was not acceptable. In contrast, sigmoidal function continued to give more acceptable results.

At this point it is important to underline, that several functions may give acceptable and similar results and perform nearly equally well. However, evaluating the RMSE, R^2_{adj}, and the significance of the parameters, sigmoidal-3 parameters function seems to perform very well for the three native trees. This could also be confirmed by Figure 1, where the plots of the above equation were produced illustrating tree height and DBH relationships for the three selected species. Only few values were out of the region of uncertainties in predicting (95% prediction band). In Figure 2 values of the error were more likely to be low for low DBH and higher for higher DBH but always between the prediction bands. The dissemination of the predictions on the other two species seemed to be smoother. Literature confirms that Chapmans' model has been widely applied in forestry since decades, due to its flexibility, accuracy, and meaningful analytical properties (Cooper 1961; Pienaar & Turnbull 1973).

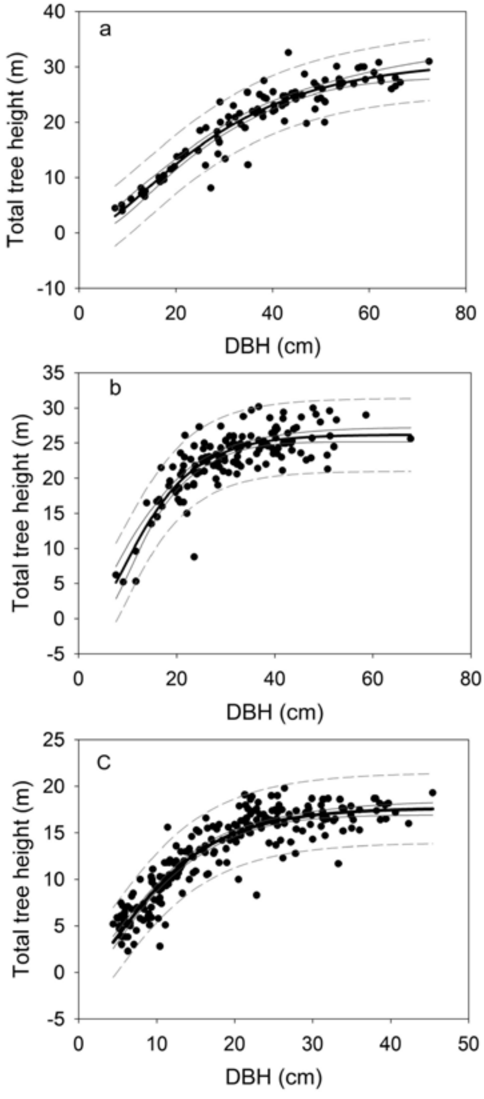

Figure 1: Plot of the tree height against DBH for a) Fir, b) Beech and c) Oak. The plots were produced by the best fitted Sigmoidal, Chapman - 4 parameter function. [95% Confidence Band (Solid line), 95% Prediction Band (dashed line)]

Abbildung 1: Darstellung der Baumhöhe versus DBH für a) Tanne, b) Buche und c) Eiche. Die Diagramme wurden mit der am besten geeigneten Sigmoidal, Chapman - 4 Parameterfunktion erstellt. [95% Konfidenzband (durchgezogene Linie), 95% Vorhersageband (gestrichelte Linie)]

Table 4: Parameter estimations for two or three parameter height-diameter functions regarding fir

Tabelle 4: Parameterschätzungen für Höhen-Durchmesser-Funktionen für Tanne

Fir Function	a (error)	b (error)	c(error)	$A_{dj}R_{sqr}$	RMSE
[1]	5.63 (0.14)	-	-	0.57	4.83
[2]	0.68 (0.02)	-0.003 (0.0006)	-	0.85	2.78
[3]	1.22 (0.21)	0.76 (0.0410)	-	0.83	2.97
[4]	29.42 (1.50)	0.05 (0.0091)	2.31(0.4611)	0.87	2.59

Note: The models and the coefficients were highly statistically significant ($p < 0.0001$) in all cases.

Table 5: Parameter estimations for two or three parameter height-diameter functions regarding beech

Tabelle 5: Parameterschätzungen für Höhen-Durchmesser-Funktionen für Buche

Beech Function	a (error)	b (error)	c (error)	$A_{dj}R_{sqr}$	RMSE
[1]	6.34 (0.076)	-	-	0.55	2.94
[2]	1.08 (0.02)	-0.01 (0.0006)	-	0.64	2.68
[3]	4.89 (0.61)	0.43 (0.0300)	-	0.56	2.97
[4]	24.84 (0.52)	0.11(0.0100)	3.44(1.01)	0.68	2.54

Note: The models and the coefficients were highly statistically significant ($p < 0.0001$) in all cases.

Table 6: Parameter estimations for two or three parameter height-diameter functions regarding oak

Tabelle 6: Parameterschätzungen für Höhen-Durchmesser-Funktionen für Eiche

Oak Function	a (error)	b (error)	c (error)	$A_{dj}R_{sqr}$	RMSE
[1]	4.23 (0.06)	-	-	0.67	2.58
[2]	0.92 (0.02)	-0.01 (0.0007)	-	0.82	1.91
[3]	2.04 (0.18)	0.59 (0.0210)	-	0.75	2.26
[4]	16.25 (0.35)	0.13 (0.0110)	2.56 (0.38)	0.84	1.83

Note: The models and the coefficients were highly statistically significant ($p < 0.0001$) in all cases

Table 7: Behavior of the two selected functions using data of the next years' measurements

Tabelle 7: Verhalten der beiden ausgewählten Funktionen unter Verwendung von Daten der Messungen der nächsten Jahre

		Fir			Beech			Oak		
		2000	2006	2009	2000	2006	2009	2000	2006	2009
Sigmoidal, Chapman-Richards-3 parameter	R^2_{Adj}	0.89	0.89	0.83	0.71	0.62	0.59	0.83	0.81	0.81
	RMSE	2.47	2.53	3.54	2.28	2.75	2.94	1.90	1.97	1.98
Polynomial-Quadratic	R^2_{Adj}	0.87	0.88	0.81	0.64	0.56	0.54	0.82	0.80	0.80
	RMSE	2.70	2.71	3.69	2.52	2.95	3.13	1.58	1.98	2.10

Note: The parameters of the functions are significant ($p<0.0001$) in all cases

In order to identify the correct function, the method of studentized residuals against the predicted values of the depended variable was employed. When the assumptions of the regression analysis are acceptable this method will show a homogenous band of residuals.

Figure 2 shows an example of a plot of Studentized residuals against the predicted height. The chosen from above sigmoidal function fitted to fir's data with unweighted and weighted nonlinear least squares.

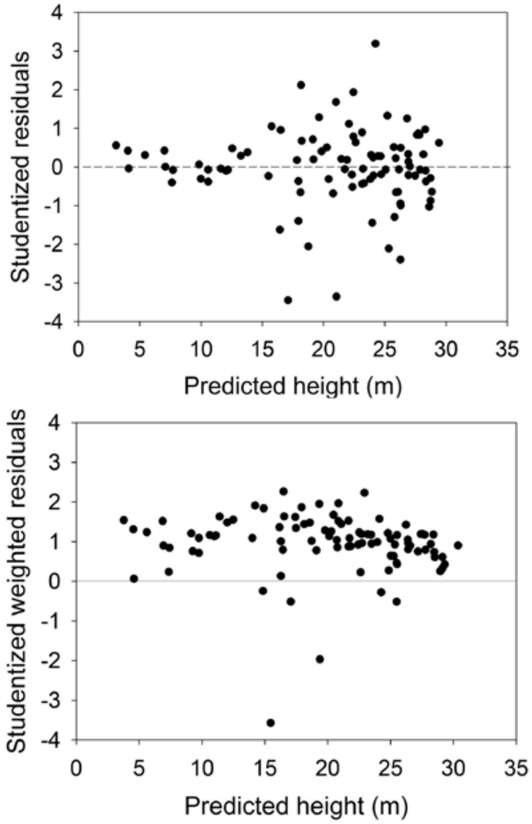

Figure 2: Residuals against the predicted height for fir using the Chapman-Richards function with and without weight

Abbildung 2: Residuen versus vorhergesagter Höhe für Tannen mit der Chapman-Richards-Funktion mit und ohne Gewichtung

At the first plot above on Figure 2, it is shown that there is an unequal error variance problem. In particular, the error seems to be larger regarding the taller trees. In order to achieve more homogenous band of residuals weighting procedure is suggested. The weight formula

$$W_i = {}^{1}/_{f(x)_i^k}$$

was tested and among *k*=1 and *k*=2, k=2 resulted to more homogenous plot (Figure 2, second plot). In beech, the same weight is suggested while in oak no unequal error variance was observed.

Although the four functions were fitted into the same data sets they resulted in different statistical performance, especially regarding the above mentioned statistical tests. The final selection was based on the accurate implementation of the steps that was described in methodology. This curve fitting methodology is a common data analysis in nonlinear regression. The statistical performance of the four models which their curves were close to data of this study, provided a satisfied answer at the choice of the most appropriate model.

Monitoring forests requires information provided by these models. More specifically, it is referred that it requires extensive planning and methodology either for the achievement of national goals, or for addressing sustainable forest management (Moffat et al., 2008). This information could be significant in order to limit future pressures that European forests are expected to face due to climate change and air pollution effects. In parallel, their significance remains high while individual-tree height and diameter are still essential forest inventory measurements such as growth, yield, timber quality, stand structure, production and economics, in relation to species or even for the determination of policy-relevant indicators.

An issue that must be discussed here is the importance of this kind of models at national level. Most of the studies that present models for the prediction of the height-diameter (H-D) relationship of a stand, use a representative sample from the target stand. In addition, most of the times, the sample size needed is too large for practical proposes (Huang, 1999, Petras, 2014, Liu, 2017 and others). Nevertheless, Mehtatalo (2005) refers that in the stand wise inventory for forest management planning, only one or a few sample trees from a stand measure can be measured. Moreover, Kindermann (2016) used a small number of trees intending to examine several growth functions for their ability to follow observed height developments. In our case, we cannot state that our measurements are adequate for the construction of a general model due to the use of only three stands for the three examined species. Moreover, it is suggested to perform further tests to similar stands across Greece. We can only characterize our models as "local" and "static". It is true, that at first sight, the models are local because of their local implementation and "Static" because the H-D relationship of a stand is not stable but develops over time (Curtis 1967; Flewelling & De Jong, 1994; Lappi 1997). Thereafter, our models represent the H-D relationship at a given point in time, as these kinds of models are classified in the literature (e.g. Eerikainen, 2003; Hokka, 1997). Considering that the forest inventory in Greece is outdated (data from 70's and 80's), and not accurate (species are classified only under a general category such us "pine" or "fir") it's impossible to connect these models with current forest inventory data and suggest currently more general use. In conclusion, we are presenting a tool that could be tested as a tool to similar stands with the same age and site conditions.

However, sigmoidal function gave satisfactory results regarding the measurements in the coming years (after 1996), meaning that it fits well when the trees are older as well, so the age does not seem to be an obstacle for broader implementation.

Finally, the distribution and the importance of our examined species need to be analyzed. Oak, beech and fir are of major importance to Greece for managerial and economic reasons. Some connections with forest inventory data are indicating this importance. Strid & Tan (1997) analyzed their distribution, which seems to be extended, clearly. Hungarian Oak is common in Greece, although it has suffered declines (Fotelli et al., 2000). The tree is found mainly in the mainland of Greece but also in the East Aegean (Rivers et al., 2017). In Greece, it is used for reforestation on degraded lands for production of wood, nuts and wildlife food (Radoglou et al., 2003). The oak forests in general occupy the largest range of the Greek industrial forests. According to the latter national inventory data, Greek forests could give 7.674.217 cum tradeable industrial roundwood of oak or 5.56 % of the total production (Ministry of Agriculture, 1992). European Beech is common across all parts of Europe and in the mainland of Greece as well (Barstow & Beech 2018). It is reported by the national Inventory data that is more common in the northwest and east part of the mainland. According to the latter national inventory data, Greek forests could give 27.693.914 cum tradeable industrial roundwood of beech or 20.05 % % of the total production (Hellenic Ministry of Agriculture, 1992). Bulgarian fir forests extend sparsely from the Northern Peloponnese up to the northern border of the country (600-2000 m), forming pure stands or stands mixed with European beech. According to the latter national inventory data, Greek forests could give 43.133.020 cum tradeable industrial roundwood of fir or 30.23 % of the total production (Hellenic Ministry of Agriculture, 1992). Those characteristics, even that are taken from the past, are straightening the importance of functions that explain growth relationships, for proposes like monitoring, forest management or even forest inventory development.

Conclusions

Nonlinear growth functions are commonly used for modelling tree height-diameter relationships. The best equation is selected based on its statistical performance and its predictive capabilities. In this study, the comparison of nonlinear height-diameter functions and their evaluation using independent data from subsequent years indicated that the sigmoidal–Chapman is an appropriate flexible function for predictions regarding Fir, Oak and Beech in Greece.

In our study in comparison with the other models, Chapman's function provided better statistical performance, better performance during the years (giving more flexibility when applying to older trees), greater proximity to observed values and better distribution of residual percentages after the selection of a weighting factor. The comparative results of this study should make this methodology applicable to other species and other tree allometry relationships as well. Simultaneously, the extent of using similar nonlinear functions to model other forestry-relevant relationships such as volume-age, height-age, basal area-age etc. is suggested. Their role is to improve the knowledge of the forest and solve problems when management procedures are too expensive and time consuming (e.g. many trees in the stand to be measured or large forest heterogeneity). Chapman's function could also be tested and extrapolated for application to silver fir and Greek fir because those two species appear to have great resemblance in terms of morphology. The satisfying performance of our models could be considered as a first step for further testing larger datasets for future use in management plans or for the development of the new revised national forest inventory, which is currently under development in Greece.

Finally, taking into consideration that climate change is one of the major challenges for Mediterranean forests in the coming years, the contribution of these models to the efficient monitoring and the observation of forest resources is always crucial in order to continue to provide multiple wood and non-wood forest goods and services.

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