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Applying taper function models for black locust plantations in Greek post-mining areas

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Abstract:

A key process in forest management planning is the estimation of tree volume and, more specifically, merchantable volume. The ability to predict cumulative stem volume to any upper stem diameter on standing trees or stands is essential for forest inventories and management of forest resources. In the 1980s, the Hellenic Public Power Corporation (HPPC) started the rehabilitation of lignite post-mining areas in Greece by planting mainly black locust (*Robinia pseudoacacia*, L.). Today, these plantations occupy an area of about 2570 ha, but the stem volume has not yet been estimated. Therefore, we aimed at estimating the over- and under-bark stem volume using taper function models for 30 destructively sampled

trees. Of the nineteen calibrated fixed-effects models, Kozak's (2004) performed best for both the over-bark and under-bark datasets, followed by Lee's (2003) and Muhairwe's (1999) equations. The addition of random effects on a single-stem basis for two coefficients of Kozak's (2004) equation improved the model fit significantly. Two locally calibrated models were cross validated with calibration coefficients from Poland and the United States. Integrated taper functions were found to slightly outperform three tested volume equations for volume predictions of single stems over and under bark. A validation data set for the taper model verified that those models can be used to predict diameter at a specific point along the stem, merchantable volume, and total stem volume of black locust plantations. Finally, it can be said that taper models permit flexible volume estimation for the population average as well for specific trees.

Key words: forest landscape restoration, stem taper, tree volume, fixed- and mixed-effects modelling, random coefficients, *Robinia pseudoacacia* L.

Statements and Declarations:

- The authors have no competing interests to declare that are relevant to the content of this article.
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1. Introduction

Black locust (*Robinia pseudoacacia*, L.) is a tree species native to North America. The medium-sized, deciduous, thorny, fast-growing species grows on a wide range of soil types and is one of the most important and widespread broadleaved alien tree species in Europe (Sitzia et al. 2016). The ability of black locust to perform well in various habitats, especially during early succession, is noted in the review of Cierjacks et al. 2013. The authors refer to the documentation of black locust invasion on abandoned gravel-sand pits and landfills, urban brownfield sites, secondary forests on farmland, coppice forests and pastures, along disturbed roadsides as well as on burned sites. Black locust was introduced to Europe at the beginning of the 17th century (Peabody 1982) and is now the second most often planted tree species worldwide, after eucalyptus (Nicolescu et al. 2020). Black locust's resistance to heat and drought, its salt tolerance, and its symbiosis with nitrogen-fixing bacteria are particularly important in extreme environmental conditions and therefore for the rehabilitation of degraded areas (Monk and Wiebe 1961; Rahmonov 2009; Umarov 1986). Because of these ecological and biological properties, black locust is often planted in the steppe zone of Ukraine to create forest plantations, rehabilitate forests and reclaim degraded soils (Masiuk et al. 2020; Sytnyk 2017, 2018; Zverkovsky and Zubkova 2019). Black locust is widely used to obtain above-ground biomass in short rotation coppices (Danilović et al. 2013; Engel 2020; Grünewald et al. 2009; Malvolti et al. 2015; Mantovani et al. 2012). Moreover, it is a suitable tree species for the restoration of sites that have been significantly degraded through anthropogenic activities, such as former open-cast mining areas (Mantovani et al. 2015). However, there is some concern about the future management of black locust in Europe due to its possible ecological disadvantages related to invasiveness, threats to biodiversity and induced changes to microclimate and soil traits (Brundu et al. 2020; Keskin and Makineci 2009; Usuga et al. 2010; Vítková et al. 2017).

In Greece, the National Forest Service introduced and planted black locust to stabilize torrents on mountains and prevent soil erosion near rivers, roads and railway banks. It has also been used as fodder in silvopastures (Papachristou et al. 2020) and as an alternative plantation crop for privately owned marginal agricultural lands, in line with the 2080/92 and 1257/99 European Union (EU) Regulations (Dini-Papanastasi 2004). In the 1980s, the Hellenic Public Power Corporation (HPPC) started the rehabilitation of the open-cast coal mining fields in the Lignite Center of Northwest Greece by planting mainly black locust, both alone and in mixture with other species. The establishment of plantations is still ongoing, but already with a planted area of 2570 ha, the HPPC is the largest private forest plantation owner in Greece, owning 26% of the country's black locust plantation area (YPEKA 2014). To date, there is no inventory or management plan for those plantations.

One of the key processes in forest management planning is the estimation of tree volume and, more specifically, merchantable volume (McTague and Weiskittel 2021). There is no accurate and direct method to calculate tree volume due to the unique and complex shape of the stem. Water displacement methods require destructively sampled trees and are both time consuming and expensive. Therefore, tree volume estimation is usually based on empirical – heuristic volume models. Although a tree stem cannot be completely described in mathematical terms, it is convenient to assume that segments of a tree bole approximate various geometric solids. The lower portion of the stem is generally assumed to be a neiloid frustum, the middle portion a paraboloid frustum and the upper portion a cone (Burkhart and Tomé 2012; Husch et al. 1972) . The form factor approach is widespread in forest practice and is used to calculate volume (Bruchwald 1996). A limitation of this method is that while it can result in accurate estimates of whole stem volume, it is not useful for estimating tree section or log volumes. This problem can be overcome by describing the stem profile through the development of taper curves and equations. There are two common methodologies for obtaining taper and volume models (Byrne and Reed 1986; Rustagi and Loveless Jr. 1991). One is to develop volume ratio equations that predict merchantable volume as a percentage of total tree volume (Burkhart 1977); the other is to define an equation describing the stem taper.

Taper equations are flexible models that can provide estimates of 1) total stem volume, 2) merchantable volume to any top diameter and from any stump height diameter, 3) log volumes of any length at any height from the ground and 4) biomass (Calegario et al. 2017). Moreover, taper equations may be used to produce assortment tables based on log lengths or specific diameter thresholds (Kozak 2004; McTague and Weiskittel 2021). Closely related volume models can only estimate the total or merchantable volume of the tree. Tree taper is important for making accurate estimates of standing timber, especially in terms of product potential. Taper equations can be useful in predicting the volume of an individual tree or a stand of trees (Cormier et al. 1992; Spellmann and Nagel 1992). Many empirical models have been used to describe tree profiles. Ormerod (1986) cites Höjer's (1903) logarithmic equation as the first attempt to model tree taper. Research proved that stem profile could not be described with simple equations. The idea was that the new taper equations should produce the whole stem volume estimate as existing volume equations. Goulding and Murray (1976) provided the so-called compatible taper equations, but these exhibited significant bias in certain regions of the stem. Grosenbaum (1966) pointed out that tree profile is best modeled in sections and necessary conditions are that the sub-models produce identical diameters at joint points and that diameters decrease monotonically from the base of tree to the top. Max and Burkhart (1976) used their segmented polynomial model and demonstrated the superiority of three sub-models over two. Thomas and Parresol (1991) applied flexible trigonometric taper equations for both coniferous and broadleaved tree forms.

Many forms and types of stem profile models have been published (Sterba 1980) and evaluated for accuracy and precision (Alberta Forest Service 1987; Cao et al. 1980; Martin 1981). Martin (1981) evaluated five profile models for predicting diameter, height, and volume and found that no single model performed best for all applications. He reported that the Max and Burkhardt (1976) model was best overall. Cao and others (1980) evaluated six profile models for predicting diameter and ranked Max and Burkhardt's segmented-profile polynomial model first and Cao's segmented-profile model second. Cao's segmented-profile model was ranked first for estimating volumes to various top diameters. A polynomial ratio model was ranked second, Burkhardt's (1977) ratio model was third, and Max and Burkhardt's segmented-profile model fourth. The Alberta Forest Service (1987) evaluated 15 stem-profile models and judged Max and Burkhardt's model best because of its accuracy and ease of computation.

While the number of taper equations now available has grown significantly, they can generally be classified into two categories: parametric and non-parametric equations (Salekin et al. 2021). Parametric approaches include polynomial, trigonometric and variable-exponent equations. Segmented polynomial equations, e.g. Max and Burkhardt 1976, contain conditional clauses with different parts of the function applying to the taper depending on relative height along the stem. Elaborate functions with a large number of independent variables and coefficients to be estimated, especially variable-exponent equations (Kozak 2004; Muhairwe 1999) are often found to perform better than less complex counterparts (de-Miguel et al. 2012).

The empirical data intended to create taper models are characterized by a hierarchical structure containing information about individual diameters, trees or sites. One possibility of modeling this data in the case of parametric equations is the mixed-effects modelling approach (Bronisz and Zasada 2020; Mehtätalo and Lappi 2020; Pinheiro and Bates 2006). The fixed component defines the level for a typical basic group (e.g., tree or sites). Whereas the random part describes the difference between each group and a typical value. This approach allows both the capture of all dependencies occurring in the analyzed data and the assessment of variability occurring at various levels, as well as the use of the obtained information in the prediction of the modeled parameter (usually the diameter along the tree, (de-Miguel et al. 2012). While machine-learning methods, artificial neural networks especially, have been explored as viable non-parametric approaches to modelling tree taper (Diamantopoulou 2005; Sakici and Ozdemir 2018; Socha et al. 2020). Calibrated taper models may in turn be applied to predict the timber assortment to be harvested from each stem.

Because there are no models available for calculating the wood volume of black locust stands and no taper functions to estimate the merchantable volume at any stem diameter along the trunk for Greek conditions, the aims of this study were to (i) calibrate taper equations for black locust from the restored area of the Lignite Center of Northwest Greece, (ii)

validate the taper equations with other published taper models for planted black locust in restored coal mines, and (iii) calibrate volume equations along tree volume using the best performing taper models.

2. Materials and methods

2.1. Site description

In this study, we inventoried the black locust restoration plantations on the former open-cast mining areas of the lignite center of Western Greece (Figure 1). The plantations are located near Amyntaio (40.56° to 40.61° N and 21.62° to 21.69° E) and Ptolemaida (40.39° to 40.51° N and 21.7° to 21.89° E), in Northwest Greece (Figure 1). Black locust covers more than 95% of the observed planted area, followed by weaver's broom (*Spartium junceum* L) and Arizona cypress (*Cupressus arizonica* Greene), covering 2.45% and 1.44%, respectively. Other planted species include oaks, maples, pines and various deciduous broadleaves but these make up only very small percentages of the total planted area. The plantations are established on open-cast mining deposits with varying topography (moderate to steep slopes, plains and terraces) and in altitudes ranging from 530 to 950 m. The landscape is fragmented by different land uses, which, in addition to forest plantations, also include grasslands, agricultural lands and bare lands used for photovoltaic parks and recycling facilities. The air temperature of the region ranges from 6.1 to 17.4 °C with a mean annual temperature of 12.2 °C. The total annual precipitation is 664 mm (mean values over the last 50 years).



Figure 1 Map of the Amyntaio and Ptolemaida open-cast mine sites. The green colored polygons represent the restored areas planted with black locust.

2.2. Sampling and measurements

Sampling took place in Aug. –Sep. 2019 and Jul. –Sep. 2020. In total, 30 trees representing the locally present diameter range (3–22cm) were destructively sampled. Each tree was then cut into 6 sections using a chainsaw or branch cutter, depending on diameter. The sections are located at 1) stump height = 0.3m, 2) breast height = 1.3m, 3) mid-bole height, which was defined as the middle point between ground and crown base height, 4) live crown base height, 5) lower third of the crown, and 6) upper third of the crown. Crown base height was defined as the lowest knot of a live branch.

Stem and branch section discs were sanded and subsequently scanned with an Expression 11000XL scanner (Seiko Epson, Japan). Tree ring increment and section diameters were digitally recorded using WinDENDRO 6.0.4 software (Regent Instruments Inc. 2000a) and analyzed via the associated XLStem add-in (Regent Instruments Inc. 2000b) for Microsoft Excel (Microsoft Corporation 1995).

On each disc, increment paths were identified in four perpendicular directions. For the sections between ground and crown base (sections 1–4), one disc was identified and digitally analyzed. For the crown sections (sections 5 and 6), every branch dissecting the respective imaginary line was cut and a disc was sampled. The three discs with the largest diameters per crown section were subsequently used for further analysis in WinDENDRO (Regent Instruments Inc). In cases where discs were damaged due to stripped bark or being rotten, the digital measurements were conducted on the next intact disc. Reference stem volume [m³] was calculated via Smalian’s Equation by the XLStem analysis output.

2.3. Taper equations for fixed-effect models

Since the nature of taper datasets violates the assumption of homogenous variance, modelling was not conducted via the basic nonlinear least squares (*nls*) approach. Instead, using the generalized nonlinear least squares function *gnls* of the nlme package (Pinheiro et al. 2021), a power type function was applied to model residual variance, as reported by Bronisz and Zasada (2020).

Some taper equations only use a single explanatory variable such as the segmented model or the trigonometric model (Max and Burkhardt 1976; Thomas and Parressol 1991), while others use up to four explanatory variables (Kozak 1995; Westfall and Scott 2010). The selection criteria for taper equations were to include this spectrum of simple to complex functions, while focusing on those that were shown in the literature to perform well.

In order to predict the same dependent variable ‘section diameter squared’, all functions were modified according to Bruce et al. 1968; de-Miguel et al. 2012.

Nomenclature:

D	- section diameter [cm], over or under bark
DBH	- diameter o.b. [cm] at breast height
H	- total tree height [m]
HD	- section height [m]
RH	- $\frac{HD}{H}$ section height [m] / total tree height [m]
$\beta_1 \dots \beta_{10}$	- fixed-effect parameters to be calibrated

193 Taper equations:

Eq. 1 Bi and Long 2001

$$D^2 \sim \left\{ \left[\frac{\ln \left(\sin \left(\frac{\pi}{2} * RH \right) \right)}{\ln \left(\sin \left(\frac{\pi}{2} * t \right) \right)} \right]^{\beta 1 + \beta 2 * \sin \left(\frac{\pi}{2} * RH \right) + \beta 3 * \cos \left(\frac{3\pi}{2} * RH \right) + \beta 4 * \frac{\sin \left(\frac{\pi}{2} * RH \right)}{RH} + \beta 5 * D + \beta 6 * RH * \sqrt{D} + \beta 7 * RH * \sqrt{H}} \right\} * DBH^2$$

Where $t = \frac{1.3m}{H}$, all other variables are described above

Eq. 2 Biging 1984

$$D^2 \sim \left\{ \left[\beta 1 + \beta 2 * \ln \left(1 - RH^{\frac{1}{3}} \right) * \left(1 - e^{\left(-\frac{\beta 1}{\beta 2} \right)} \right) \right] * DBH \right\}^2$$

Eq. 3 Bruce et al. 1968

$$D^2 \sim \{ [\beta 1 * k^{0.1} + \beta 2 * [k^{1.5} - k^3] * DBH * 0.01 + \beta 3 * [k^{1.5} - k^3] * H * 0.001 + \beta 4 * [k^{1.5} - k^{32}] * HD * 0.0001 + \beta 5 * [k^{1.5} - k^{32}] * H^{0.5} * 0.001 + \beta 6 * [k^{1.5} - k^{40}] * H^2 * 0.00001] * DBH \}^2$$

Eq. 4 Cao 1980 as found in
Parresol et al. 1987

$$D^2 \sim \left[\sqrt{\frac{2 * z + \beta 1 * (3 * z^2 - 2 * z) + \beta 2 * (z - \beta 4)^2 * (z \geq \beta 5) + \beta 3 * (z - \beta 4)^2 * (z \geq \beta 5)}{\beta 3 * (z - \beta 4)^2 * (z \geq \beta 5)}} * DBH \right]^2$$

Where $z = \frac{H - HD}{H}$, all other variables are described above

Eq. 5 Demaerschalk 1972

$$D^2 \sim [\beta 1 * DBH^{\beta 2} * (H - HD)^{\beta 3} * H^{\beta 4}]^2$$

Eq. 6 Kozak et al. 1969

$$D^2 \sim \{ [\beta 1 * (RH - 1) + \beta 2 * (RH^2 - 1)] * DBH \}^2$$

Eq. 7 Kozak 1995

$$D^2 = \left[\beta 1 (DBH^{\beta 2}) + (H^{\beta 3}) + \left(\frac{1 - \sqrt{RH}}{1 - \sqrt{t}} \right)^{\beta 4^{0.1}} + \beta 5 (RH^4) + \beta 6 * \arcsin(1 - \sqrt{RH}) + \beta 7 * \left(\frac{1}{e^{DBH/H}} \right) + \beta 8 \right. \\ \left. * DBH \left(\frac{1 - \sqrt{RH}}{1 - \sqrt{t}} \right) \right]^2$$

Where $t = \frac{1.3m}{H}$, all other variables are described above

Eq. 8 Kozak 2004

$$D^2 \sim \left[\beta 1 * DBH^{\beta 2} * H^{\beta 3} * C^{\beta 4 * H^4 + \beta 5 * \left(1 - e^{-\frac{DBH}{H}} \right) + \beta 6 * C^{0.1} + \beta 7 * \frac{1}{DBH} + \beta 8 * H^Q + \beta 9 * C} \right]^2$$

Where $C = \frac{1 - \left(\frac{HD}{H} \right)^{\frac{1}{3}}}{1 - \left(\frac{1.3}{H} \right)^{\frac{1}{3}}}$, $Q = 1 - \left(\frac{HD}{H} \right)^{\frac{1}{3}}$, all other variables are described above

Eq. 9 Laasasenaho 1982 as $D^2 \sim \{[\beta 1 * RH + \beta 2 * RH^2 + \beta 3 * RH^8 + \beta 4 * RH^{34}] * DBH\}^2$
found in de-Miguel et
al. 2012

Eq. 10 Lee et al. 2003

$$D^2 \sim \beta 1 * DBH^{\beta 2} * \left[(1 - RH)^{(\beta 3 * RH^2 + \beta 4 * RH + \beta 5)} \right]^2$$

Eq. 11 Max and Burkhardt 1976

$$D^2 \sim [\beta 1 (RH - 1) + \beta 2 (RH^2 - 1) - \beta 3 (\alpha 1 - RH)^2 * I_{\beta 5 - RH} + \beta 4 (\alpha 2 - RH)^2 * I_{\beta 6 - RH}] * DBH^2$$

where: $I_{\beta 5-RH} = 1, \beta 5 - RH \geq 0; I_{\beta 5-RH} = 0, \beta 5 - RH < 0; I_{\beta 6-RH} = 1, \beta 6 - RH \geq 0; I_{\beta 6-RH} = 0, \beta 6 - RH < 0$

Eq. 12 Muhairwe 1999

$$D^2 \sim \beta 1 * DBH^{\beta 2} * \left[(1 - RH)^{\beta 3 * RH + \beta 4 * RH^2 + \frac{\beta 5}{RH} + \beta 6 * RH^3 + \beta 7 * DBH + \beta 8 * (\frac{DBH}{H})} \right]^2$$

Eq. 13 Newberry and Burkhardt
1986

$$D^2 \sim \left[\beta 1 * DBH * \left(\frac{H - HD}{H - 1.3} \right)^{\beta 2} \right]^2$$

Eq. 14 Riemer et al. 1995

$$D^2 \sim \left\{ \frac{\beta 1 * DBH}{1 - e^{\beta 3 * (1.3 - H)}} + \left(\frac{DBH}{2} - \beta 1 * DBH \right) * \left[1 - \frac{1}{1 - e^{\beta 2 * (1.3 - H)}} \right] + e^{-\beta 2 * H} * \left[\frac{\left(\frac{DBH}{2} - \beta 1 * DBH \right) * e^{1.3 * \beta 2}}{1 - e^{\beta 2 * (1.3 - H)}} \right] - e^{\beta 3 * H} * \left[\frac{\beta 1 * DBH * e^{-\beta 3 * H}}{1 - e^{\beta 3 * (1.3 - H)}} \right] \right\}^2$$

Eq. 15 Sharma and Oderwald
2001

$$D^2 \sim DBH^2 * \frac{HD^{2-\beta 1}}{1.3} * \frac{H - HD}{H - 1.3}$$

Eq. 16 Sharma and Zhang
2004

$$D^2 \sim \left\{ DBH * \beta 1 * \left(\frac{HD}{1.3} \right)^{\left[2 - (\beta 2 + \beta 3 * RH + \beta 4 * RH^2) * \left(\frac{H - HD}{H - 1.3} \right)^{0.5} \right]} \right\}^2$$

Eq. 17 Sharma and Parton
2009

$$D^2 \sim \left\{ DBH * \beta 1 * \left(\frac{HD}{1.3} \right)^{\left[2 - (\beta 2 + \beta 3 * RH + \beta 4 * RH^2) * \left(\frac{H - HD}{H - 1.3} \right)^{0.5} \right]} \right\}^2$$

Eq. 18 Thomas and Parressol
1991

$$D^2 = \left[\beta_1(RH - 1) + \beta_2 \sin(2 * \pi * RH) + \beta_3 \cotan\left(\pi * \frac{RH}{2}\right) \right] * DBH^2$$

Eq. 19 Westfall and Scott 2010

$$D^2 = DBH^2 * \left(\frac{1.3}{\beta_5} \right)^{\beta_{10}} * \left(\frac{1 - \frac{HD}{H}}{1 - \beta_5} \right)^{\left(\varphi_{1j} + \beta_{1j} \right) + \left[\frac{\varphi_{2j} + \beta_7}{\left(1 + \frac{HD}{H} \right)^{\beta_9}} \right]} * \left(\frac{1 - \frac{HD}{H}}{1 - \beta_6} \right)^{\beta_2 * \frac{\left(\frac{HD}{H} \right)^{\beta_4 * \frac{DBH}{H}}}{1 + \left(\frac{HD}{H} \right)^{\beta_4 * \frac{DBH}{H}}}}$$

Where $\varphi_{1j}, \varphi_{2j}$ - random effects for tree j

2.4. Validation

The predicted values from the present Greek dataset were compared with two sets of calibrated coefficients of closely related publications: the Western Polish model for Kozak's 1995 taper equation (Eq. 7) for 48 black locust trees (Bronisz and Zasada 2020) and the North-Eastern US taper equation (Eq. 19) calibrated with a tree species group including black locust (Westfall and Scott 2010). Both models were analyzed alongside the fixed-effect models for diameters over bark. The lack of fit compared to the present calibration was observed via residual plots and correlation testing with a linear model.

2.5. Mixed-effect taper models

As a result of the fixed-effect (FE) model ranking, the best taper model was selected to be fitted with random effects. Mixed-effect (ME) modelling was conducted using the same application of the power type function to model the residual variance as previously described for FE. Random effects were assigned at the tree grouping-level to improve the individual tree fit along the stem, thus accounting for possible differences in taper behaviour e.g. by age. To include all possible combinations of random effects for every coefficient, a grid search with 1, 2 and 3 random effects was performed. ME model performance was ranked using the same selection of goodness-of-fit metrics as the FE models. In the third step, analysis of variance (ANOVA) was applied to confirm a statistically significant difference of coefficients between the best performing ME model and its FE counterpart. Finally, possible decreases in heteroscedasticity through the addition of random effects over the FE model were assessed via residual analysis. Residuals were plotted against relative height RH along the stem and section diameter D_{ob} and D_{ub} .

2.6. Stem volume equations

The reference stem volume [m^3] was calculated using Smalian's equation applied to the measured section diameters. Predicted stem volume for FE models was derived using numerical integration provided by the *integrate()*-function in R. Three volume equations from the literature (previously tested for black locust by Bronisz and Zasada (2020) as a function $f(DBH, H)$ were used for comparison without recalibrating their coefficients. In contrast to some taper equations that require other variables, volume functions require only one diameter and height measurement per tree, eliminating the eventual multicollinearity of repeated measurements (i.e., section diameters along the stem). The argument of simplicity prevails, as the volume equation terms do not include conditional clauses (Eq. 4, Eq. 11) or complex exponents (Eq. 7, Eq. 19).

222 Smalian's equation: $V = \sum_{i=1}^{n-1} \frac{g_i + g_{i+1}}{2} * l + V_n$

223 where g_i is the cross-sectional area of the i -th section, l is the section length and V_n is the cone at the tip of the tree.

224 **Formulae for stem volume equations**

Eq. 20 Sopp and Kolosz 2000

$$V_{stem} = 10^{-8} * DBH^2 * H * \left[\frac{H}{(H - 1.3)} \right]^2 * (0.6326 * DBH * H + 20.23 * DBH + 3034)$$

Eq. 21 Moshki and Lamersdorf 2011

$$V_{stem} = 0.4 * H * DBH^2$$

Eq. 22 Lockow and Lockow 2015

$$V_{stem} = 4.848577837 * 10^{-5} * DBH^{1.946545395} * H^{0.96112739}$$

225

226 **2.7. Statistical analysis**

227 All statistical computations were executed using the R programming language, version 4.0.3 (R Core Team 2020). R-
228 packages used were *minpackLM* (Florent Baty et al. 2015) and *nlme* (Pinheiro et al. 2021). A significance level of $\alpha =$
229 5% was applied to confirm the statistical significance of model coefficients. Five goodness-of-fit metrics were used to
230 evaluate model performance. While it has been argued that Root Mean Square Error (*RMSE*) (Eq. 23) is a worse assessor
231 of average errors than Mean Absolute Error (*MAE*) (Eq. 24) (Willmott and Matsuura 2005), it is widely used in
232 performance rankings of taper model calibrations and is included here for comparability with other publications. Mean
233 Bias (*MB*) (Eq. 25) and Mean Percent Bias (*MPB*) (Eq. 26) are both used to quantify a trend in the model's predicted
234 values. *MPB* was chosen in addition to *MB* in order to be able to assess bias relative to the actual value. As taper data
235 naturally covers a wide range of diameters, the same absolute error value is increasingly more influential with decreasing
236 diameter. Lastly, Akaike's Information Criterion (*AIC*) (Eq. 27) (Akaike 1974) measures the model fit by likelihood
237 testing. *AIC* favors parameter parsimonious functions, i.e., the model performance receives a better score for fewer
238 parameters being estimated. For *RMSE*, *MAE* and *AIC*, the lowest values are desired, whereas for *MB* and *MPB*, values
239 closer to 0 indicate the best performance.

$$240 \quad RMSE = \sqrt{\frac{\sum (y - \hat{y})^2}{n}} \quad (\text{Eq. 1})$$

$$241 \quad MAE = \frac{\sum |y - \hat{y}|}{n} \quad (\text{Eq. 2})$$

$$242 \quad MB = \frac{\sum (y - \hat{y})}{n} \quad (\text{Eq. 3})$$

$$MPB = 100 * \frac{\sum(y-\hat{y})}{\sum y} \quad (\text{Eq. 4})$$

$$AIC = 2k - 2 * \ln(\hat{L}) \quad (\text{Eq. 5})$$

where: y = observed value, $\hat{y}$ = predicted value, n = sample size, k = number of estimated parameters,

$\hat{L}$ = likelihood of the estimator

A model's relative $Rank_i$ (Eq. 28) by a certain goodness-of-fit metric (e.g. $RMSE$), i.e., between the best and worst performing model, was calculated using the ranking method of (Poudel and Cao 2013):

$$Rank_i = 1 + \frac{(n-1) * (M_i - M_{min})}{M_{max} - M_{min}} \quad (\text{Eq. 6})$$

where:

n - number of compared models

M_i - respective evaluated value of the model

M_{min}, M_{max} - the lowest (mostly best) and highest (worst) overall values of a metric.

The final model performance was assessed by ranking the mean of each metric performance as $RankAVG$.

2.8. Data overview

The dendrochronological analysis showed that the age of the trees was between 4 and 24 years. Tree age was derived via ring count at the stump height (HST) section disc (0.3m). Mean DBH was 10.91 ± 4.52 cm and mean tree height was 11.79 ± 3.28 m (Table 1). Due to the overall small stem dimensions, the volumes of the observed trees were small with a maximum of 0.23m^3 . Stem volume also displayed the highest coefficient of variation with almost 100% around the mean.

Table 1 Summary statistics for diameter at breast height = DBH, tree height = H, crown base height = HCB and stem volume = V (N=30)

	Mean	±SD	CV%	Min	Max
DBH [cm]	10.91	4.52	41.43%	3.20	21.93
H [m]	11.79	3.28	27.79%	5.95	17.80
HCB [m]	6.64	2.57	38.69%	1.70	11.90
V [m ³]	0.07	0.06	92.34%	0.002	0.238

The section-wise diameter distribution is displayed in Figure 2. With the exception of one outlier, values recorded for crown diameters were less than 5cm. There was a sharp absolute decrease in mean section diameter from crown base (DCB = 7.5cm) to the lower section within the crown branches (D23 = 4.0cm).

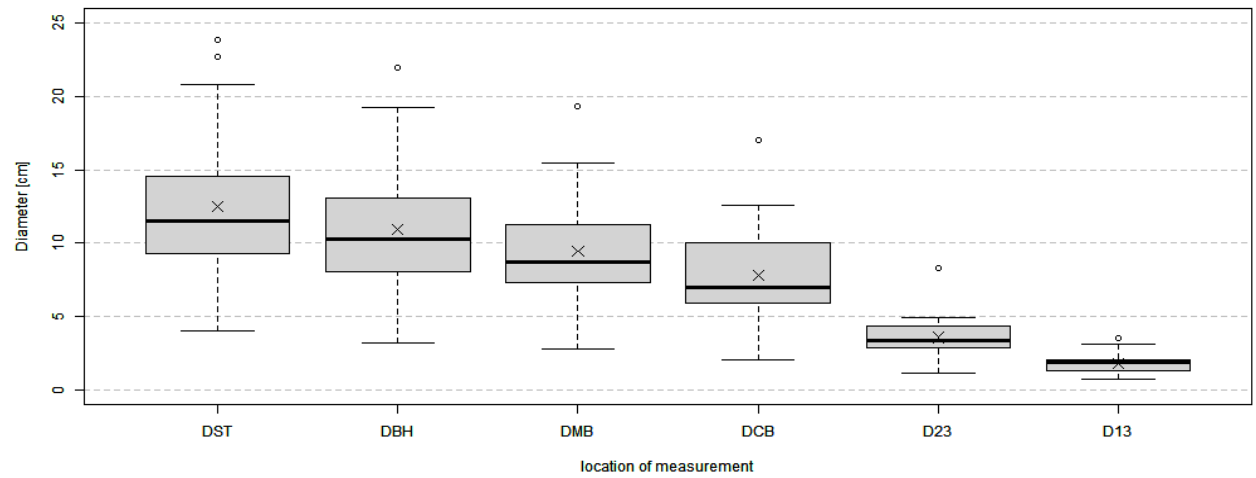


Figure 2 Diameter distribution at section heights with DST = diameter at stump height, DBH = diameter at breast height, DMB = diameter at mid-bole, DCB = diameter at base of live crown, D23 and D13 = diameter at lower and upper third of live crown. Mean values are represented by crosses and median values by horizontal bars.

Error! Reference source not found. shows the total tree height as well as height distribution for each section. Total tree height H ranged from

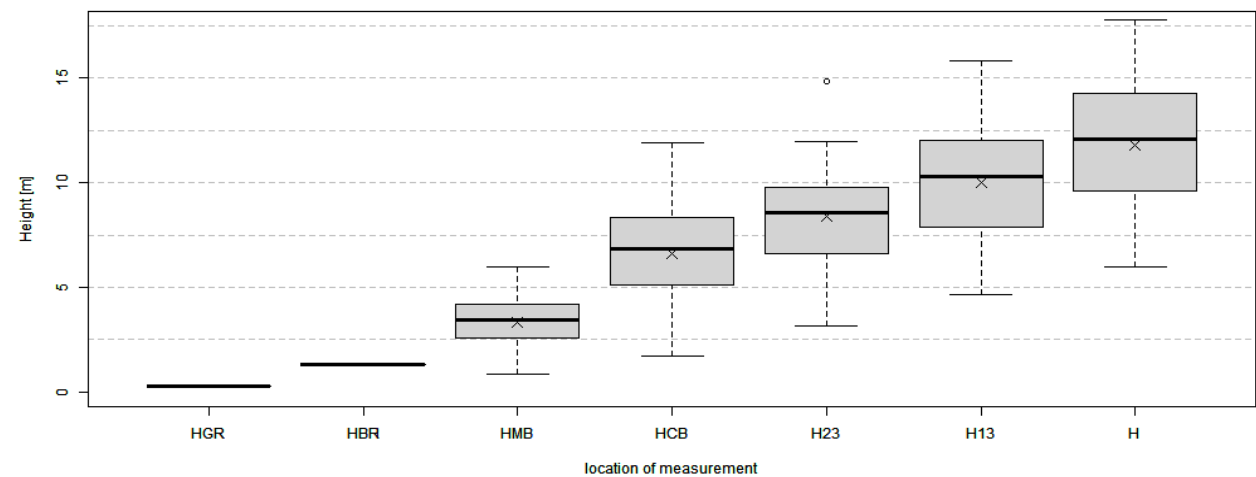


Figure 3 Distribution of each section height; HGR = stump height (0.3m), HBR = breast height (1.3m), HMB = mid-bole height, HCB height at the base of live crown, H23 and H13 = ~lower and upper third of live crown. Mean values are represented by crosses and median values by horizontal bars.

6 to 18m. Mid-bole height HMB was recorded lower than breast height for two small trees.

3. Results

3.1. Fitting fixed-effects (FE) taper models

Nineteen over-bark (o.b.) taper functions were fitted to model tree taper of black locust. Out of 19 over-bark (o.b.) gnls models, 11 converged with fully significant coefficients. Table 2 summarizes the statistics for the trees selected for taper functions o.b. and Table 3 for the under-bark (u.b.) dataset. The model with the highest number of calibrated coefficients and without non-significant terms was Eq. 11 for both o.b. and u.b. With just three coefficients overall, Eq. 15 had one non-significant coefficient when calibrated for $D_{o.b.}^2$. Eq. 19 did not converge for either dataset using the gnls() approach and is therefore only included for the validation in 3.2.

Table 2 Estimated FE coefficients of the calibrated taper models, dependent variable: diameter over bark squared $D_{o.b.}^2$; values in parentheses represent standard errors of the coefficients; ns marks non-significant coefficients at $p > 0.05$

	$\beta 1$	$\beta 2$	$\beta 3$	$\beta 4$	$\beta 5$	$\beta 6$	$\beta 7$	$\beta 8$	$\beta 9$
Eq.1 Bi 2000	210.776 (13.441)	-43.872 (4.084)	-13.522 (1.454)	-121.624 (8.716)	0.542 (0.06)	-14.074 (1.574)	1.822 (1.402) ns		
Eq. 2 Biging 1984	1.278 (0.009)	0.359 (0.008)							
Eq. 3 Bruce 1986	0.725 (0.041)	2.552 (6.151) ns	-153.154 (67.335)	2712.965 (3025.749) ns	8.636 (10.017) ns	-179.753 (105.092) ns			
Eq. 4 Cao 1980	1.108 (0.041)	-3.713 (0.31)	30.606 (17.763) ns	0.263 (0.02)	0.888 (0.029)				
Eq. 5 Demaerschalk 1972	1.269 (0.069)	0.9 (0.028)	0.762 (0.023)	-0.715 (0.05)					
Eq. 6 Kozak 1969	0.621 (0.052)	0.483 (0.047)							
Eq. 7 Kozak 1995	0.852 (0.108)	0.852 (0.052)	0.18 (0.041)	0.328 (0.053)	-7.922 (1.131)	-0.632 (0.479) ns	0.5 (0.488) ns	0.087 (0.026)	

Eq. 8 Kozak 2002	0.856 (0.045)	0.921 (0.021)	0.135 (0.037)	1.146 (0.142)	-1.076 (0.206)	0.561 (0.086)	1.602 (0.313)	0.018 (0.018) ns	-0.011 (0.077) ns
Eq. 9 Laasenaho 1982	7.688 (0.352)	-14.11 (0.811)	16.467 (2.084)	-111.061 (31.169)					
Eq. 10 Lee 2003	1.458 (0.038)	0.912 (0.01)	4.718 (0.538)	-4.955 (0.534)	1.975 (0.134)				
Eq. 11 Max 1976	-5.837 (0.784)	3.041 (0.463)	-6.607 (1.821)	8.649 (1.973)	0.606 (0.052)	0.334 (0.042)			
Eq. 12 Muhairwe 1999	29.765 (15.61) ns	0.916 (0.013)	-3.999 (1.551)	1.546 (3.309) ns	3.035 (0.51)	2.17 (2.4) ns	-0.015 (0.007)	0.505 (0.14)	
Eq. 13 Newberry 1986	1.022 (0.005)	0.754 (0.022)							
Eq. 14 Riemer 1995	0.135 (0.003)	0.11 (0.013)	0.602 (0.621) ns						
Eq. 15 Sharma 2001	2.116 (0.009)								
Eq. 16 Sharma 2004	0.977 (0.015)	2.137 (0.017)	-0.868 (0.182)	1.435 (0.251)					
Eq. 17 Sharma 2009	0.989 (0.007)	-0.054 (0.008)	0.683 (0.086)	-0.492 (0.119)					
Eq. 18 Thomas 1991	-5.016 (0.416)	2.821 (0.382)	0.024 (0.002)						

279

280 **Table 3 Estimated FE coefficients of the calibrated taper models, dependent variable: diameter under bark squared $D_{u.b.}^2$; values in parentheses represent standard**
281 **errors of the coefficients; ns marks non-significant coefficients at $p > 0.05$**

	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9
Eq.1 Bi 2000	128.289 (8.798)	-21.322 (3.15)	-4.65 (0.863)	-76.292 (5.928)	0.534 (0.068)	-8.179 (1.221)	-0.756 (0.84) ns		
Eq. 2 Biging 1984	1.15 (0.008)	0.321 (0.007)							

Eq. 3 Bruce 1986	0.587 (0.033)	2.345 (4.989) ns	-122.326 (54.518)	1682.335 (2416.473) ns	8.758 (8.119) ns	-161.396 (85.533) ns			
Eq. 4 Cao 1980	1.222 (0.03)	-4.762 (0.394)	7.228 (1.205)	0.271 (0.017)	0.755 (0.03)				
Eq. 5 Demaerschalk 1972	1.063 (0.059)	0.889 (0.028)	0.752 (0.021)	-0.665 (0.05)					
Eq. 6 Kozak 1969	0.538 (0.045)	0.457 (0.04)							
Eq. 7 Kozak 1995	0.671 (0.085)	0.863 (0.048)	0.22 (0.041)	0.323 (0.049)	-7.572 (0.951)	-0.636 (0.404) ns	0.704 (0.407) ns	0.079 (0.023)	
Eq. 8 Kozak 2002	0.761 (0.041)	0.917 (0.022)	0.145 (0.038)	1.044 (0.131)	-0.746 (0.201)	0.481 (0.084)	1.164 (0.324)	0.008 (0.018) ns	0.017 (0.082) ns
Eq. 9 Laasenhah 1982	6.908 (0.311)	-12.656 (0.725)	14.723 (1.88)	-99.43 (28.124)					
Eq. 10 Lee 2003	1.247 (0.031)	0.931 (0.01)	4.383 (0.506)	-4.601 (0.503)	1.887 (0.126)				
Eq. 11 Max 1976	-4.718 (0.729)	2.436 (0.424)	-3.712 (0.522)	8.73 (1.301)	0.657 (0.045)	0.234 (0.028)			
Eq. 12 Muhairwe 1999	20.686 (10.39)	0.937 (0.013)	-4.132 (1.452)	2.846 (3.045) ns	2.839 (0.488)	0.835 (2.177) ns	-0.016 (0.006)	0.535 (0.142)	
Eq. 13 Newberry 1986	0.924 (0.004)	0.734 (0.021)							
Eq. 14 Riemeier 1995	0.029 (0.007)	-0.154 (0.017)	-2.695 (0.257)						
Eq. 15 Sharma 2001	2.064 (0.013)								
Eq. 16 Sharma 2004	0.793 (0.012)	2.139 (0.016)	-0.934 (0.174)	1.514 (0.24)					
Eq. 17 Sharma 2009	0.892 (0.006)	-0.041 (0.008)	0.642 (0.086)	-0.494 (0.12)					
Eq. 18 Thomas 1991	-3.857 (0.363)	4.035 (0.312)	0.023 (0.002)						

The subsequent ranking of the 18 models was performed for four error metrics and AIC. Next, rankAVG was calculated as the horizontal mean of each individual rank. The top five equations by rankAVG are displayed in Table 4 (o.b. models) and Table 5 (u.b. models). Eq. 8 (Kozak 2004) performed best by lowest rankAVG for both the o.b. and u.b. datasets. As Eq. 10, Eq. 12 and Eq. 7 were the next three best models, only the fifth highest ranking equation changed from Eq. 10 for o.b. to Eq. 17 for the u.b. models. Generally, the first three models performed similarly, with only slight deviations in a single metric. This is particularly the case for Eq. 12, which had the combined mean bias (MB) of Eq. 8 and Eq. 10.

Table 4 Goodness-of-fit statistics for the five best performing FE models (diameter over bark squared $D_{o.b.}^2$); RMSE = Root Mean Square Error, MAE = Mean Absolute Error, MB = Mean Bias, MPB = Mean Percent Bias, AIC = Akaike's Information Criterion

	RMSE	MAE	MB	MPB	AIC	
Eq. 8 Kozak (2002)	16.984	9.601	1.207	-0.079	1385	
Eq. 10 Lee (2003)	17.422	9.619	1.779	-0.029	1390	
Eq. 12 Muhairwe (1999)	17.368	9.506	2.881	0.022	1388	
Eq. 7 Kozak (1995)	19.821	11.346	-0.063	-0.185	1419	
Eq. 11 Max (1976)	18.469	10.854	-1.497	-0.103	1437	
	rankRMSE	rankMAE	rankMB	rankMPB	rankAIC	rankAVG
Eq. 8 Kozak (2002)	1	1.02	1.35	1.3	1	1.134
Eq. 10 Lee (2003)	1.04	1.03	1.52	1.04	1.13	1.152
Eq. 12 Muhairwe (1999)	1.03	1	1.85	1	1.08	1.192
Eq. 7 Kozak (1995)	1.24	1.46	1	1.86	1.86	1.484
Eq. 11 Max (1976)	1.12	1.34	1.43	1.43	2.32	1.528

Overall, the u.b. models showed lower absolute errors, which is due to these diameter values being naturally lower than their o.b. equivalent. In terms of relative errors, regarding mean percent bias (MPB), the u.b. models performed almost exclusively worse than the o.b. calibrations. Only Eq. 12 had a substantially lower u.b. MPB compared to o.b. MPB, while also being the only model with a positive MPB for o.b. and negative for u.b.

Table 5 Goodness-of-fit statistics for the five best FE models (diameter under bark squared $D_{u.b.}^2$); RMSE = Root Mean Square Error, MAE = Mean Absolute Error, MB = Mean Bias, MPB = Mean Percent Bias, AIC = Akaike's Information Criterion

	RMSE	MAE	MB	MPB	AIC	
Eq. 8 Kozak (2002)	14.919	7.921	0.875	-0.134	1307	
Eq. 10 Lee (2003)	15.268	7.982	1.703	-0.041	1312	

Eq. 12 Muhairwe (1999)	15.177	7.853	2.447	-0.014	1310	
Eq. 7 Kozak (1995)	16.808	9.244	-0.113	-0.182	1338	
Eq. 17 Sharma (2009)	16.387	8.887	-0.269	-0.245	1338	
	rankRMSE	rankMAE	rankMB	rankMPB	rankAIC	rankAVG
Eq. 8 Kozak (2002)	1	1.03	1.42	1.62	1	1.214
Eq. 10 Lee (2003)	1.08	1.05	1.84	1.14	1.13	1.248
Eq. 12 Muhairwe (1999)	1.06	1	2.22	1	1.08	1.272
Eq. 7 Kozak (1995)	1.43	1.55	1.03	1.86	1.79	1.532
Eq. 17 Sharma (2009)	1.33	1.41	1.11	2.19	1.79	1.566

Therefore, the best generalized nonlinear least squares model for o.b. regression is Eq. 8, reduced by the non-significant terms β_8 and β_9 :

$$D^2 \sim \left[0.856 * DBH^{0.921} * H^{0.135} * \frac{\left[1 - \left(\frac{HD}{H} \right)^{\frac{1}{3}} \right]^{1.146 * H^4 - 1.076 * \left(1 - e^{-\frac{DBH}{H}} \right) + 0.561 * C^{0.1} + 1.602 * \frac{1}{DBH}}}{\left[1 - \left(\frac{1.3}{H} \right)^{\frac{1}{3}} \right]} \right]^2$$

and for u.b., equally reduced by the same non-significant terms:

$$D^2 \sim \left[0.761 * DBH^{0.917} * H^{0.145} * \frac{\left[1 - \left(\frac{HD}{H} \right)^{\frac{1}{3}} \right]^{1.044 * H^4 - 0.746 * \left(1 - e^{-\frac{DBH}{H}} \right) + 0.481 * C^{0.1} + 1.164 * \frac{1}{DBH}}}{\left[1 - \left(\frac{1.3}{H} \right)^{\frac{1}{3}} \right]} \right]^2$$

When analyzing model performance for relative height by RMSE of $D_{o.b.}^2$, Eq. 8 reached the lowest error in four classes (Table 6), including the lowest segment at the stump. Five other models achieved the lowest RMSE in a single class. As bark volume per meter decreases to the tip of the stem, the lower stem regions should be prioritized for reducing errors. It is notable that RMSE decreases from at least 25cm for measurements in the lowest tenth to less than 5cm in the next, while increasing again to ca. 15cm in the third.

Table 6 Comparison of Root Mean Square Error (RMSE) over 10 classes of relative height (RH) for FE models of diameter over bark squared ($D_{o.b.}^2$)

RH class	0<R H ≤0.1	0.1< RH≤ 0.2	0.2< RH≤ 0.3	0.3< RH≤ 0.4	0.4< RH≤ 0.5	0.5< RH≤ 0.6	0.6< RH≤ 0.7	0.7< RH≤ 0.8	0.8< RH≤ 0.9	0.9< RH≤ 1	N lowes t RMS E

N of meas.	41	18	21	13	7	11	23	18	27	1	
Eq. 4 Cao (1980)	28.72 5	2.892	24.88 7	9.416	9.944	16.17 7	31.52 3	7.060	6.388	4.657	1
Eq. 8 Kozak (2002)	25.86 0	3.281	15.20 2	7.813	29.40 0	13.57 2	20.22 6	6.465	3.826	5.259	4
Eq. 10 Lee (2003)	26.20 4	2.802	13.17 8	10.93 5	14.72 8	15.32 6	26.31 5	5.745	4.211	5.955	2
Eq. 12 Muhairwe (1999)	27.36 9	3.973	15.52 0	9.194	26.97 0	10.83 1	20.29	5.769	4.928	6.231	1
Eq. 13 Newberry (1986)	28.82 1	4.335	18.23 8	13.12 2	23.90 5	27.07 0	25.69 1	6.677	9.980	0.719	1
Eq. 15 Sharma (2001)	25.91 6	1.423	13.77 2	15.83 5	21.59 6	21.38 4	32.54 1	11.92 8	21.16 5	6.463	1

As for $D_{u.b.}^2$, no single equation achieved the lowest RMSE in more than two classes (Table 7), with Eq. 8 once again being among them. Eq. 7 performed best for the lowest segment, Eq. 10 for the second.

Table 7 Comparison of Root Mean Square Error (RMSE) over 10 classes of relative height (RH) for FE models of diameter under bark squared ($D_{u.b.}^2$)

RH class	0<R H ≤0.1	0.1< RH≤ 0.2	0.2< RH≤ 0.3	0.3< RH≤ 0.4	0.4< RH≤ 0.5	0.5< RH≤ 0.6	0.6< RH≤ 0.7	0.7< RH≤ 0.8	0.8< RH≤ 0.9	0.9< RH≤ 1	N lowes t RMS E
N of meas.	41	18	21	13	7	11	23	18	27	1	
Eq. 6 Demaerschalk (1972)	26.58 9	4.795	9.872	10.29 5	24.75 6	22.88 8	19.31 1	5.715	7.952	0.198	1
Eq. 7 Kozak (1995)	23.90 7	3.292	7.536	9.099	19.53 3	12.66 8	26.43 3	7.704	11.16 3	3.924	2
Eq. 8 Kozak (2002)	24.32 6	2.703	8.193	7.102	21.60 4	12.03 3	18.51 2	5.611	3.254	3.498	2
Eq. 10 Lee (2003)	24.58 6	2.502	7.738	10.32	12.73 7	12.98 0	21.53 2	4.899	3.447	4.210	2
Eq. 11 Max (1976)	26.00 5	3.138	13.69 8	7.489	7.649	11.23 2	25.17 2	5.287	4.669	3.308	1
Eq. 12 Muhairwe (1999)	25.83 0	3.400	7.872	7.697	21.92 6	10.10 1	16.84 1	5.027	3.560	4.367	2

3.2. Cross-validation for over-bark fixed effect models

The first comparison between a foreign and the current Greek (GR) calibration was conducted with a west-Polish model (PL) of Eq.7 (Bronisz and Zasada 2020). While the calibration of Eq.7 for the Greek sample yielded two non-significant coefficients β_6 and β_7 , the sample from Poland showed a different selection with β_3 , β_6 and β_7 being non-significant (Table 8).

Table 8 Coefficients for Eq. 7 calibrated by Bronisz et al. 2020 (fixed effects, over bark)

Coefficient	Estimate	Coefficient	Estimate
β_1	0.962	β_5	-7.643
β_2	0.983	β_6	n.s.
β_3	n.s.	β_7	n.s.
β_4	0.289	β_8	0.061

Secondly, Eq. 19 was calibrated in the North-Eastern United States (Westfall and Scott 2010). In their original study, FE coefficients for $D_{o.b.}^2$ were provided for a sample of “species group 18” trees (Table 9). No coefficient was reported as non-significant. However, in the present study, the Greek sample produced non-significant estimates for β_1 , β_2 and β_{10} using the o.b. dataset. Furthermore, the addition of both random effects φ_{1j} and φ_{2j} , as they are included in the equation of the original study, did not lead to a converging model. The Greek calibration is therefore an FE model rather than a mixed model.

Table 9 Coefficients for Eq. 19 calibrated by Westfall and Scott 2010 (fixed effects, over bark diameter squared)

Coefficient	Estimate	SE	Coefficient	Estimate	SE
β_1	1.298	0.06	β_6	0.456	0.03
β_2	0.768	0.05	β_7	9.051	1.10
β_3	0.541	0.02	β_8	0.024	0.00
β_4	4.182	0.77	β_9	1.668	0.20
β_5	0.068	0.01	β_{10}	0.177	0.01

Figure 4 (left) shows the comparison of actual D^2 with both locally calibrated coefficients (GR) and coefficients from the Polish model (PL). While a visual inspection only showed slight differences in deviation from the equality line for PL points, RMSE was about 16% higher compared to the GR calibration.

Observing the values predicted by the North-Eastern US calibration however, errors were much higher than for the Greek model (Figure 4 right). The increase in RMSE amounted to 77% over the Greek *nlsLM()* equivalent.

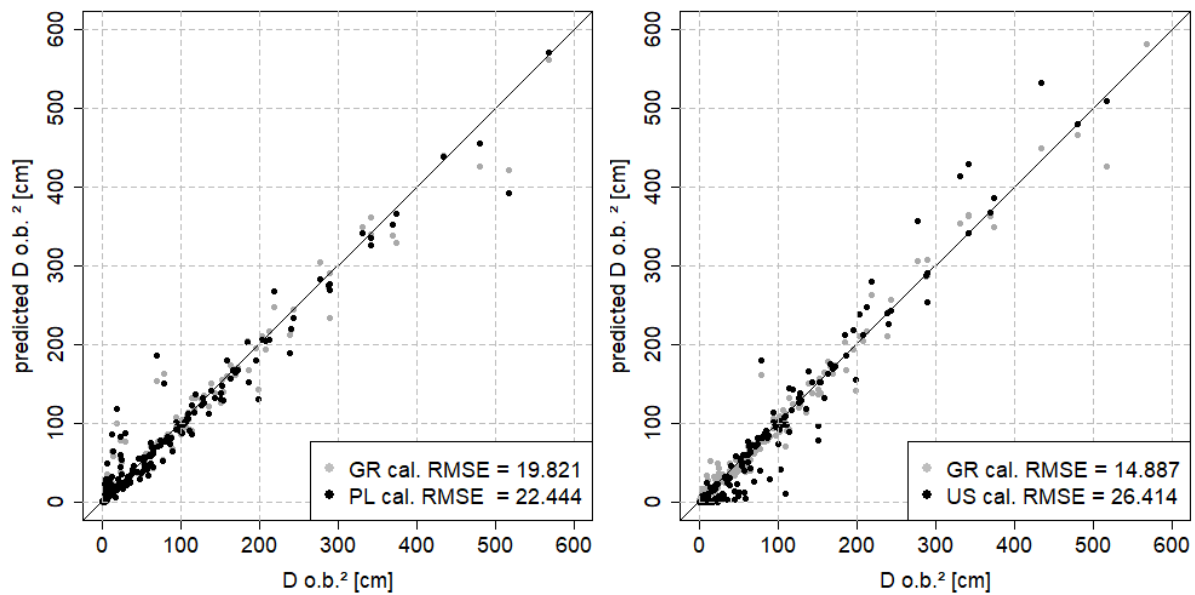


Figure 4 Actual section diameter squared ($D\ o.b.^2$) vs. GR and PL predictions of Eq. 7 (left) and vs. GR and US predictions of Eq. 19 (right)

3.3. Mixed-effect taper models

Kozak's Eq. 8 (2004) proved to be the best performing FE model for the o.b. dataset. In the subsequent grid search for the best allocation of 1, 2 or 3 random effects, the model assigned with random effects for parameters β_6 and β_8 reached the best goodness-of-fit out of 91 created models (Table 10). There was a substantial increase in model accuracy by all four means of error calculation, while AIC also decreased by 20.

Table 10 Goodness-of-fit comparison for the Eq. 8 fixed-effect (FE) model and best mixed-effect (ME) model; RMSE = Root Mean Square Error, MAE = Mean Absolute Error, MB = Mean Bias, MPB = Mean Percent Bias, AIC = Akaike's Information Criterion

over bark	RMSE	MAE	MB	MPB	AIC
FE	16.984	9.601	1.207	-0.080	1385
ME	11.021	6.410	0.075	-0.109	1359
under bark	RMSE	MAE	MB	MPB	AIC

FE	14.919	7.921	0.875	-0.134	1307
ME	8.518	5.154	0.081	0.001	1300

While the FE model featured the two non-significant coefficients β_8 and β_9 in both o.b. and u.b. calibrations, the o.b. ME model had no non-significant coefficients. The u.b. ME model showed a total of four non-significant coefficients (β_3 , β_7 , β_8 and β_9). The fixed coefficients of both ME models are displayed in Table 11.

Table 11 Calibrated coefficients for the best ME models

over bark		under bark	
β_1	0.914	β_1	0.812
β_2	0.973	β_2	0.983
β_3	0.060	β_3	0.056 n.s.
β_4	0.995	β_4	1.636
β_5	-0.980	β_5	-1.282
β_6	0.548	β_6	0.584
β_7	1.610	β_7	1.376 n.s.
β_8	0.025	β_8	-0.007 n.s.
β_9	-0.037	β_9	0.163 n.s.

Both random effects β_{6j} and β_{8j} showed a standard deviation of less than 0.2. Correlation between the two effects almost reached -1 (-0.97). The ANOVA test between the FE and ME models of Eq. 8 revealed a statistically significant difference for o.b. as well as for the u.b. calibrations (Table 12).

Table 12 Summary of random effects for the best ME model; ANOVA results for fixed vs. mixed models; SD = Standard Deviation, AIC = Akaike's Information Criterion

over bark	SD	Correlation	under bark	SD	Correlation
β_{6j}	0.175		β_{6j}	0.173	
β_{8j}	0.080	-0.97	β_{8j}	0.078	-1
	AIC	p-value		AIC	p-value
fixed effects	1385		fixed effects	1307	

mixed effects	1359	$2.91 * 10^{-7}$	mixed effects	1274	$1.47 * 10^{-8}$
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Residual plots for the FE and best ME model of Eq. 8 are displayed in Figure 5. The weighted ME model (crosses) provides the largest decrease in residual variance for both responses D^2 and RH over the original FE model (dots), whereas the weighted FE (circles) already decreased the residual spread. It is notable that additional variance modelling yielded a bigger gain in goodness-of-fit metrics (FE with weights: AIC = 1385) than random effects (ME without weights:

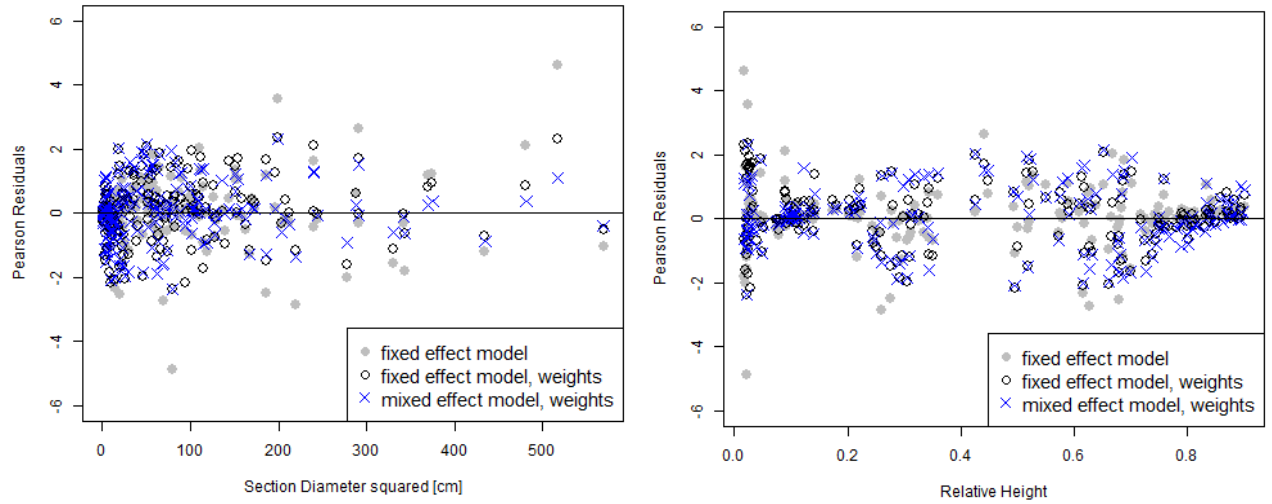


Figure 5 Residual plots for FE (without and with weights) and ME models (weights) for Eq. 8, Section Diameter squared (D^2) left, Relative Height (RH) right.

AIC = 1444) over the basic FE model.

3.4. Stem volume

All three volume equations showed a tighter volume error spread compared to the numerically integrated FE models in the o.b. category (Figure 6). In contrast, the taper models were less biased with medians closer to zero. Overall, stem volume errors ranged between -0.07 and 0.8m³. While Eq. 22 clearly had the tightest error spread for o.b. stem volume, the Eq. 8 ME model surpassed all other equations for u.b. Calculating o.b. volume using the PL calibration, a slightly wider spread could be observed compared to the respective Greek equivalent. For the US calibration, the errors were also higher compared to the Eq. 19 FE model. However, there were no coefficients available for a respective u.b. calibration

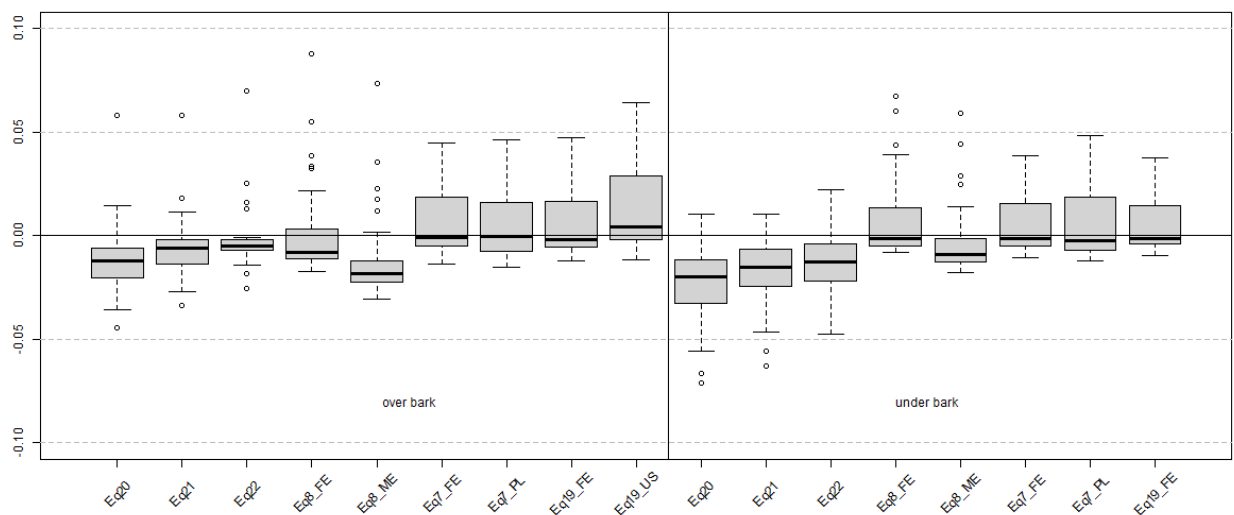


Figure 6 Stem volume error distribution [m³] for three volume models and integrated Eq. 7, Eq. 8 compared to reference volume; left: over bark– right: under bark.

of said equation.

The Kruskal-Wallis test indicated statistically significant differences in volume error depending on the equation used for prediction. A subsequent Dunn-test revealed further differences between the Eq. 8 ME model and almost all other equations in the selection in both the o.b. and u.b. categories. Aside from a few exceptions, the FE models and volume equations did not differ significantly among each other.

4. Discussion

Exotic species can be recommended for the rehabilitation of former open cast bare coal mine spoils due to their fast growth and establishment (Dutta and Agrawal 2003). Black locust is an appropriate tree species for the regeneration of post-mining sites. Black locust wood is very dense because it is among the most dimensionally stable species upon drying. Additionally, because it is attractive, black locust wood is suitable for almost any product made from wood (Hanover et al. 1991). However, the growth and taper of black locust on degraded sites are not well studied. Some studies have

focussed on black locust as a suitable tree species for agroforestry systems (Grünewald et al. 2007; Grünewald et al. 2009; Hanover et al. 1991; Huber et al. 2016; Küppers et al. 2018; Ntayombya and Gordon 1995). In short-rotation agroforestry systems, the harvested annual yield is between 8.1 and 9.7 t_{odt} ha⁻¹ year⁻¹ (Grünewald et al. 2009; Huber et al. 2016). In such systems, the aboveground biomass is mostly used to produce bioenergy.

To model both o.b. and u.b. taper of black locust, 18 different equations were analysed. The models were ranked using a relative ranking of five separate goodness-of-fit metrics: root mean square error (RMSE), mean absolute error (MAE), mean bias (MB), mean percentage bias (MPB) and Akaike's Information Criterion (AIC). The variable exponent equation Eq. 8 (Kozak 2004) ranked best for both o.b. and u.b. datasets. Kozak's 1995 variable exponent model Eq. 7, which had been identified as the best performing model for black locust in Bronisz and Zasada (2020), was found to be the fourth-best model in this study. In their own study, Kozak (2004) found Eq. 8 to be superior to Eq. 7 for 38 species groups in British Columbia, Canada. Rojo et al. 2005 found Eq. 8 to be the best equation among 31 taper functions applied to Maritime pine (*Pinus pinaster* Ait.). Poudel et al. 2018 also observed that Eq. 8 performed best for Douglas fir (*Pseudotsuga menziesii* Franco) compared to three variable-exponent equations.

Variable exponent equations of Eq. 12 (Muhairwe 1999) and Eq. 10 (Lee et al. 2003) were the second and third best models respectively, adding to the hypothesis that complex, i.e. non-parameter-parsimonious equations perform better than their less complex counterparts. This has been observed in multiple studies comparing several taper equations, including (de-Miguel et al. 2012; Bronisz and Zasada 2020). These equations aim to achieve good predictive ability for all parts of the stem, which was confirmed by measuring RMSE by 10 classes of relative height. Kozak's (2004) Eq. 8 scored best four times for o.b. and twice for u.b., followed by further variable-exponent models.

Recently published taper models for black locust from Poland (Bronisz and Zasada 2020) with Eq. 7, Kozak's (1995) variable exponent model, and Eq. 19, the Westfall and Scott (2010) model, achieved error values of 115–175% of the Greek calibration. Therefore, neither taper model calibrated for foreign datasets proved suitable for predicting stem diameters of the present sample. As these two studies are among, if not the only, applications of taper modelling for black locust, further research is needed to provide adequate predictions for stands within Europe and North America. In addition, the tapering properties of planted black locust in post-mining areas might differ from black locust growing in forest sites due to different growing conditions on disturbed soils. Research showed that even among and within black locust families there is a large amount of genetic variation for growth, form, thorn length and other important traits (Hanover et al. 1991).

A grid search for all possible combinations of random effects was performed on the best FE taper equation. Thus, the addition of two random effects to the generalized least-squares model of Eq. 8 provided a substantial decrease in errors. Secondly, non-significant equation parameters from the FE model were found to be significant in the best ME model. Variance modelling, i.e., applying weights to the FE and ME models on a single-tree basis depending on a power-type function of DBH, also decreased errors. The resulting effect was observed to be more influential in terms of error reduction than the addition of random effects per coefficient to the base FE model. Overall, the ME model with weights applied yielded the best performance in terms of goodness-of-fit metrics.

In the direct comparison between the three stem volume functions and numerically integrated taper equations, the ME model was able to surpass the other methods slightly. However, as all three volume equations presented a negative bias, predictions could be adjusted. That said, given the small sample size of 30 stems in this study, bias should be investigated on a larger sample that may also expand the diameter and height range of these relatively young trees. Without destructively sampled allometric data and a locally calibrated model, the three volume equations from previous studies (Lockow and Lockow 2015; Moshki and Lamersdorf 2011; Sopp and Kolosz 2000) serve as a rather precise means of estimating o.b. and u.b. stem volume for the Greek plantation black locust trees. Therefore, diameter at breast height and total tree height would be the only required measurements of the respective sample trees. Under-bark diameter would then need to be sampled via a bark gauge along the stem to verify an additional model for stem wood volume.

Valentine and Gregoire (2001) point out that the butt part of the stem is the most error-prone in taper modelling. In contrast, the number of measurements taken in this area is relatively low, with only stump height and breast height in most taper datasets. Westfall and Scott 2010 also indicate that using few measurements in the lowest part of the stem might result in an underestimation of errors. This issue is present with this study especially, as the small dataset of just 180 measurements may only serve as a minimum sample. In turn, the primarily desired area of application in the Western Macedonian Lignite Center covers about 2500 ha. However, Yang and Burkhart (2020) found that withholding certain classes of DBH for parametric fitting approaches, i.e. the smallest or largest diameter trees, did not effectively influence the predictive ability of taper functions Eq. 8 and Eq. 11 for the rest of their sample. Therefore, the present dataset of young trees used for calibration might be sufficient to predict larger tree diameters in the growing stands of the Western Macedonian Lignite Center. Suitable trees should be measured in 10 years to confirm the taper models applied for the 2020/2021 sample.

Nevertheless, with more sample trees from Greece and the broader Balkan region, a larger dataset could be obtained. With plans to phase out the use of fossil resources (especially lignite) for energy in Europe in line with international

agreements to limit the effects of human-induced climate change, most open-cast mines will be depleted or abandoned within coming decades. The cited research from several European countries, such as Germany, Greece and Ukraine, shows that black locust is indeed a suitable species for reforesting these disturbed sites. The production of woody biomass in unfavorable forest vegetation conditions of disturbed lands in combination with effective soil erosion protection is increasingly important to respond to the growing demand for bioenergy and conservation (Cierjacks et al. 2013; DeGomez and Wagner 2001; Liu et al. 2020; Mantovani et al. 2015; Vítková et al. 2017). Due to its environment-creating and productive functions, black locust is a very promising tree species in the fight against desertification and climate change as global challenges. However, as a non-native and invasive species, it should be used for land reclamation purposes in a clearly defined area of contaminated sites and for the production of durable and long-lived wood products if it is to be regarded as environmentally justified (Vítková et al. 2017; Vítková et al. 2020). A wider network of allometric datasets from reforestation areas, including taper and volume models, would be beneficial for more precise predictions of timber assortments, volume and carbon accounting for post-mining landscapes in the near future.

5. Conclusions

The following conclusions that can be drawn from the present study:

- From the eighteen different taper equations that were analysed, Kozak's (2004) model performed best for both the o.b. and u.b. data followed by the Muhairwe's (1999), Lee's et al. (2003), Kozak's (1995) and Sharma & Parton's (2009) equations.
- ME model regression substantially increased the taper model accuracy by all four means of error calculation, AIC also decreased by 20 units at the black locust restoration plantations of the Lignite Centre of Northwest Greece and presented the largest decrease in residual variance for both responses D^2 and RH over the original FE models.
- Validation for weighted fixed effects o.b. showed that Kozak's variable exponent model (1995) exhibited two non-significant coefficients in contrast to three other non-significant coefficients in Bronisz and Zasada's (2020) Polish dataset.
- Stem volume equations proved to be performing well and close to the numerically integrated taper equations.

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