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A generalized nonlinear mixed-effects height–diameter model for *Eucalyptus globulus* L. in northwestern Spain

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ABSTRACT

A generalized height–diameter model was developed for *Eucalyptus globulus* Labill. stands in Galicia (northwestern Spain). The study involved a variety of pure stands ranging from even-aged to uneven-aged. Data were obtained from permanent circular sample plots in which trees were sampled within different radii according to their diameter at breast height. A combination of weighted regression, to take into account the unequal selection probabilities of such an inventory design, and mixed model techniques, to accommodate local random fluctuations in the height–diameter relationship, were applied to estimate fixed and random parameters for several models reported in the relevant literature. The models that provided the best results included dominant height and dominant diameter as fixed effects. These models explained more than 83% of the observed variability, with mean errors of less than 2.5 m. Random parameters for particular plots were estimated with different tree selection options. Height–diameter relationships tailored to individual plots can be obtained by calibration of the height measurements of the three smallest trees in a plot. An independent dataset was used to test the performance of the model with data not used in the fitting process, and to demonstrate the advantages of calibrating the mixed-effects model.

1. Introduction

Tasmanian blue gum (*Eucalyptus globulus* Labill.) is one of the most important tree species in Galicia (northwestern Spain). More than 3.5 million cubic meters of this eucalypt were harvested in the region in 2008 (FEARMAGA, 2009), making it the major species in terms of volume harvested. However, stands of Tasmanian blue gum lack proper management, mainly due to the lack of management tools for the species.

Measuring total height (h) is not as easy as measuring diameter at breast height (d). Total height is usually measured indirectly with height measuring instruments based on angle and distance measures. As a result of the difficulty in measuring tree height and the cost associated with field inventories, and as h and d are correlated, it is common practice to fit height–diameter (h–d) models to predict h from measured d. Such models are thus essential for estimating individual tree volume and sometimes site index, and for describing stand growth dynamics and succession over time (Curtis, 1967) when height is not measured. Parresol (1992) described h–d models as important components in yield estimation, stand description and damage appraisal. Moreover, they are also important in characterizing canopy height diversity and wildlife habitat relationships (Spies and Cohen, 1992; Morrison et al., 1992). Dominant height, competition indices and height/diameter ratios can also be easily calculated by use of this relation, without investing large amounts of money in height measurement (Calama and Montero, 2004), at least if these variables are not included in the model formulation. Finally, Newton and Amponsah (2007) described these models as important in product recovery, value estimation, stand structural analyses, growth and yield projection systems, and carbon budgeting models.

The h–d relationship varies from stand to stand, and even within the same stand the relationship is not constant over time (Curtis, 1967). Therefore a single curve cannot be used to estimate all the possible h–d relationships that can be found within a forest (Castedo Dorado et al., 2006). The most widely used method, which minimises this level of variance, is to estimate h–d regressions for each plot and measurement occasion. If sufficient data are not available for these regressions, an h–d model that includes stand variables that account for the special characteristics of each stand is often used (Curtis, 1967; Larsen and Hann, 1987; Temesgen and Gadow, 2004).

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It is frequently argued that the scatter plot of h against d reveals a sigmoid curve over the full range of diameters. In accordance with this, Niklas (1995) generalized (from his study on *Robinia pseudoacacia*) that growth in tree height is asymptotic and essentially definite. Researchers have since tested numerous nonlinear functions to model the h–d relationship on the basis of this biological phenomenon. Fang and Bailey (1998) investigated the performance of 33 functions to develop h–d models for diverse tree species of tropical forest on Hainan Island and selected a modified form of the exponential model (Meyer, 1940). In a cross-validation study of six nonlinear growth functions for modelling h–d relationship for ten conifer tree species, Zhang (1997) concluded that Bertalanffy–Richards (Bertalanffy, 1949, 1957; Richards, 1959), Weibull-type (Yang et al., 1978), and Schnute (Schnute, 1981) functions provided more accurate results than other models. Peng (1999) also fitted 25 nonlinear h–d model forms for nine tree species and reached a similar conclusion to Zhang (1997). Huang et al. (2000) evaluated 27 functions for modelling the h–d relationship of white spruce grown in Alberta's boreal forests and concluded that the logistic-type function produced the most satisfactory fit. According to Yuancai and Parresol (2001), the Schnute function and the Bertalanffy–Richards function are probably the most flexible and versatile functions available for modelling h–d relationships. Peng et al. (2001) also found the Bertalanffy–Richards, Weibull and Schnute functions to be superior to other models as regards prediction performance.

The hierarchical structure in the h–d data (i.e., trees within plots within stands), usually results in a lack of independence among measurements, since observations from the same sampling unit may be highly correlated (West et al., 1984; Gregoire, 1987). Mixed model techniques have been used successfully (e.g., Lappi, 1997; Calama and Montero, 2004; Castedo Dorado et al., 2006) to deal with this problem. These models estimate both fixed and random parameters simultaneously for the same model, and allow the variability detected for given phenomena among different locations to be modelled after defining a common fixed functional structure (Lindstrom and Bates, 1990). This characteristic makes mixed-effects models more efficient when a prediction for a new individual is required and prior information is available (Trincado et al., 2007).

The main objective of the present study was to develop a model relating diameter at breast height and total height for Tasmanian blue gum growing in Galicia, on the basis of data from the Spanish National Forest Inventory. The particular nature of the circular plots used in this inventory, in which trees were sampled within different radii according to their diameter at breast height, obliged us to use a special technique to account for the unequal selection probability of each tree. Use of an h–d relationship, a disaggregation system and a taper function enabled volume classification by merchantable sizes, and this will become important tools for the sustainable management of the species in the study area.

Table 1
Characteristics of the Spanish National Forest Inventory (SNFI) plots.

Plot radius (m)	Minimum d threshold (cm)	p_{ij}	$1/p_{ij}$	$Fexp_{ij}$	$RFexp_{ij}$
5	7.5	0.04	25	127.3	3.092
10	12.5	0.16	6.25	31.83	0.7731
15	22.5	0.36	2.778	14.15	0.3436
25	42.5	1	1	5.093	0.1237

p_{ij}: selection probability of the ith tree in the jth plot, depending on its diameter, relative to that of the largest radius plot; $Fexp_{ij}$: hectare expansion factor (inverse of the selection probability on a per hectare basis); and $RFexp_{ij}$: rescaled expansion factor.

2. Methodology

2.1. Data

Data from the Second (ICONA, 1993) and Third (DGCONA, 2001, 2002a, 2002b) Spanish National Forest Inventory (SNFI) in Galicia (northwest Spain) were used to develop the h–d model (Table 1). The SNFI is a systematic sample of circular combined sample plots (Loetsch et al., 1973), distributed on a square grid of 1 km, with a remeasurement interval of 10 years. In each plot and for each measurement occasion, species, d and h are recorded for each sample tree over 7.5 cm, along with tree quality and shape, and other variables. All plots with more than 90% Tasmanian blue gum stems were selected for the present study (1518 plots). The number of stems per hectare (N_j) and stand basal area (G_j) were calculated with all trees in the jth plot. However, the mean height ($\bar{h}_j$) was only calculated for Tasmanian blue gum trees, and dominant diameter ($ddom_j$) and dominant height ($hdom_j$) were calculated with the proportion of the 100 thickest healthy Tasmanian blue gum trees (unforked and with no apparent damage) per hectare. Some outliers were observed in the dataset, but as they represented only a minor percentage (less than 0.2%), they were omitted from the analysis. Some plots (15) showed an illogical h–d tendency (larger h for smaller d), and so were not used. Excessively open plots were not used in this study either. The Hart index (i.e., $100/(hdom_j N_j^{1/2})$) was used as a criterion for distinguishing the competition level within each plot. A Hart index value of 50 was subjectively selected as the limit for considering that trees start to grow in competition-free conditions. This resulted in the elimination of 278 plots and 656 trees. It should be mentioned that the SNFI is a systematic sample, in which open plots, or plots with outliers, usually correspond to trees planted in lines at the edge of agricultural land. Despite the reduction in data, some quite open stands were still included (Table 2), so that the developed model would be useful for a wide variety of stand conditions. A total of 26117 pairs of h–d measurements, taken from 417 plots from the second SNFI and from 808 plots from the third SNFI were finally used to fit the models. Summary statistics of the

Table 2
Summary statistics of the fitting and the validation datasets.

	Fitting dataset (26117 trees in 1225 plots)				Validation dataset (475 trees in 88 plots)			
Variable	Mean	Min.	Max.	Std. dev.	Mean	Min.	Max.	Std. dev.
d_{ij} (cm)	14.4	7.5	85.9	6.8	19.6	5.0	80.5	12.4
h_{ij} (m)	16.7	3.0	51.0	5.9	19.8	5.0	46.6	8.3
N_j (stems ha^{-1})	895	41	2744	504				
G_j (m^2 ha^{-1})	17.8	1.8	85.7	11.5				
dg_j (cm)	16.5	8.3	51.6	5.6				
$ddom_j$ (cm)	24.6	8.7	58.3	8.5	24.8	6.6	62.6	9.9
$\bar{h}_j$ (m)	17.0	5.9	43.2	4.6				
$hdom_j$ (m)	21.9	8.0	43.2	6.8	22.4	6.4	38.8	8.0

d_{ij}: diameter at breast height (1.3 m above ground level); h_{ij}: total tree height; N_j: number of trees per hectare; G_j: stand basal area; dg_j: quadratic mean diameter; $ddom_j$: dominant diameter; $\bar{h}_j$: mean height; and $hdom_j$: dominant height.