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Tree height prediction approaches for uneven-aged beech forests in northwestern Spain

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ABSTRACT

Artificial neural network methods appear to be a reliable alternative to traditional methods of tree height prediction in even-aged stands. However, this has not been demonstrated for uneven-aged forests. Two back-propagation artificial neural networks were constructed, and their performance in estimating the height of pure uneven-aged stands of common beech (*Fagus sylvatica* L.) in northwestern Spain was compared with that of the models most commonly used to estimate tree height (nonlinear calibrated local and generalized mixed-effects models and generalized fixed-effects models). All approaches produced accurate results, reducing the root mean squared error by more than 22% relative to basic nonlinear regression. Nonetheless, considering practical use of the models, the traditional approaches require measurement of several trees for calculation of stand-specific variables (generalized models) and for model calibration (mixed-effects models). Back-propagation artificial neural networks require less sampling effort because no height measurements are required for their implementation. However, this technique was not the best height predictor, because of the high degree of variability in site quality between stands. In this case, the local mixed-effects models yielded the best results and provided the best balance between the accuracy of the model and sampling effort.

1. Introduction

Individual tree height (*h*) and diameter at breast height outside bark (*dbh*, measured 1.30 m above ground level) are essential tree attributes in forest inventories. However, although diameter can be measured quickly, easily and accurately at little cost, height is considerably more difficult and costly to measure for several reasons (Colbert et al., 2002): the time required, possible observational error, and visual obstructions. While the first two reasons may be considered insignificant because of the availability of devices based on ultrasound or laser pulses, which have reduced the time needed to measure tree heights and the measurement errors, heights cannot be measured without examining the whole stem. This is particularly difficult in beech stands because of visual obstructions. The leaf area index is particularly high in beech forests (Bequet et al., 2012), and the position of the leaves and the existence of various canopy layers (Teissier du Cros, 1981) also contribute to measurement errors. Therefore, models that relate tree height and diameter at breast height in beech forests are very important tools for forest inventory and management purposes.

Height–diameter (*h–d*) models are very useful in forest management, and they have many applications: in timber volume, stand biomass and carbon budget estimation (e.g. Curtis, 1967; Huang et al., 1992; Newton and Amponsah, 2007); stand structure analysis over time (Clutter et al., 1983; Curtis, 1967); development of stand density management diagrams and growth and yield models (Sharma and Zhang, 2004); and for determining dominant height and site index (Peng, 2001). Moreover, these models are also important for characterizing canopy height diversity and wildlife habitat relationships (Morrison et al., 1992; Spies and Cohen, 1992) and for estimating losses in damage appraisals (Parresol, 1992).

Conventionally, height–diameter equations have been applied to pure even-aged stands or plantations by using only the diameter at breast height as a predictor variable (Huang et al., 1992). Several height–diameter equations have been developed in this way (e.g. Curtis, 1967; Fang and Bailey, 1998). However, the resultant *h–d*

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models do not adapt well to all possible situations that are found within and between stands. In fact, the relation between the diameter of a tree and its height varies between stands because of differences in e.g. site quality (Bailey and Brooks, 1994; Sharma and Zhang, 2004), stand density (Zeide and VanderSchaaf, 2002), and relative position of trees within a stand (e.g. Temesgen et al., 2007), and the relationship changes over time – even within the same stand (Curtis, 1967). This situation is particularly evident in mixed and uneven-aged stands, in which different species, ages, sizes, crown types and levels of tolerance coexist. The method most widely used to minimize this level of variance is to fit a local *h*–*d* equation for each set of measurements. However, this approach requires a large sampling effort.

An alternative approach that reduces this effort is to develop a generalized height–diameter equation that includes the dynamics of each stand and that estimates *h* from *dbh* and stand-specific variables such as stand age, basal area, dominant height and stand density. Several generalized and region-wide equations have been developed for many tree species around the world (e.g. Curtis, 1967; Sharma and Zhang, 2004; Soares and Tomé, 2002; Temesgen et al., 2008; amongst many others). Such models have been shown to be applicable to both even-aged (e.g. Castedo-Dorado et al., 2006; Soares and Tomé, 2002) and uneven-aged stands (e.g. Sharma and Zhang, 2004) and even to a mixture of both types of stand (e.g. Crecente-Campo et al., 2010).

However, the hierarchical structure of the datasets used in the previous *h*–*d* models (i.e. trees within plots and plots within stands) usually leads to a lack of independence among measurements, because observations from the same sampling unit are highly correlated (West et al., 1984). Trees from the same plot tend to be more similar to each other than to trees from different plots, and the classical regression assumption that observations are independent does not hold (Neter et al., 1990). Mixed model techniques have been used successfully to deal with this problem (Hall and Bailey, 2001), providing a statistical method capable of explicitly modelling this nested stochastic structure.

Mixed-effect models allow for both *population-averaged* and *subject-specific* responses. The first considers only fixed parameters, common to the population, while the second considers both fixed and random parameters, common to each subject. The inclusion of random parameters enables the variability of a given phenomena among different locations and time to be modeled (Lappi and Bailey, 1988) once a common fixed functional structure has been defined (Lindstrom and Bates, 1990). This characteristic makes these models more efficient when a prediction for a new individual is required and additional information is already available (e.g. some trees measured for tree height). This methodology was first introduced to forest biometry by Lappi (1986, 1991), and it has been widely applied ever since (e.g. Calama and Montero, 2004; Castedo-Dorado et al., 2006; Trincado et al., 2007, amongst others). From a practical perspective, linear and nonlinear mixed-effects models have been reported to allow a more accurate and precise estimation of the height–diameter relationship than conventional linear and nonlinear regression models (Temesgen et al., 2008; Trincado et al., 2007), providing realistic variance estimates for modelling natural variability (Lappi, 1991).

In the last few decades, artificial neural network (ANN) modelling has been successfully used in the field of forest modelling, for effective management of complex, nonlinear systems when an appropriate nonlinear equation is not available. Although regression analyses are based on rules or equations, many systems exist for which the rules are either not known or are difficult to discover and it is these systems to which neural computing techniques can be applied (Fausett, 1994; Swingler, 2001). ANNs can identify relationships in data without any assumptions about the form of a fitting function, and they are capable, through a small-learned example, of generalizing the knowledge assimilated and applying it to a set of unknown data (Hagan et al., 1996), i.e. the network is trained to find the relationship between input and output. ANNs are generally defined as mathematical-computational systems inspired by the functioning of the human brain (Fausett, 1994). Specifically, ANNs are used in forest science in many applications, for predicting/estimating the following: types of forest cover (e.g. Moisen and Frescino, 2002); diameter (Leduc et al., 2001) and species distribution (Corne et al., 2004); bark (Diamantopoulou, 2005) and wood volume of standing trees (Diamantopoulou and Milios, 2010; Özçelik et al., 2010); site index in homogeneous stands (Aertsen et al., 2010); inside-bark diameter and heartwood diameter (García-Leite et al., 2011); and even to predict tree survival (Guan and Gertner, 1991) and identify forests that are susceptible to wind damage (e.g. Hanewinkel et al., 2004). However, to our knowledge, only two studies have applied this methodology to *h*–*d* relationships (Diamantopoulou and Özçelik, 2012; Özçelik et al., 2013), specifically in even-aged stands of Brutian pine, Cedar of Lebanon, Cilica fir and Crimean juniper in Turkey.

Most of the above-mentioned studies have demonstrated the superiority of ANNs over regression models for even-aged coniferous forests (Diamantopoulou, 2005; Diamantopoulou and Milios, 2010; Diamantopoulou and Özçelik, 2012; García-Leite et al., 2011; Leduc et al., 2001; Özçelik et al., 2010, 2013), which constitute a restricted field in forest modelling. Several studies have shown that methodological results obtained for even-aged forests cannot always be extrapolated to uneven-aged forests (e.g. Peng, 2000). However, we hypothesize that neural networks will also provide the best results for tree height estimation in uneven-aged stands because the individual dimensional variability present in these forests should not affect the capacity of ANNs to identify relationships between variables.

The common beech (*Fagus sylvatica* L.) is the most abundant broad-leaved forest tree in Europe (Teissier du Cross, 1981). However, populations of the species in the southernmost part of its distribution range (e.g. northern Spain) are restricted to mountain slopes higher than 600 m above sea level (Gandullo et al., 2004). In the Cantabrian Range (NW Spain) – considered as the boundary between the Euro-Siberian and Mediterranean regions – the beech is a climax species, which usually forms uneven-aged forests characterized by natural forest regeneration and fast growing stocks (Ruiz de la Torre, 2006). These forests form part of habitats of endangered and emblematic species, such as the Cantabrian capercaillie (*Tetrao urogallus* sbsp. *cantabricus*) (Storch et al., 2006) and brown bear (*Ursus arctos*) (Wiegand et al., 2008), which has led to their inclusion in protected areas that are relatively unaffected by human influence. However, there is a lack of inventory and management tools for the species.

As far as we know, there are no reports of any comparative studies of the most commonly used tree height estimation methods and the backpropagation ANN modelling technique in total tree height estimation in broad-leaved uneven-aged forests. The aim of this study was to compare and evaluate the performance of a machine learning technique (ANNs) with that of nonlinear local and generalized growth functions fitted by ordinary nonlinear least squares and by nonlinear mixed-effects model techniques for modelling the *h*–*d* relationships in natural, uneven-aged beech forests in northwestern Spain.

2. Materials and methods

2.1. Data

Data for this study were obtained from two independent sources. One source comprised 112 sample plots installed in uneven-aged, natural, beech-dominated stands (90% or more of the