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A comparison of fixed- and mixed-effects modeling in tree growth and yield prediction of an indigenous neotropical species (*Centrolobium tomentosum*) in a plantation system

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ABSTRACT

Centrolobium tomentosum is a multipurpose pioneer tree species, indigenous in tropical South America and suitable for forest restoration, agroforestry and plantation systems. Despite its economic and ecological interest, no growth and yield models have been developed for this species so far. Fixed- and mixed-effects modeling can be used in model fitting, each technique having its pros and cons. Marginal predictions can be computed from fixed-effects models or randomized mixed-effects models. In forestry practice, models are seldom calibrated and mixed-effects models are mostly used to provide conditional predictions using only the fixed parameters, assuming that the random effects are zero. This study developed the first set of individual-tree growth and yield models for *C. tomentosum* and, by using the models, assessed the performance of three prediction approaches: fixed-effects models, conditional predictions of mixed-effects-models and marginal predictions of mixed-effects models. The fitted models predict maximum mean annual bole volume increments of 5.6–16.6 m^3/ha and optimal rotation lengths ranging from 11 to 21 years, depending on site quality. Fixed-effects modeling was the best approach in growth and yield prediction, followed by conditional predictions of mixed-effects models, whereas marginal predictions based on mixed-effects models were in general the least accurate. Fixed-effects models should therefore be preferred in the absence of calibration data. However, since calibration is sometimes a feasible option, research articles should report both fixed- and mixed-effects models in order to enable the computation of the best predictions with and without the possibility of model calibration.

1. Introduction

Most datasets used for growth and yield modeling of forest trees and stands have hierarchical structures containing several sample plots from the same site, many trees from the same plot and several measurements from the same tree. To account for the correlation among observations at the same hierarchical level, mixed models with site-, plot- and tree-specific random parameters have been proposed in the literature (Biging, 1985; Gregoire, 1987; Lappi, 1986). When fixed-effects models are fitted to these kinds of datasets, estimates of the statistical significance of the parameters are biased (McCulloch and Searle, 2001). Fixed-effects models are also inferior to mixed-effect models when the aim is to make inferences about the population. Moreover, mixed-effects models allow the user to calibrate the model for a particular site, stand or tree. Because of this, it is often proposed that mixed-effects models should be used as the primary model type in growth and yield modeling.

On the other hand, fixed-effects models fitted for instance by ordinary least squares, nonlinear least squares or generalized least squares, minimize the sum of squared differences between observed and predicted values in the modeling data. The sum of squared errors is smaller than for mixed-effects models when the random parameters are not used in prediction. Fixed-effects models result in more accurate predictions when the random parameters of mixed-effects models are assumed to be zero and there are no data to calibrate the model (Garber et al., 2009; Groom et al., 2012; Guzmán et al., 2012a, 2012b; Heiðarsson and Pukkala, 2012; Pukkala et al., 2009; Shater et al., 2011; Temesgen et al., 2008). Therefore, fixed-effects models should be preferred in the absence of calibration data if the purpose of the model is prediction and no empirical models (Trasobares et al., 2004) are available for predicting the random parameters. This is the situation in the

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practical application of most growth and yield models. However, it cannot be straightforwardly concluded that fixed-effects models are better prediction tools for forestry practice since the accuracy and precision of the models may be different in independent datasets (e.g., Robinson and Wykoff, 2004). Moreover, individual-tree mixed-effects models may be randomized to derive marginal predictions as the mean of a large number of stochastic predictors (e.g., de-Miguel et al., 2012; Fortin and Langevin, 2012). These predictions may be competitive with the predictions of a fixed-effects model, especially outside the modeling data.

This study analyzed the suitability of fixed- and mixed-effects models for tree growth simulation using a tropical tree species (*Centrolobium tomentosum*) growing in Bolivian lowlands, as an example. The territory of Bolivia consists of highland and lowland regions. The lowlands belong to the Amazonian basin and are often characterized by hot and moist climate. Not too many tree species have been used so far in plantation forestry in the Amazonian basin and exotics have been utilized most. However, indigenous species, when available, should be preferred for ecological reasons as they belong to the natural flora. The use of indigenous species would increase the diversity of plantation species and products, decreasing both biological and economic risks (Keenan et al., 1999). Plantation species are mostly fast growing pioneers, adapted to survive and grow without the protective canopy of large trees. Climax native species have been found problematic as plantation species and they are seldom economically profitable in plantations, due to their slow initial grow and high mortality (Sands, 2005). However, they may appear naturally under a canopy of planted pioneer species, which would allow a similar species succession in plantations as would happen in natural forest after a major disturbance (Parrotta et al., 1997).

A few promising pioneer species that can be successfully planted have been tested in Bolivia. The most important of these are *Ochroma pyramidale*, *Schizolobium parahyba* and *C. tomentosum*. The latter species is known as "tejeyeque" in Bolivia and as "araruva" or "araribá" in Brazil. *C. tomentosum* is a broadleaved tree whose wood can be utilized for construction, carpentry, flooring and furniture, among many other uses. It also provides good quality firewood and charcoal and it is recommended for barrel construction due to its high content in tannins. Its leaves are used in folk medicine as a poultice for wounds and bruises, its seeds are appreciated as food by rural communities, and its bark can be used in dyes. It is also of great interest for forest ecosystem restoration purposes. It is used as a shade tree for coffee and fruit trees in agroforestry systems, and it can be used also in silvopastoral systems (Carvalho, 2005). As a leguminous tree able to fix nitrogen, tejeyeque has been suggested as a potential species to restore and maintain soil fertility in nutrient deficient tropical soils (Marques et al., 2001). As a promising indigenous multipurpose tree, its stand dynamics and yield deserve to be studied intensively. Growth and yield models for *C. tomentosum* would enable sound evaluations of the yield and economic profitability of tejeyeque plantations and help to optimize their management. So far, no growth and yield models have been reported for this species.

The objective of this research was to compare the suitability of fixed- and mixed-effects models in practical growth and yield prediction in situations where no calibration data are available. A complete set of models for the prediction of growth and yield of *C. tomentosum* on different growing sites was developed, using both fixed- and mixed-effects modeling approaches. The set of models consists of a dominant height model, and individual-tree models for diameter increment, height–diameter relationship, survival, bole length and stem taper. Predictions of both versions (fixed- and mixed-effects) of all models were compared with the observed values, in both modeling data and independent validation data.

2. Materials and methods

2.1. Materials

All the materials were collected from 46 permanent sample plots established in privately owned plantations in Chapare province, located in the Bolivian part of the Amazonian basin. The plot size ranged from 340 to 1780 m^2. Most of the woodlots were planted in 2003 and 2004 except one which was planted in 1999. The first measurement took place in 2008 and the subsequent measurements in 2009, 2010 and 2012. All plots were not measured in every year; the number of repeated measurements varied from 2 to 4, which means that the number of 1-year growth intervals available for modeling was 1–3. The stand age at the last measurement ranged from 6.6 to 12.7 years. The average number of trees per plot considering all measurement occasions was 47.5 and the standard deviation was 6.5, ranging from a minimum of 28 to a maximum of 57 trees per plot.

Diameter at breast height (dbh), total tree height, height to crown base and survival were recorded from each tree in every measurement except the last, in which the total tree height and height to crown base were measured only for about 10 sample trees per plot. The measurements resulted in 6085 observations for tree height modeling, 5885 observations for tree survival modeling, 5802 observations for diameter increment modeling, 6013 observations for modeling the bole ratio (height to crown base divided by total tree height), and 128 pairs of stand age and dominant height for modeling dominant height development (Table 1). However, analysis of the data showed that there had been exceptionally high mortality in four plots during one measurement interval with around 50% of trees died. The probable reason for these hazards is fire, which the landowners use to boost grass growth; most probably the fire had spread from grazing areas to the woodlot and killed many trees. Since the purpose of mortality modeling was to describe the "regular" competition-induced mortality, the hazardous interval was removed from the diameter increment and survival modeling data of four plots.

Ten trees from every plot were measured for stem taper in 2011. The stem diameters of these trees were measured at 0.3 m and 2 m heights and thereafter at 2-m intervals until crown base. The number of measurements per tree varied from three to eight. Diameters at different heights were measured from standing trees using an angle gauge. These measurements resulted in 1323 observations for taper modeling.

2.2. Methods

As the first step of data preparation, dominant diameter (*Ddom*) and dominant height (*Hdom*) were calculated for each plot and measurement as the mean of 100 thickest trees (in dbh) per hectare. For the last measurement, in which height was not measured for all trees, a diameter–height model was fitted for every plot and used to predict the missing heights. The model proposed by

Table 1
Summary of the data used in growth modeling.

Variable	Minimum	Mean	Maximum
Number of trees per hectare	264.1	878.0	1342.3
Dominant height, m	5.9	14.8	23.5
Stand age, years	3.9	6.8	12.7
Dominant diameter, cm	7.4	17.7	27.3
Site index, m	12.2	19.0	23.7
Tree height, m	1.4	12.3	25.8
Diameter at breast height, cm	0.3	12.4	31.3
Stand basal area, m^2/ha	2.2	11.1	20.7
Diameter increment, cm/yr	0.0	1.1	6.5