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A growth and yield projection system for a tropical rainforest in the Central Amazon, Brazil

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ABSTRACT

The aim of this study was to develop and apply an implicit yield model based on the Weibull probability density function for the predictions of yield by diameter class for a logged tropical rainforest located in the center of Amazon. The study area is located in the Tropical Forest Experimental Station, 90 km from the urban center of Manaus, AM, Brazil. The data came from 12 permanent 1 ha plots, logged at three levels of basal area removal intensities. In each plot all individuals with DBH $\geqslant$ 10 cm between 1990 and 2009 were measured annually. Functions were used to describe the dynamics of tree abundance (recruitment and mortality), basal area, summed diameters per hectare, and a new statistic for classification of forest yield, in order to estimate the sample moments of minimum, average and quadratic mean diameter in 2009. The Weibull diameter distribution was fitted using the method of moments and validated by data collected in 2009. The inclusion of variables that reflect the productive potential in the proposed model facilitates the evaluation of forests that have undergone changes in its structural characteristics in the different sites. The use of an alternative technique for classification led to a better understanding of the management regimes applied to the forests under analysis. The proposed model proved efficient by the Kolmogorov–Smirnov test, and thus may be used in updating inventory statistics, calculations of annual cut and in planning forest by companies that work in uneven aged and mixed forests in different sites of the Amazon.

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1. Introduction

The use of tropical forest for benefit of society requires sound decisions regarding the level of imputes to be used in forest exploitation. Optimal decisions require accurate growth and yield predictions under different production scenarios that in turn require flexible models able to provide several possibilities for logging. The lack of easily interpretable analytical models determine the optimal logging levels is one of the factors that sustainable use of uneven aged and heterogeneous forests in tropical regions.

Prominent among forest growth and yield modeling techniques are diameter distribution projection models, known as implicit growth and yield models (Vanclay, 1994; Scolforo, 2006). This technique was first employed by Clutter and Bennett (1965) and is based on the recovery of the coefficients of the Beta probability function in order to forecast yield. Hyink and Moser (1979) were the first researchers to apply the technique to model yield in uneven-aged forests.

Since 1965 the technique became widely used in predicting plantation and natural forest yield. This technique and in particular the Weibull probability density function (pdf) was demonstrated successfully to model such a forest type in 1973, when it was introduced in forestry science by Bailey and Dell (1973). Since then it has been the most widely used probabilistic function in describing the diameter distribution in forest plantations in all-aged and heterogeneous forests (Barros et al., 1979; Little, 1983; Clutter et al., 1983; Umanã and Alencar, 1998).

The efficiency of the Weibull pdf in modeling tropical or subtropical forests is evidenced in several papers worldwide (Burk and Burkhart, 1984; Atta-Boateng and Moser, 2000; Abreu et al., 2002; Arce, 2004; Machado et al., 2010; Koehler et al., 2010; Nascimento et al., 2012), since their coefficients are highly correlated with forest population attributes, they can be estimated with models that describe the dynamics of these population estimators.

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For these reasons and in order to fulfill certain technical needs of managers in the Amazon rainforest, the aim of this work is to develop and apply an implicit model of yield based on the Weibull pdf to predict yield in terms of numbers of trees, volume, biomass and carbon per hectare for both pioneer species and for all species present in a given area of rainforest located in the Central Amazon.

2. Materials and methods

2.1. Study area and data used

The study area is located within the Tropical Forestry Experimental Station (EEST) in the Suframa Agricultural District of the Tropical Forestry Research Committee of the National Institute for Amazonian Research (EEST/CPST/INPA).

Data came from 12 one hectare permanent plots, annually measured from 1990 to 2009. The plots were divided into four treatments with three replicates of each. Each treatment was subjected to logging of varying intensities in 1987/88. All trees with DBH > 10 cm were measured, tagged and identified by common and scientific name, ecological group and located geographically within the permanent plots of the experiment.

The experiment was composed of the following 4 treatments with replicates in each.

- T0 = Control (unlogged plot), in which with DBH $\geqslant$ 10 cm were measured from 1990 to 2009.
- T1 = Low intensity logging treatment with removal of 25% of basal area of commercial listed species (LE) and cutting and skidding of all LE species with DBH $\geqslant$ 55 cm. Average DBH of logged individuals was 62 cm and average commercial volume was 34 $m^3\ ha^{-1}$ with a total volume extracted of 65 $m^3\ ha^{-1}$± 12%. This treatment was carried out between August and September, 1987.
- T2 = intermediate intensity logging treatment with removal of 50% of the basal area of commercial listed species (LE) and cutting and skidding of all LE species with DBH $\geqslant$ 57 cm. Average DBH of logged individuals was 70 cm and the commercial average volume was 49 $m^3\ ha^{-1}$ with a total volume of 73 $m^3\ ha^{-1}$±17%. The treatment was carried out between October and November 1987.
- T3 = heavy intensity logging treatment with removal of 75% of the basal area of commercial listed species and cutting and skidding of all EL species with DBH $\geqslant$ 40 cm, average logged DBH of 56 cm; average commercial volume of 67 $m^3\ ha^{-1}$, and total extracted volume of 71 $m^3\ ha^{-1}$±26%. The treatment was carried out between September and November 1988.

In each treatment all species were classified into two ecological groups: pioneer and non-pioneer, as proposed by Swaine and Whitmore (1988). This classification was performed to determine the Diameter Variation Index of Pioneers Species ($VI_{\%}$) (Nascimento, 2012), a variable that modifies the models proposed for modeling survival, basal area and the summed diameters per unit area, both for the pioneer species group and for the total population.

The control treatment was used only as a referential of primary forest; other treatments and their replicates were used for adjusting the system of the models proposed. The results were presented for the average of treatments, showing their different experimental features.

Eighteen years of measurements were used, and the year 2009 was not incorporated into the mathematical model, but served as the base year for projections and verification of the growth and projection model of proposed yield. Detailed information about the study area, data used, classification of species in ecological groups of the experiment and the use of $VI_{\%}$ are given by Nascimento (2012).

2.2. Diameter variation index of pioneers species

The structural variability of a logged forest reflects the logging intensity and site characteristics (Joviste, 1998). The amplitude of this structural variability can be measured by statistical dispersion, and their degree of homogeneity is inversely related to total production capacity of biomass of the site (Nascimento, 2012).

When considering the diameter variability of pioneer species, especially in secondary forests, it is possible to identify the conditions of the site and its dynamic in time (Chave, 1999). Sites with higher total production, or that require shorter time for restructuring after a disturbance, have lower structural variability when compared to others. For all sites, this structural variability is increasing over time, proportional to the rate of recomposition after a disturbance.

However, in the same age of post-exploitation, in different management regimes and replicates, the number of trees that enter in the canopy is dependent on the configuration of gaps (Chave, 1999), an aspect that influences the diametric variability of population and compromises comparison between gaps caused by different logging intensities.

That dynamic can be modeled and measured over time using Diameter Variation Index of Pioneers Species ($VI_{\%}$). $VI_{\%}$ is a measure of the structural dispersion of the forest, allowing different sites to be comparted in terms of diameter variability, ecological composition and per unit area yield (Nascimento, 2012). This ratio is a dimensionless measure of dispersion that was initially proposed by Pimentel Gomes (1991) for comparing the relative variability among different populations of unequal size, which is calculated as follows:

$$\mathrm{IV}_{\%} = \frac{\mathrm{CV}}{\sqrt{n}} \tag{1}$$

where n = number of pioneer species per unit area (N ha^{-1}), CV = Coefficient of Variation (%) of the diameters of the pioneers, $IV_{\%}$ = Diameter Variability Index of Pioneer Species (%).

For all post-logging years beginning in 1990, $VI_{\%}$ of pioneer species was calculated for all treatments and replicates in the analysis. $VI_{\%}$ dispersion over time was found as well as its dynamic range in order to incorporate the variable in the model output in terms of numbers of individuals per unit area.

2.3. The Weibull function and its sample moments

The used technique for diameter distribution prognosis was the recovered of the coefficients of the Weibull pdf by the ratio of the three population attributes with the three sample moments of the function, namely the minimum diameter (d_{min}), mean diameter ($\bar{d}$), and mean square diameter (d_g) of each treatment and ecological group in analysis:

$$F(d) = 1 - e^{-\left(\frac{d-a}{b}\right)^c} \tag{2}$$

$$d_{min} = a + \frac{b\Gamma\left(1+\frac{1}{c}\right)}{\left(n^{1+\frac{1}{c}}\right)} \tag{3}$$

$$\bar{d} = a + b\Gamma\left(1+\frac{1}{C}\right) \tag{4}$$

$$d_g = \sqrt{a^2 + 2ab\Gamma\left(1+\frac{1}{C}\right) + b^2\Gamma\left(1+\frac{2}{C}\right)} \tag{5}$$

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