USING DIAMETER VARIATION INDEX OF PIONEER SPECIES FOR CLASSIFICATION AND MODELING TROPICAL FOREST YIELD

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Abstract

This study sought to classify the productivity of a representative area of tropical forest, as well as to analyze the relationship between the structural variability of pioneer species and the yield of three management regimes. The study area is located at the Tropical Forestry Experimental Station belonging to INPA (National Institute for Amazon Research), approximately 90 km from downtown Manaus, in the State of Amazonas, Brazil. Data were collected from twelve 1 ha sample plots. Diameter was measured annually for all individuals with DBH $\geq$ 10 cm between the years 1990 and 2008. Pioneer species served as the basis for calculating the Diameter Variability Index $VI_\%$ over time. Three classes of variability were established according to the guide curve technique used for site classification by the dominant height. Biological and probabilistic functions were used to model $VI_\%$ as a function of time of exploitation, as well as the volumetric yield over time as a function of $VI_\%$. There is an inverse relationship between $VI_\%$ and yield, which allows classification of site yield and conception of global yield models to which present good statistics of precision and adjustment, allowing the prediction of productivity and their dynamics throughout the time.

Keywords: Amazon Rainforest; Ecological groups; Yield models; Site classification; Growth analysis.

Resumo

Uso do índice de variação diamétrica das espécies pioneiras para classificação e modelagem da produção de florestas tropicais. Esse trabalho teve como objetivo classificar a produtividade de uma área de floresta tropical, bem como analisar a relação existente entre a variabilidade estrutural das espécies pioneiras e a produção de três regimes manejo. A área de estudo esta situada na Estação Experimental de Silvicultura Tropical do INPA distante aproximadamente 90 km do centro urbano de Manaus, Amazonas, Brasil. Os dados são provenientes de 12 parcelas permanentes de 1 ha, com medições anuais de todos os indivíduos com DAP $\geq$ 10 cm entre os anos de 1990 e 2008. As espécies pioneiras serviram como base de cálculo do Índice de Variação Diamétrico (IV%) ao longo dos anos. Três classes de variabilidade foram estabelecidas conforme a técnica da curva guia utilizada na classificação de sítio pela altura dominante. Foram usadas funções biológicas e probabilísticas para modelar o IV% em função da idade de exploração, bem como a produção volumétrica ao longo do tempo em função de IV%. Existe relação inversa entre o IV% e a produção, que permite a classificação da produção do sítio e a concepção de modelos de

Palavras-chave: Floresta Amazônica; Grupos ecológicos; Modelos de produção; Classificação de sítio; Análise do crescimento.

INTRODUCTION

The dynamics of yield in primary, uneven aged and heterogeneous forests are determined by the occurrence of *n* events that alter the structure and number of species present in the environment. The quality and speed of a forest response to these disturbances are dependent on the nature of the site and severity of the disturbance. These variables are measured in terms of increases in biomass

and number of species per unit of area over time (NASCIMENTO, 2012).

The species that initiate forest succession and compose a significant proportion of biomass in a disturbed forest are the pioneer species that colonize clearings and disturbed areas and initiate forest recovery (SWAINE; WHITMORE 1988). Regardless of whether natural processes or humans are responsible, the density and dominance of these species in the forest are indicative of recent or historical disturbances that shaped their appearance (SPIES; FRANKLIN, 1989; WHITMORE 1989).

By observing the horizontal structure of a disturbed forest, it is possible to observe the increased establishment of pioneer species in a forest by natural succession alters the variability in diameter of the forest population, because of the increased number of small individuals (FRANKIN *et al*., 2002). Their presence modifies the physical attributes of the forest, as well as the ecological group to which they belong (SPIES; FRANKLIN, 1989). This change of variability in diameter can be measured, and their degree of homogeneity is inversely related to the productive capacity of the site (NASCIMENTO, 2012).

Many scientific studies have corroborated this statement, not only in different science areas but mainly in forest science (BAILEY; TAPPEINER, 1998). In production quality control, the lower the variability around a desirable average of the physical and chemical characteristics of a product, the greater the total yield (SPIEGEL, 1969; MARQUES, 2003; LATTIN *et al*., 2011). Minimizing variability is the goal in silvicultural processes. An example is the planting of homogeneous stands, and when this method does not suffice, clonal plantations from a single specimen can often improve yield still further. In tropical forestry, several silvicultural methods exist to achieve species homogeneity, mainly for production purposes (LAMPRECHT, 1990), but often neglecting the species of different ecological groups and their influence on the site yield.

However when considering the structural variability of pioneer species, according to the dimensions of the individues of the ecological group, mainly in secondary forests, the conditions of the site and their dynamics over time can be identified. In more productive sites, or in sites which proceed through more rapid restructuring after a disturbance, the structural variability is lower, and the more mature forest stands, or more time after the disturbance, the greater the variability in structural and ecological terms.

The productive capacity of a site is closely related to forest exuberance in terms of biomass, number of species, ecological and structural diversity (NASCIMENTO, 2012). However the productivity of a forest is linked to the previous definition of the indicator variable of forest yield (MACHADO, 1977). The layout of the indicative variable in graphic arrangements, tables, and mathematical models to classify forest productivity is relative new in tropical forests studies.

Classify productive capacity on different forest sites is extremely important for forest managers that aim to optimize the use of forest resource. Prior identification of productive capacity of site facilitates decision making, improves selection of cultural treatments, improves choice of species to be managed, and provides an indication of appropriate silvicultural techniques to local studies and regional practices (NASCIMENTO, 2012; WEISKITTEL *et al*., 2011; BONTEMPS; BOURIAUD 2014). The wide number of species and diversity of ages that compose the tropical rain forests are restrictions on the use of techniques widely applied for assessment of forest plantations and homogeneous forests, like Eichhorn's rule (SKOVSGAARD; VANCLAY, 2008) or Site Index (ASSMANN, 1970), because they do not work well as a way of productive capacity classification (VANCLAY, 1992).

Aiming go to classify the forest yield under different forest management regimes, this study tested the hypothesis that the Diameter Variability Index of pioneer species can serve as a tool for analyzing forest yield under selective logging at different cutting intensities. As such this index constitutes a new method for classifying forest sites in tropical forests, as well as it can be used as independent a new variable for whole stand and size class modeling of uneven aged and heterogeneous forest.

MATERIALS AND METHODS

Study Area Description

The Tropical Silviculture Experimental Station (EEST) is located in the Suframa Agricultural District and managed by the Tropical Forestry Research Committee of the National Institute for Amazonian Research (CPST/INPA). Also called the "ZF-2" the research base is located is located about 90 km northwest of Manaus, State of Amazonas, Brazil.

According to the Köppen classification system, the climate is "Amw", characterized by humid tropical weather, warm temperatures, and diurnal temperature variation which is greater than the annual temperature variation. The average annual temperature is 26.7ºC, and mean maximum and minimum temperatures were 31.2ºC and 23.5ºC, respectively. According to Silva (2001), the average annual rainfall for the period 1980-2000 was 2,610 ± 124 mm (95% CI), with two distinct seasons during the year, a rainy season, occurring between November and May, and a dry season lasting until October. Higuchi *et al.* (2011) analyzed data from 2000 to 2005 and found that the average annual rainfall at the INPA forestry lab base camp ranged between 2353 and 2708 mm. The annual average relative humidity is 84%, ranging from 77-88% (FALESI, 1971).

The soils can be classified into yellow latosols on plateaus, red-yellow podzols on slopes and hydromorphic arenosols in valleys. All of the soils are very acidic and the largest negative charges were found in low-lying portions of the transect where hydromorphy is clearly present from drainage channels and the elevation of the water table up to the soil surface.

The vegetation of the area is representative of unflooded "terra-firme" dense tropical rainforest. Higuchi *et al.* (1985), working in the same experiment, found 14,992 individuals with a diameter at breast height (DBH) ≥ 25 cm, 19.3 $m^2.ha^{-1}$ of basal area and 190.5 $m^2.ha^{-1}$ standing timber with bark, and 409 species belonging to 206 genera and 59 botanical families. Jardim and Hosokawa (1986) conducted a structural analysis of a sample of 8 ha of the same forest, measuring all individuals whose total height ≥ 10 cm and found 324 species, from 173 genera and 57 botanical families.

Data Source

The data were collected from a trial based on a randomized block design initiated in 1980, with four blocks and six sub-blocks, occupying a total area of 96 hectares. All trees with DBH ≥ 10 cm were measured, numbered sequentially, georeferenced within each plot, evaluated bole quality, and identified at species level. However in this study only blocks 1, 2 and 4 were used, each occupying an area of 24 ha (600 x 400 m), 6 treatments of 4 ha (200 x 200 m), for a total of 15 permanent 1- hectare plots (100 x 100 m) installed inside the treatments.

A randomized block design was used in the experiment which included plot subdivisions for the silvicultural treatments, for a total of 6 treatments and 4 replicates. The intervention in the native forest through cutting at various intensities began in 1987 with the demarcation of the experimental blocks and was logged first in 1987 and in 1988. The experiment was composed of the following 4 treatments with replicates in each.

- T0 = Control (unlogged plot), all trees DBH ≥ 25 cm measured (1980-1986) and beginning in 1986 all trees DBH ≥ 10 cm.
- T1 = Low intensity logging treatment with removal of 25% basal area of commercially listed species (EL) and cutting and skidding of all EL species DBH ≥ 55 cm. Average DBH of logged individuals was 62 cm and average commercial volume was 34 $m^2.ha^{-1}$ with a total volume extracted from 65 $m^2.ha^{-1}$ ± 12%. The treatment was conducted between August and September 1987.
- T2 = intermediate intensity logging treatment with removal of 50% basal area of commercially listed species (EL) and cutting and skidding of all EL species with DBH ≥ 57 cm. Average DBH of logged individuals was 70 cm and the commercial average volume was 49 $m^2.ha^{-1}$ with a total volume of 73 $m^2.ha^{-1}$ ± 17%. The treatment was conducted between October and November 1987.
- T3 = heavy intensity logging treatment with removal of 75% of the basal area of commercially listed species and cutting and skidding of all EL species with DBH ≥ 40 cm, average logged DBH of 56 cm; average commercial volume of 67 $m^2.ha^{-1}$, and total extracted volume of 71 $m^2.ha^{-1}$ ± 26%. The treament was conducted between September and November 1988.

After logging in 1987/88 the average number of trees remaining per treatment for T1, T2 and T3 was 518, 505 and 475, respectively. The basal area after logging was 23.5, 22.5 and 21.4 $m^2.ha^{-1}$ for T1, T2 and T3 respectively. The average per treatment post-logging volume of all species was: 297.8 $m^2.ha^{-1}$ in T1; 283.1 $m^2.ha^{-1}$ in T2; and 270.1 $m^2.ha^{-1}$ in T3 (PINTO, 2008).

Between 1990 and 2008 measurements were taken normally each year in the month of July, lasting approximately 15 days and formed the basis for this study.

Diameter Variation Index of Pioneer Species (VI%)

The structural variability of a logged forest reflects the logging intensity and the site

characteristics (NASCIMENTO, 2012). The extent of this structural variability can be measured by dispersion statistics such as the coefficient of variation (CV) of diameters. However, when the effect of the treatments were taken into account, the number of species that colonize the area within plots of the same post-logging age are further affected by the size of the clearing, manifesting in the variability in diameter of the population and hindering comparisons between clearings caused by different logging intensities.

The CV is a measure of dispersion that "gives some idea of the variation" of an experiment. However, in comparing two or more disturbed areas each with a different number of species, the CVs for these areas are meaningless for comparative purposes, since it is influenced by the number of observations upon which its calculation is based. These values, which directly influence the confidence interval for each average in the F-test and in the mean comparison tests, clearly show that the highest coefficient of variation is not always the least precise (PIMENTEL-GOMES 1991). That is, in the analysis of the variability of an attribute describing the structure of a population, a high CV does not necessarily indicate high structural variability (PIMENTEL-GOMES; GARCIA, 2002).

To measure, compare and rank the dispersion of structural variability of the forest within the different treatments and their replicates, the $VI_\%$ was used. The Variability Index is a dimensionless measure of dispersion that is employed to compare the relative variability between populations of unequal size and according to Pimentel-Gomes (1991) it is calculated as follows:

$$s_{\bar{x}} = s/\sqrt{n} \tag{1}$$
$$CV = (s/\bar{x}).100 \tag{2}$$
$$CV.\bar{x} = s.100 \tag{3}$$
$$\bar{x} = (s.\ 100)/CV \tag{4}$$
$$VI_\% = (s_{\bar{x}}/\bar{x}).\ 100 \tag{5}$$

Substituting expressions (1) and (4) into (5):

$$VI_\% = \{(s/\sqrt{n})/[(s.\ 100)/CV]\}.\ 100 = (s.CV.\ 100)/(\sqrt{n}.s.\ 100) = CV/\sqrt{n} \tag{6}$$

Where: $s_{\bar{x}}$ is the standard error of the DBH (cm) of the pioneers; s is the standard deviation (cm) of the sample; n is the number of pioneer trees per unit area (N.ha^{-1}); $\bar{x}$ is the arithmetic mean of the diameters at breast height (cm) of pioneers; CV is the coefficient of variation (%) of the diameters of the pioneers; and $VI_\%$ = 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. The dispersion of $VI_\%$ over time was found, as well as the magnitude and behavior for purposes of modeling using mathematical functions widely recognized in forestry.

VI% modeling and classification

In order to model the dynamics of the variability in diameter of pioneer species, biological growth functions were used in their differential form. Meanwhile probability density functions were used to model $VI_\%$ (Table 1). The functions have been modified to meet the behavioral constraints of the variable, where:

$$f(t) = 1 - VI_\% \tag{7}$$
$$VI_\% = 1 - f(t) \tag{8}$$
$$f(t) = k + g(t) \tag{9}$$

Substituting (9) into (8):

$$VI_\% = 1 - [k + g(t)] \tag{10}$$
$$VI_\% = 1 - k - g(t) \tag{11}$$
$$b_0 = 1 - k \tag{12}$$

Substituting (12) into (11):

$$VI_\% = b_0 - g(t) \tag{13}$$

Where $f(t)$ is the complement of the Variability Index as a function of time (%); $VI_\%$ is the Diameter Variability Index of Pioneer Species (%); b_0 is the estimated Diameter Variability Index of Pioneer Species in dynamic equilibrium (%), and; $g(t)$ is the probability density function or biological growth function in its differential form, as a function of time (%).

Table 1 presents the used models for the $VI_\%$ modeling. After choosing the best fit using statistical criteria for model selection, an reference age was defined for rearranging the model. In a forest plantation the reference age is chosen arbitrarily or when maximum productivity occurs being this age the time for technical rotation (ASSMANN, 1970). To classify yield according to $VI_\%$, time was recorded beginning with the logging date, also called the "post-logging age."The reference age adopted here occurred at the minimum point on the $VI_\%$ curve with time.

Table 1. Tested functions for modeling the Diameter Variation Index of Pioneer Species and for volume yield as a function of time based on Zeide (1993) and Krishnamoorthy (2006)

Models	Formulation	
	Cumulative	**Differential**
Hossfeld IV	$F(t) = \dfrac{t^c}{\left(b + \frac{t^c}{a}\right)}$	$g(t) = \dfrac{bct^{c-1}}{\left(b + \frac{t^c}{a}\right)^2}$
Gompertz	$F(t) = ae^{-be^{-ct}}$	$g(t) = abce^{-ct}e^{-be^{-ct}}$
Logistical	$F(t) = \dfrac{a}{(1 + ce^{-bt})}$	$g(t) = \dfrac{abce^{-ct}}{(1 + ce^{-bt})^2}$
Monomolecular	$F(t) = a(1 - ce^{-bt})$	$g(t) = abce^{-bt}$
Bertalanffy	$F(t) = a(1 - e^{-bt})^3$	$g(t) = 3abe^{-bt}(1 - e^{-bt})^2$
Chapman – Richards	$F(t) = a(1 - e^{-bt})^c$	$g(t) = abce^{-bt}(1 - e^{-bt})^{c-1}$
Levakovic I	$F(t) = a\left(\dfrac{t^d}{b + t^d}\right)^c$	$g(t) = \dfrac{abcd\left(\frac{t^2}{b+t^d}\right)^c}{t(b + t^d)}$
Levakovic III	$F(t) = a\left(\dfrac{t^2}{b + t^2}\right)^c$	$g(t) = \dfrac{2abc\left(\frac{t^2}{b+t^2}\right)^2}{t(b + t^2)}$
Korf	$F(t) = ae^{-bt^{-c}}$	$g(t) = abct^{-c-1}e^{-bt^{-c}}$
Weibull	$F(t) = a\left(1 - e^{-bt^c}\right)$	$g(t) = \left(\dfrac{c}{b}\right)\left(\dfrac{t - a}{b}\right)^{c-1}e^{-\left(\frac{x-a}{b}\right)^c}$
Yoshida I	$F(t) = a\dfrac{t^c}{(b + t^d)} + c$	$g(t) = \dfrac{abdt^d}{t(b + t^d)^2}$
Sloboda	$F(t) = ae^{-be^{-ct^d}}$	$g(t) = abcde^{-be^{-ct^d}}t^{d-1}e^{-ct^d}$
Gamma	$F(t) = \dfrac{1}{\Gamma(a)}\displaystyle\int_0^t e^{-x}x^{a-1}dx$	$g(t) = \dfrac{e^{-\frac{t}{b}}t^{a-1}}{\Gamma(a)b^a}$
Beta	$F(t) = \dfrac{\Gamma(a + b)}{\Gamma(a)\Gamma(b)}\displaystyle\int_0^t x^{a-1}(1 - x)^{b-1}\,dx$	$g(t) = \dfrac{\Gamma(a + b)(t - c)^{a-1}(d - t)^{b-1}}{\Gamma(a)\Gamma(b)(d - c)^{a+b-1}}$
SB de Johnson	$F(t) = \Phi\left[a + bLn\left(\dfrac{t - c}{d - t}\right)\right]$	$g(t) = \dfrac{e^{-\frac{\left[a+bLn\left(\frac{t-c}{d-t}\right)\right]^2}{2}}}{\sqrt{2\pi}}$
Normal	$F(t) = \Phi\left[\dfrac{t - a}{b}\right]$	$g(t) = \dfrac{e^{-\frac{(t-a)^2}{2b^2}}}{b\sqrt{2\pi}}$
Log normal	$F(t) = \Phi\left[\dfrac{Ln(t) - a}{b}\right]$	$g(t) = \dfrac{e^{-\frac{[Ln(t)-a]^2}{2b^2}}}{tb\sqrt{2\pi}}$

Where: $F(t)$ = biological growth or probability density function as a function of time, $g(t)$ = biological growth function in its differential form or probability density function as a function of time; t = time in years from logging; a, b, c, d = coefficients of the models; Φ = accumulated Standard Normal density function; Γ = Gamma function; and e = Euller exponential.

After the age at which minimum variability in diameter of pioneer species is determined, the

dispersion in the VI% data with time was separated into three classes of variability: low, medium and high. Specifically, the amplitude of the variation at its minimum was divided into three sectors, or limits for the three established classes in the Variability Index curves. This technique is identical to that used in construction of site index curves presented in several forestry studies and the rearranged model takes on the following form:

$$VI_{\%_{Iref}} = b_0 - g(Iref) \tag{14}$$
$$bo = VI_{\%_{Iref}} + g(Iref) \tag{15}$$

Substituting (15) into (13):

$$VI_\% = \left[VI_{\%_{Iref}} + g(Iref)\right] - g(t) \tag{16}$$
$$VI_\% = VI_{\%_{Iref}} + g(Iref) - g(t) \tag{17}$$
$$VI_{\%_{Iref}} = VI_\% + g(Iref) - g(t) \tag{18}$$

Equation (17) was used to define the limits of the classes adopted for the years in question, where only the Variability Index of Pioneer Species ($VI_\%$) and age (t) in the year of the minimum variation ($Iref$) was known in determining the respective limits. Equation (18) estimates the Reference Variability Index (VI_{Iref}) at the reference age ($Iref$), beginning at a certain age and the known VI% values in the plots being analyzed.

The three classes of variability were applied to the average of the treatments in order to verify the effect of different logging intensities on the diametric structure of the pioneer species and also all of the species in the experiment. Furthermore the relationship between variability and yield was also verified, by correlating the VI% of pioneer species with the per unit area wood volume yield.

Correlation of Yield and VI%

We tested the hypothesis that yield according to any attribute of the population is inversely proportional to the variability in diameter of the pioneer species and is an indicator of site quality in logged forests. To test this hypothesis, we generated linear correlation matrices with the data, by treatment and for all treatments in analysis. The F-test was applied as a means of verifying the existence of a model that represents the inverse relationship between production volume and Variation Index of Pioneer Species over time. Biological growth models and cumulative probability density functions were fitted in attempt to model the per unit area volume for the average of treatments under analysis. The modified model fit was performed as follows:

$$Y = Y_i(0) + \left(1/VI_\%^{-b_0}\right).b_1.F(t) \tag{19}$$

Where Y is the production in m³.ha⁻¹ in year t; $Y_i(0)$ is the yield of the treatment i at the year zero, ie, the year in which logging occurred; $IV_\%$ is the Diameter Variability Index of pioneer species (%); $F(t)$ is the biological growth function or the cumulative probability density function used in the model; and b_0 and b_1 are the coefficients to be estimated, where b_1 will always be equal to 1 when $F(t)$ is a function of biological growth.

The fitting of the adapted models occurred simultaneously, i.e., the coefficients b_i and the coefficients of the biological and probability functions were estimated together, rather than applying the regression technique in its truncated form for each model. Table 1 presents the biological growth and probability functions tested to represent the per unit area yield volume for the treatment average of the analysis. The post-logging increment in absolute and relative terms was compared to the classification of the variability index of the pioneer species, where low, medium and high variability classes indicate high, medium and low yield, respectively. This procedure was performed to exclude the remaining post-logging volume, removing from the analysis the past standing stock above the yield of the site after disturbance.

Once these relationships and the global volume yield of the treatments were established, the graphical relationship was established between the curves, as well as their accuracy in estimating V.ha⁻¹.

RESULTS AND DISCUSSION

Modeling and classification of the VI%

Table 2 presents the coefficients and statistics of the two best fits for modeling VI% and volume per hectare over time. The Log Normal probability density function followed by the Sloboda differential biological growth function showed the best performances. The Log Normal pdf was more appropriate because it provided an adjusted and corrected R^2 of 0.7439 and a recalculated standard error of estimate of 15.79%, although there was less flexibility because the coefficients were fewer than in the other models. Meanwhile the Sloboda model proved very flexible, since it revealed an R^2 of 0.7364 and standard error of estimate of 16.02%, which were nearly the best performing model and yielding equally satisfactory results.

Table 2. Coefficients and statistics of fit and precision of the two bests fits equations for the relationship between post-logging age and $VI_\%$ and the two best fit equations for modeling volume per hectare over time, estimated as a function of the post-logging age and $VI_\%$

Estimated coefficients	Fitted models			
	Age ~ f ($VI_\%$)		V(m^3) ~ f (Age, $VI_\%$)	
	Log Normal	*Sloboda*	*Weibull*	*Beta*
b_0	0.0648	0.0644	0.245	0.249
b_1	-	-	42.928	42.559
a	3.2038	1.714	2.9998	1.4209
b	0.629	7,3E+04	13.861	210.46
c	-	8.0154	1.264	2.968
d	-	0.0984	-	1993.1
R^2	0.7439	0.7364	0.9778	0.9768
$Syx_\%$	15.79%	16.02%	1.28%	1.31%
F	78.0	38.0	527.1	403.1

Using the adjusted Log Normal function we identified the year of least variability in diameter of pioneer species for all treatments and their replicates, which occurs in the 17th year after logging, and thereafter there is a gradual increase in the variability in diameter of pioneer species (Figure 1). This figure shows that logging at different intensities affects the variability in diameter of pioneer species, since in the control plots, this variability remains relatively constant over time, and contrasting the behavior of the logged treatments.

The amplitude of variability in diameter at 17 years was 3.57%, consisting of three classes of variation of constant intervals of 1.19%. From this information the model was rearranged to determine the class limits for the various post-logging age groups (Figure 1). Figure 1 shows that replicates of each treatment did not yield the same class of variation over time. This fact indicates highlights the uneven effect of logging on the treatments, as well as in their replicates, and suggests that there is a subtle difference between replicates with respect to the characteristics of regeneration and development based on the site where they are located.

Analyzing the average of the treatments, the effect of the logging intensity on the variability in diameter of pioneer species revealed a similar result to that found in the percentage of species in the treatments. The results from Treatment 2 were unexpected, since the variability was greater than T1 and T3 and its reaction to logging more moderate, since there were fewer pioneer species identified in the continuous forest inventory for this treatment than the others.

By harvesting using the mean intensity of exploitation, $VI_\%$ in this treatment was expected to be lower than in T1 and higher than in T3. In calculating the Variability Index, the number of observations is inversely proportional to the variability of the data (PIMENTEL-GOMES, 1991), and therefore a medium intensity logging treatment (T2) was expected to affect the structural variability of forest more than a light logging treatment (T1), rather than the reverse.
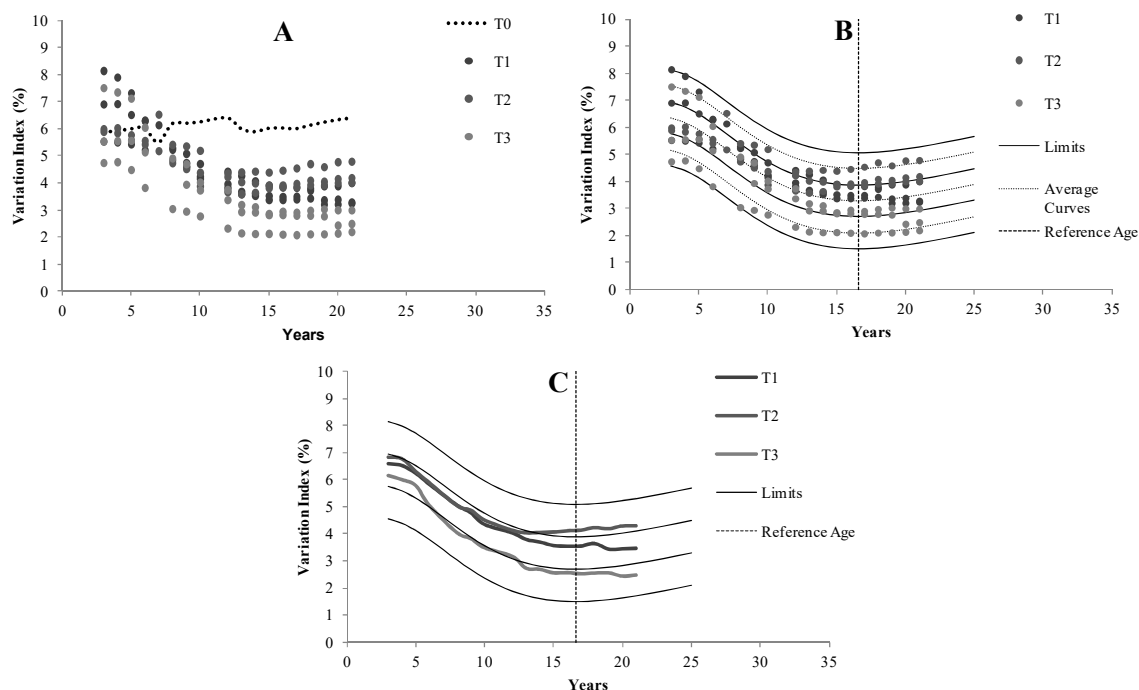
Figure 1. Diameter Variation Index of Pioneer Species in treatments T0, T1, T2 and T3 in all replicates (a), modeling and classification of VI% in the three logged treatments (b), as well as dynamic of the average values of all treatments after the exploitation (c).

This result does not corroborate with those obtained in Figure 2, where the simple linear correlation statistics between productive variables, time, VI% and logged treatments are given. VI% and time appear to be highly correlated. The ρ values obtained between VI% and the productivity variables was -0.4622 for basal area (m².ha^{-1}), -0.4173 for volume (m³.ha^{-1}) and -0.4995 for tons of carbon per hectare (Mg.ha^{-1}), indicating an inverse relationship between these variables.

**Correlation between yield and VI%**

Results from the correlation matrix between the main productivity variables per unit area with time and VI% for the control plots (T0) indicate that there is a simple inverse linear correlation with a high degree of interdependence between all variables. All ρ values obtained between VI% and the productivity variables was -0.8195 for basal area (m².ha^{-1}), -0.7624 for volume (m³.ha^{-1}) and -0.8489 for tons of carbon per hectare (Mg.ha^{-1}), However, the correlation was low between the variable time in years and VI% (0.0811), a result which may be explained by the constant yield per unit area in T0, which remains dynamically constant over time as would be expected of a primary forest (380.67 ± 3.10 m³.ha^{-1}).

The results in Figure 2 indicate a low correlation between the treatment and the Diameter Variation Index of Pioneer Species. This result also indicates that there is an order of magnitude difference in VI% values which does not correspond to the order of treatments. This result indicates that the intensity of logging bares no direct relation to VI%, such that the sequence of treatments ordered by increasing VI% values is T3, T1 and T2. In Figure 3 the classification of VI% and accumulated volume increment after logging are compared. In relative terms, the inverse relationship between the VI% and volumetric productivity is evident.

According to Weiskittel *et al.* (2011) there are four requisites that must be met for adoption of an attribute as forest productivity indicator: replicable and consistent over long periods of time; little influenced by the structure, composition, and management regimes applied to the forest; correlated to productive potential of the site, and; as good as any other measure of productivity. It is possible to see in Figure 1 that the classification proposed by the VI% modeling proved to be consistent over time. The comparison of treatments with different diametric structures by using VI% evidences low correlation between the exploitation intensity and site yield as can be observed in Figure 2. Therefore,

confirms that exist a strong correlation between VI% and production capacity of the different sites under analysis.
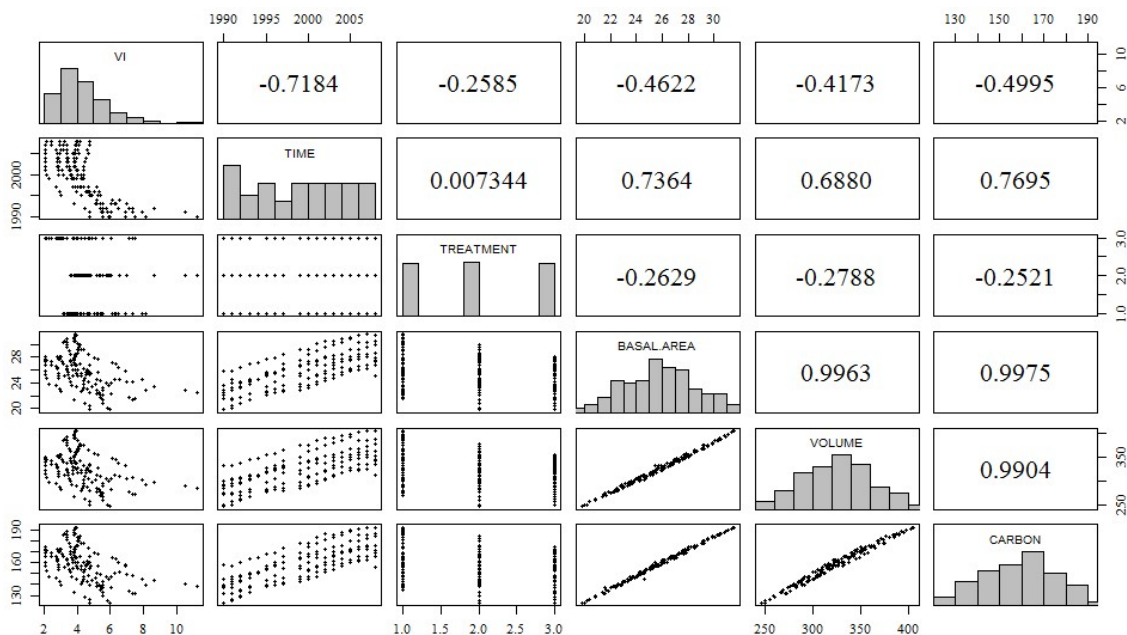
Figure 2. Correlation matrix between the main per unit area productive variables, time, treatment and the Diameter Variation Index of Pioneer Species for all treatments subjected to selective logging.

Due to different cutting intensities, the effect of logging on treatments did not directly affect the number of pioneer species, as there was no direct correlation between logging intensity and emergence rates of these species. It is noted that the maximum occupancy by pioneer species is fewer in T2 (22.49%), followed by T1 (24.26%) and then by T3 (25.74%), as well as the percentage of pioneer species in the T0 treatment was roughly 12.17 ± 0.91%, an average that was generally stable over time. This result is related to the gaps distribution in the different treatments and site characteristics. More sparse gaps caused minor impact on the canopy in T2, resulting in the reduced emergence of pioneer species in this treatment (PINTO, 2008). Another aspect is related to the site characteristics, which induce to a different response to the logging treatments, where T2 has characteristics that affect its recovery at a lower intensity due to the climate, soil and biota in the geographic region in which it is located (ASSMANN, 1970; SHUGGART, 1984).

The treatments that had high, medium and low variability in diameter of pioneer species had low, medium and high volumetric yields, respectively. Analyzing the aggregate output in relative terms, and disregarding the stock in year zero, or volume remaining after logging, it is evident that the VI% is related to site yield for each treatment, since per unit area yield was highest in the most structurally homogeneous treatment, whereas in treatment T2, which had greater variation than the others, also had an accumulated relative increment that was lowest among all the treatments.

D'Oliveira (2000) stated that the establishment characteristics of pioneer plants impede commercial species from growing at desirable rates. Because of competition, the pioneer effect imposes a long cutting cycle and reduces yield. According to Vieira (1996), who studied the same area six years after logging, there was no correlation between diversity of species and gap size, despite changes in the abundance of individuals within each treatment. This finding suggests that depending of the treatment, the emergence of pioneer species is correlated with site features, as can be observed on these gaps with many pioneer species.

**Modeling volume per hectare as a function of time and VI%**

Table 2 presents the models tested in the correlation between volumetric yields over time as a function of VI%. All the models tested had a standard error of estimate of less than 1.7%, and R² was

greater than 0.96, a result that reflects a high correlation between the variables. The value of the F-test applied to all the fits indicated the existence of a significant correlation between the proposed models and the data at 5% and 1% levels. The Weibull and Beta probability density functions provided the best performing models of the proposed relationship, and thus the most suitable models of all the tested with an R² of 0.9778 and 0.9768 and Syx% of 1.28% and 1.31%, respectively.

In studying the stand models for a tropical rainforest in the municipalities of Juruá Teffe and the state of Amazonas, Brazil, Figueiredo Filho (1983) tested widely used models in forestry, as well as models developed using forward regression modeling for primary forest, obtaining R² and Syx% greater than 0.9825% and 4.88%, respectively. However, this significant result was possible due to the inclusion of variables such as basal area per hectare and average height of the forest in the models tested, variables that are reflective of the productive capacity of the site environments in primary uneven aged and heterogeneous forests (ASSMANN, 1970; VANCLAY, 1994).

The standard error of estimate of the tested models in general is very low, indicating better performance than the commonly used equations in several papers in the region dominated by tropical forests (MOSER; HALL, 1969; MOSER, 1972; ATTA-BOATENG; MOSER, 2000). Azevedo *et al.* (2007) used the SYMFOR model to simulate ecological processes of growth, mortality and recruitment and the management of an upland forest in the eastern Amazon, both in disturbed and undisturbed environments at light, moderate and heavy cutting intensities. These authors concluded that the model is efficient only in the simulation scenarios in primary environments, it presents outliers when applied aiming the simulation in logged forests.

Modeling volume in m³.ha^{-1} resulted in satisfactory curves fitted to the observed data. In Figure 3 it is possible to see that the best performing model fits the data well, producing curves that include the treatment averages and are absent of significant deviations, or other similar effects.
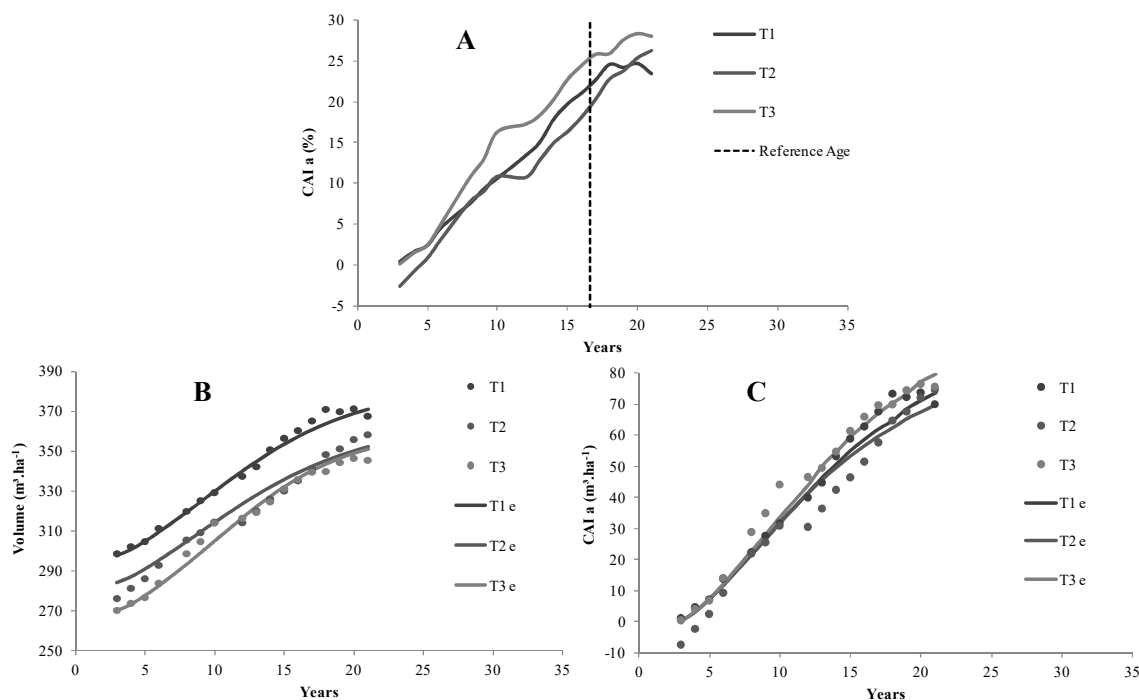
Figure 3. The accumulated current volumetric increment as a percentage (CAI%) in T1, T2 and T3 (a), estimated curves of the observed volume (m³.ha^{-1}) (b) and the accumulated Current Annual Increment in treatments that underwent light (T1), moderate (T2) and heavy (T3) logging over time, as a function of the Diameter Variation Index of Pioneer Species (c).

One way to classify site in uneven aged primary forests takes the magnitude of the values of basal area, volume or other per unit area productive variable, when the site is at maximum stock capacity or at climax situation (ASSMANN, 1970; VANCLAY, 1994). According to Pinto (2008), before logging the average volume for each treatment was 376.8 m³.ha^{-1} for T1, 352.9 m³.ha^{-1} for T2 and 372.5 m³.ha^{-1} for T3, indicating at first that T2 is a less productive site, since its yield was the least of

the tree. Its yield was approximately 20 m³ less than the others, and cannot be explained by the effect of recent disturbance or by measurement error.

Pinto (2008), working in the same area of study and with the same data, used analysis of variance to assess whether there were significant differences at the ☐ < 0.01 level and ☐ < 0.05 level, between treatments T1, T2 and T3 with respect to the yield volume, and corrected for the existence of repeated measures in the F statistic. The author observed that there are significant differences indicating that the per unit area volume varies according to the treatment and over time, with highly significant ρ values. Based on the curves shown in Figure 3 one can say that the site comprising Treatment 1 is approximately equal or the same as T3, because of similar productivity in the period before logging as well as the slope of the yield curve in Figure 1. Figures 1 and 3 show that Treatment 3 had a yield curve steeper than T2, suggesting that the overall yield of this treatment will soon overtake the moderate intensity treatment.

When the fit is analyzed both in absolute and relative terms for each treatment in the analysis, the models are highly effective in describing the data, with ogives very close to those obtained from the averages of the treatments. T1 and T3 have notably more balanced deviations and better fit in their estimated curves (Figure 3). The Figure 3 also shows that Treatments 1 and 3 approaches to an asymptote value in volumetric growth, which is similar to the level that preceded logging, since the accumulated increment curve changes shape beginning at the 19th and 20th year post-logging. In treatment T2, the fit was not as efficient due to the growth discontinuity. The observed data show a time series with truncated development in this treatment, as represented by a curve that follows the general trend of the data.

The development of treatments is associated with site quality, since the treatments with better physical/structural site conditions allowed better improved recovery of the disturbed areas. In terms of pioneer species emergence, variability in diameter of these species and, ultimately, the treatment yields when they were primary forests, the results corroborate those in Figures 1 and 3, where T2 reveals yields below the other treatments and indicates the inferior site quality according to the proposed classification. The figures also show that according the results, T3 is the most productive in total volume per unit area of all the sites.

CONCLUSIONS

The increase in the number of pioneer species logged in different treatments alters the structural variability of these species in each site. Also, there is an inverse relationship between the Diameter Variation Index of Pioneer Species and site yield, as supported by the statistical values of ρ and *F*, obtained from the correlation matrices and in the global volumetric modeling of logged treatments.

The Diameter Variability Index of Pioneer Species proved to be an efficient tool for comparing and modeling the structural variability of different environments logged over time. Also, VI% of Pioneer Species over time and at the reference age indicated that T3 was the most productive, followed by T1 and then T2.

The classification of variability in diameter using the Variability Index of pioneer species can be used to classify and modeling yield in managed forests, and is a technique similar to that adopted in constructing site curves by dominant height for forest plantation.

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REFERENCES

AMARAL, D. D. do; VIEIRA, I. C. G.; ALMEIDA, S. S. de; SALOMÃO, R. de P.; SILVA, A. S. L. da; JARDIM, M. A. G. *Checklist* da flora arbórea de remanescentes florestais da região metropolitana de Belém e valor histórico dos fragmentos, Pará, Brasil. **Boletim do Museu Paraense Emílio Goeldi**, v.

4, n. 3, p. 231-289, 2009.

ASSMANN, E. **The principles of Forest yield study: Studies in the organic production, structure, increment and yield of Forest stands**. New York: Pergamon Press Ltd., 1970. 506 p.

ATTA-BOATENG, J.; MOSER, J. W. Growth and yield model application in tropical rain forest management. In: Integrated tool for natural resources inventories in the 21st century, 2000, Boise. **Proceedings...** Boise: Eds HANSEN, M.; BURK, T., 2000, p. 473 - 480.

AZEVEDO, C. P. de; SANQUETTA, C. R.; SILVA, J. N. M.; MACHADO, S. do A. Efeito da exploração de madeira e dos tratamentos silviculturais no agrupamento ecológico de espécies. **Floresta**, v. 38, n. 1, p. 53-69, 2007.

BAILEY, J. D.; TAPPEINER, J. C. Effects of thinning on structural development in 40-to 100-year-old Douglas-fir stands in western Oregon. **Forest Ecology and Management**, v. 108, n. 1, p. 99-113, 1998.

BONTEMPS, J. D.; BOURIAUD, O. Predictive approaches to forest site productivity: recent trends, challenges and future perspectives. **Forestry an International Journal of Forest Research**, v. 1, n. 87, p.109-128, 2014.

D'OLIVEIRA, M. V. N. **Sustainable Forest management for small farmers in Acre State in the Brazilian Amazon**. 2000. 207 f. Tese (Doutorado em Ciências do Solo e Plantas) - University of Aberdeen, Aberdeen, 2000.

FALESI, I. C. Solos do Distrito Agropecuário da Suframa. **Boletim do Instituto de Pesquisa e Experimentação Agropecuária da Amazônia Ocidental**, v. 1, n. 1, p. 1-99, 1971.

FIGUEIREDO FILHO, A. **Estudos de modelos matemáticos para estimar o volume por unidade de área em uma floresta tropical úmida da Amazônia**. 1983. 150 f. Dissertação (Mestrado em Engenharia Florestal) - Universidade Federal do Paraná, Curitiba, 1983.

FRANKLIN, J. F.; SPIES, T. A.; VAN PELT, R.; CAREY, A. B.; THORNBURGH, D. A.; BERG, D. R.; LINDENMAYER, D. B.; HARMON, M. E.; KEETON, W. S.; SHAW, D. C.; BIBLE, K.; CHEN, J. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. **Forest Ecology and Management**, v. 155, n. 1, p. 399-423, 2002.

HIGUCHI, N.; JARDIM, F. C. S.; SANTOS, J. dos; BARBOSA, A. P.; WOOD, T. W. W. Bacia 3 – Inventário florestal comercial. **Acta amazônica**, v. 15, n. 3-4, p. 327-369, 1985.

HIGUCHI, N.; SANTOS, J. dos; LIMA, A. J. N.; HIGUCHI, F. G.; CHAMBERS, J. Q. A floresta amazônica e a água da chuva. **Floresta**, v. 41, n. 3, p. 427-434, 2011.

JARDIM, F. C. S.; HOSOKAWA, R. Estrutura da floresta equatorial úmida da Estação Experimental de Silvicultura Tropical. **Acta Amazônica**, v. 16/17, p. 411-508, 1986.

KRISHNAMOORTHY, K. **Handbook of statistical distributions with applications**. Boca Raton: Chapman & Hall/CRC, 2006, 344 p.

LAMPRECHT, H. **Silvicultura nos trópicos: ecossistemas florestais e respectivas espécies arbóreas – possibilidades e métodos de aproveitamento sustentado**. Eschborn: GTZ, 1990. 343 p.

LATTIN, J.; CARROLL, J. D.; GREEN, P. E. **Análise de dados multivariados**. São Paulo: Cengage Learning, 2011. 455 p.

LIMA, A. J. N. **Avaliação de um sistema de inventário florestal contínuo em áreas manejadas e**

não manejadas do estado do Amazonas (AM). 2010. 181 f. Tese (Doutorado em Ciências de Florestas Tropicais) – Instituto Nacional de Pesquisas da Amazônia, Manaus, 2010.

MACHADO, S. A. Produtividade de florestas tropicais. **Floresta**, v. 8, n. 2, p. 47-53, 1977.

MARQUES, J. M. **Estatística: cursos de engenharia**. Curitiba: UFPR, 2003. 191 p.

MOSER, J. W.; HALL, O. F. Deriving growth and yield functions for uneven-aged forest stands. **Forest. Science**, v. 15, n. 1, p. 183-188, 1969.

MOSER, J. W. Dynamics of an uneven-aged forest stand. **Forest Science**, v. 18, n. 3, p. 184-191, 1972.

NASCIMENTO, R. G. M. **Modelagem e prognose da produção de uma Floresta Tropical Úmida Densa de Terra – Firme na Amazônia Central**. 2012. 155 f. Dissertação (Mestrado em Engenharia Florestal) - Universidade Federal do Paraná, Curitiba, 2012.

PIMENTEL-GOMES, F. **O índice de variação: um substituto vantajoso do coeficiente de variação**. Piracicaba: IPEF, Circular Técnica n. 178, 1991. 5 p.

PIMENTEL-GOMES, F.; GARCIA, C. H. **Estatística aplicada a experimentos agronômicos e florestais**. Piracicaba: FEALQ, 2002. 309 p.

PINTO, A. C. M. **Dinâmica de uma floresta de terra firme manejada experimentalmente na região de Manaus (AM)**. 2008. 167 f. Tese (Doutorado em Ciências Florestais Tropicais) – Instituto Nacional de Pesquisas da Amazônia/Universidade Federal do Amazonas, Manaus, 2008.

SHUGGART, H. H. **A theory of forest dynamics: the ecological for succession model**. New York: Springer-Verlag Inc., 1984. 278 p.

SILVA, R. P. da. **Padrões de crescimento de árvores que ocorrem em diferentes toposseqüencias na região de Manaus (AM)**. 2001. 60 f. Dissertação (Mestrado em Ciências florestais tropicais) - Instituto Nacional de Pesquisas da Amazônia/Universidade Federal do Amazonas, Manaus, 2001.

SKOVSGAARD J. P.; VANCLAY, J. K. Forest site productivity: review of the evolution of dendrometric concepts for even – aged stands. **Forestry**, v. 81, n. 1, p. 13-31, 2008.

SPIES, T. A.; FRANKLIN, J. F. Gap characteristics and vegetation response in coniferous forests of the Pacific Northwest. **Ecology**, v. 70, p. 543 - 546, 1989.

SPIEGEL, M. R. **Estatística**. Rio de Janeiro: ao livro técnico S.A., 2. ed. 1969. 580 p.

SWAINE, M. D.; WHITMORE, T. C. On the definition of ecological species groups in tropical rain forests. **Vegetatio**, v. 75, n. 1/2, p. 81-86, 1988.

VANCLAY J. K. Assessing site productivity in tropical moist forests: a review. **Forest Ecology Management**, v. 54, p. 257- 287, 1992.

VANCLAY, J. K. **Modelling forest growth and yield: applications to mixed tropical forests**. Waallingford: CAB International, 1994. 312 p.

VIEIRA G. **Gap dynamics in managed Amazonian Forest: strutural and ecophysiological aspects**. 1996. 162 f. Tese (Doutorado em Ecologia Tropical) - University of Oxford, Oxford, 1996.

WHITMORE, T. C. Canopy gaps and the two major groups of forest trees. **Ecology**, v. 70, n. 3, p. 536-538, 1989.

WEISKITTEL, A. R.; HANN, D.W.; KERSHAW, J. A. VANCLAY, J. K. **Forest Growth and Yield Modeling**. Chichester: John Wiley e Sons Ltda, 2011. 415 p.

ZEIDE, B. Analysis of growth equations. **Forest Science**, v. 39, n. 3, p. 594-616, 1993.