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Growth and yield of *Eucalyptus* sp. in tropical region of Brazil

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ABSTRACT

Background: The exhaustion of available areas for forest cultivation in regions traditionally producers in Brazil, such as the South and Southeast regions, unleashed a process of expansion of the border for new plantation areas in locations with distinct climatic characteristics. Therefore, misinformation on influences of the environment on growth and yield of forest species motivates new studies to support the forest management with appropriate and accurate information. Data from a forest inventory, carried out between June and October 2014, were collected in 2,505 temporary rectangular plots of 20 m x 25 m (500 m^2) settled down systematically in 25 thousand hectares of clonal *Eucalyptus* sp. forest stands in Maranhao State, Brazil. For classification of local productive capacity, site curves were built by the method of curve-guide from the adjustment of the Chapman-Richards model, considering the age of reference equal to seven years. Additionally, this model was applied to volume data, adapting it to predict the average yield by sites over the rotation period of the forest and, thus, allowed preparing the volume curves for current and average annual increments. The adjustment of the Chapman-Richards model for growth and yield of forest sites enabled obtaining consistent estimates of local productivity for *Eucalyptus* sp. in the same region. Four sites classes were grouped to compose the sites of greater (I and II) and lower (III and IV) productivity. This structure provided adequate estimates with biological realism for volume, average annual and current annual increments estimates, with the definition of scenarios to tailor the management practices for *Eucalyptus* sp. stands in tropical regions of Brazil.

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INTRODUCTION

The increasing worldwide demand for timber products has facilitated the search for new sources, expanding the commercial producing horizon for the Brazilian forest sector. In this sense, the culture of *Eucalyptus* has guaranteed the raw material supply, due to its lower cost of deployment and its short rotation, whose plantations are allowing competitive opportunities of investment (Rodriguez *et al*., 1997; Rezende *et al*., 2005).

The exhaustion of available areas for forest cultivation in regions traditionally producers in Brazil, such as the South and Southeast regions, unleashed a process of expansion of the border for new plantation areas in locations with distinct climatic characteristics. Therefore, misinformation on influences of the environment in the growth and yield of forest species motivates new studies to support the forest management with appropriate and accurate information.

The estimates of the productive capacity of a given forest site are fundamental elements for the management, because they contribute to determination of silvicultural practices, of crop rotation and choice of appropriate species (Vargas-Larreta *et al*., 2010). In the specialized literature, there are various methods to elaborate the classification of productivity of the forest sites, however the dominant height correlated with age has been considered the most practical and usual (Selle *et al*., 2008), since the height of trees with sociological position in the dominant classes do not suffer significant influence of silvicultural treatments (Tonini *et al*., 2002).

Allied to this, modeling is a tool that provides the verification of the behavior of forests as aid to forest planning. A model for growth and yield is understood as an abstraction of forest dynamics, which may include the growth of the forest or of trees that integrate it, mortality and any other changes in its composition and structure (Freire,

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2002; Miranda, 2012). Furthermore, it allows you to generate yield tables, which present the average growth of stands at different ages and in certain periods and locations (Spathelf and Nutto, 2000).

In view of the exposed, considering the hypothesis that there is a productive feasibility of the development of eucalypt plantations in places with distinct characteristics of commonly cultivated, the objective of this work was to determine the productivity of forest site and volumetric growth and yield of *Eucalyptus* sp. in a region of tropical climate of Brazil.

MATERIALS AND METHODS

Location and Data Collection:

Data from a forest inventory, carried out between June and October 2014, were collected in 2,505 temporary rectangular plots of 20 m x 25 m (500 m2) settled down systematically in 25 thousand hectares of clonal *Eucalyptus* sp. forest stands of in Maranhao State, Brazil (Figure 1).

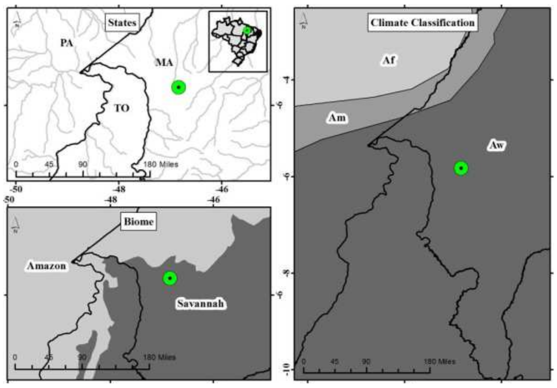

Fig. 1: Location of *Eucalyptus* sp. stands in Maranhao State, tropical region of Brazil.

The climate of the region is classified as Aw (Köppen), characterized by a rainy season from October to April and other dry from May to September, with average rainfall of 1,300 to 1,900 mm yearly and annual average temperature exceeding 26°C (Álvares *et al*., 2013). The reliefs are plans to smoothly undulating; the predominant soils are identified as Yellow Latosols and Typic Quartzipsamments (Embrapa, 2006).

Modeling of the productive capacity of the site:

For the classification of local productive capacity, site curves were built from the adjustment of the Chapman-Richards model (eq. 1), that involved the functional relationship between the variables: dominant height (h_{dom}) and age (t). In addition it was applied the concept of Assmann (1970) for the determination of the dominant trees, which corresponded to the arithmetic mean of total heights of 100 trees with the largest diameters at 1.3 m from the ground (*dbh*) per hectare, defect-free and sound.

$$h_{dom} = \beta_0 \left(1 - e^{-\beta_1 t}\right)^{\beta_2} \quad \text{(eq. 1)}$$

Where: h_{dom} = dominant height (m); β_i = regression coefficients; e = exponential; and t = age (year).

The regression coefficients of the model were estimated by the method of Levenberg-Marquardt for the minimization of the non linear residual sum of square (Marquardt, 1963), with the aid of the software Statgraphics Centurion XVI, version 16.1.02, whose criteria for the assessment of the adjustment involved the lowest standard error of the estimate in percentage (eq. 2), the highest adjusted coefficient of determination (eq. 3) and absence of unfavorable trend in the graphical analysis of residuals.

$$S_{yx}(\%) = \frac{S_{yx}}{\bar{y}} \times 100 \quad \text{(eq. 2)}$$

$$R^2_{aj.} = 1 - \left(\frac{n-1}{n-p-1}\right) \times (1 - R^2) \quad \text{(eq. 3)}$$

Where: S_{yx} = absolute standard error of the estimate; $S_{yx}(\%)$ = standard error of the estimate in percentage; R^2 = coefficient of determination; $R^2_{aj.}$ = adjusted coefficient of determination; $\bar{y}$ = mean of observed variables; n = number of observations; and p = number of regression parameters.

The guide-curve was elaborated after obtaining the equation that represented the behavior of dominant height as a function of age, while the seventh year was defined as the reference age, being as close as possible of the commercial rotation of the crop (Rodriguez *et al*., 1997; Rezende *et al*., 2005). At this age, it was verified the total amplitude of the dominant height, whose value was divided into 'n' classes of constant intervals, thus defining the limits of site classes. Subsequently, the curves in each site index limit, proportionally equidistant, were built and, after that, the guide-curve was removed.

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Modeling Growth and Volumetric Production:

The biological model of Chapman-Richards was applied to the volume data, adapting it to result the mean production along the crop evolution for the forest sites, enabling to prepare the curves of mean annual (MAI) and current annual (CAI) increments of volume at the ages of 2 to 9 years.

Due to the variability and stratification of the data set, it was chosen to perform the adjustment of the model independently in two stages, the first being to the grouping of plots belonging to the site classes of higher productivity (I and II) and the second to the grouping of plots belonging to the site classes of lower productivity (III and IV). Additionally, the curve of average production was obtained by the adjustment of the model proportional to the respective sites.

By means of the first and second derivatives, the curves of current annual increments and annual average in volume were generated in three levels: 1º) production in the sites of greater productivity (eq. 4); 2º) production in the sites of lower productivity (eq. 5); and 3º) the weighted average production of all sites (eq. 6). For the adjustment of the curve of average production, the weight (λ_i) was added to the original model, to correct the proportionality of the site classes. Moreover, the analysis of the standard error of the estimate in percentage (eq. 2), of the adjusted coefficient of determination (eq. 3) and of the residuals tendency were used as criteria for evaluation of the adjustments quality.

$$V_{1;2} = \theta_1 . \left[\frac{1-e^{-k.t}}{1-e^{-k.t_i}}\right]^{[(1-\theta_2)^{-1}]} \quad \text{(eq. 4)}$$

$$V_{3;4} = \theta_A . \left[\frac{1-e^{-kc.t}}{1-e^{-kc.t_i}}\right]^{[(1-\theta_B)^{-1}]} \quad \text{(eq. 5)}$$

$$V_{(1;2)(3;4)} = \left[\theta_1 . \left[\frac{1-e^{-k.t}}{1-e^{-k.t_i}}\right]^{[(1-\theta_2)^{-1}]}\right] . \lambda_{1;2} + \left[\theta_A . \left[\frac{1-e^{-kc.t}}{1-e^{-kc.t_i}}\right]^{[(1-\theta_B)^{-1}]}\right] . \lambda_{3;4} \quad \text{(eq. 6)}$$

Where: $V_{1;2}$ = volume of the plot i (m^3 ha^{-1}) of site classes with greater productivity; $V_{3;4}$ = volume of the plot i (m^3 ha^{-1}) of site classes with lower productivity; t = current age (year); t_i = age of reference, equal to 7 years; k, kc, θ_1, θ_2, θ_A and θ_B = coefficients of the models; $\lambda_{1;2}$ e $\lambda_{3;4}$ = proportionality of site classes; and e = exponential.

RESULTS AND DISCUSSION

Classification of The Productive Capacity of The Site:

The adjustment of the Chapman-Richards model resulted in the equation $h_{dom} = 42{,}38\left(1 - e^{-0{,}085t}\right)^{0{,}608}$, with standard error of the estimate in percentage equal to 16.56% and the adjusted coefficient of determination equal to 0.628. Furthermore, the residual graphic analysis corroborated with the quality of the adjustment and with equal dispersion of residuals (Figure 2A). Moreover, the guide-curve built by means of the adjusted model (Figure 2B) showed a growing trend of dominant height (h_{dom}) as a function of age (t), resulting in an average value of 26.6 m at seven years old.

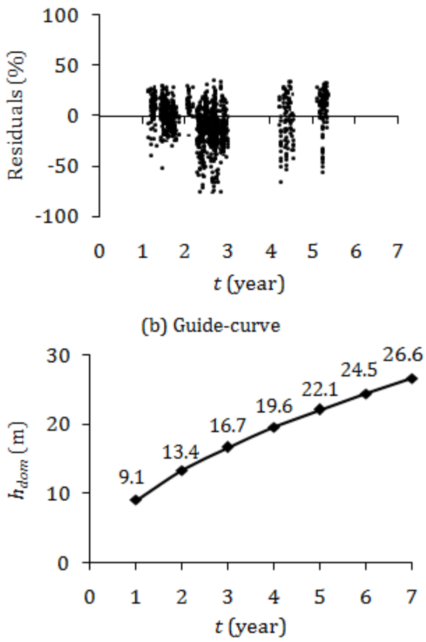

Fig. 2: Residual graphic analysis of the estimation of dominant height (a) and guide-curve resulted from the application of Chapman-Richards model (b) to *Eucalyptus* sp. stands.

By means of characteristics of the Chapman-Richards model, which allows to describe the biological growth, the coefficient β0 expressed the asymptotic length value of the average growth of the dominant height, equal to 42.38 m and higher than the observed by Miguel *et al*. (2011) in the Midwest region of Brazil, which indicates the quality of the productive capacity of the study area for introduction of *Eucalyptus* with appropriate genetic materials.

In addition, it was verified that the dominant height values in the best sites (I and II) were higher than those observed by Days *et al*. (2005), Tonini *et al*. (2006), Salles (2010) and Miranda (2012) in different locations of the country. This was due to the fast development of clonal seedlings, in which the increase in height was greater in the first two years after plantation, whose growth rate has slowed down early (Figure 3). Additionally, cultivation applied contributed to the accelerated initial development, mainly due to the intense levels of soil tillage as subsoiling, application of gypsum in line, base fertilization and coverage, and irrigation after the rainy season.

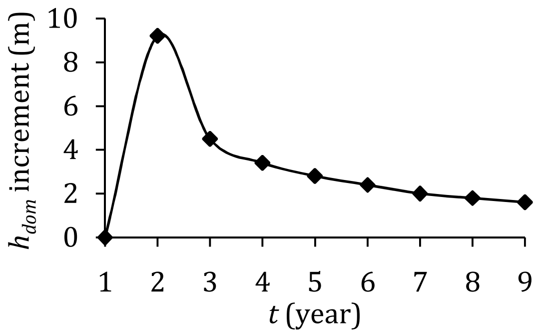

Fig. 3: Curve of dominant height increment in *Eucalyptus* sp. stands in Maranhao State, tropical region of Brazil.

With the determination of the h_{dom} magnitude observed at reference age of seven years, four curves were constructed for site index, respectively in the values of the center of class equal to 39.9 m for the site I; 31.6 m for the site II; 23.4 m for the site III and 15.1 m for the site IV, whose upper and lower limits and the center of the class are presented in Table 1.

The site curves were conceived with four classes of productive capacity with interval of 8.25 m at the reference age of seven years (Figure 4), which have covered the whole range of h_{dom} values in all ages of these *Eucalyptus* stands.

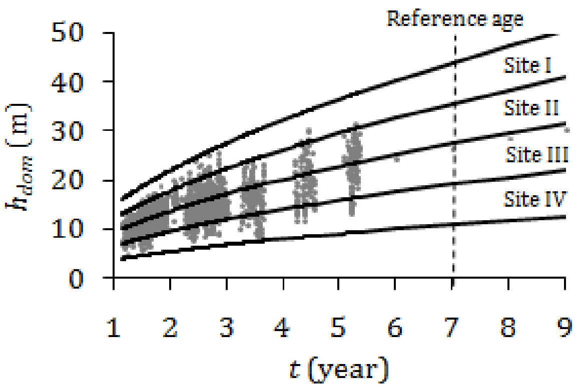

Fig. 4: Site curves for *Eucalyptus* sp. stands in Maranhao State.

The difference in productivity between site classes is due to the soil factors in the region, since the soil in more productive sites are more clayey, dominated by Yellow Latosols with clay content higher than 15%, whereas in the regions with quartz sand, formed by patches of Neossols Quartzipsamment, whose soils have clay content less than 10% and the sites have a lower capacity.

Table 1: Values of upper (UL), center (C) and under (DL) limits of site index classes of *Eucalyptus* sp. stands in Maranhao State, tropical region of Brazil.

Age (year)	Site Classes											
	I			II			III			IV		
	UL	C	DL	UL	C	DL	UL	C	DL	UL	C	DL
1	15.0	13.6	12.2	12.2	10.8	9.4	9.4	8.0	6.6	6.6	5.2	3.8
2	22.1	20.0	17.9	17.9	15.9	13.8	13.8	11.7	9.6	9.6	7.6	5.5
3	27.6	25.0	22.4	22.4	19.8	17.3	17.3	14.7	12.1	12.1	9.5	6.9
4	32.4	29.3	26.3	26.3	23.3	20.2	20.2	17.2	14.2	14.2	11.1	8.1
5	36.6	33.2	29.7	29.7	26.3	22.9	22.9	19.4	16.0	16.0	12.6	9.1
6	40.4	36.6	32.9	32.9	29.1	25.3	25.3	21.5	17.7	17.7	13.9	10.1
7	44.0	39.9	35.8	35.8	31.6	27.5	27.5	23.4	19.3	19.3	15.1	11.0
8	47.3	42.9	38.5	38.5	34.0	29.6	29.6	25.1	20.7	20.7	16.3	11.8
9	50.5	45.7	41.0	41.0	36.3	31.5	31.5	26.8	22.1	22.1	17.4	12.6

Where: UL = upper limit; C = center of the site class; and DL = under limit.

It is expected productivity improvement of sites in these places after the second or third rotation of the plantations, due to structural changes on the soil during the reformation of stands with the incorporation of organic matter in the soil, the selection of appropriate genetic materials, the enhancement of rates of fertilization and of silvicultural treatments, as well as the definition of planting ideal spacing for the homogeneous stands, aiming at the nutrition and hydric management of the soil and the control of the existing internal competition.

Growth and Volume Production:

By means of stratification of sample units of the forest inventory in the four site classes, was noticed that 1.9% of them are present in site I, while 37.8% of the permanent sample plots are present in the site II and 55.4% in the site III, while 4.9% are present in the site IV. The grouping of plots in site classes of higher productivity (I and II) and lower productivity (III and IV) expressed respectively, the proportionality of 39.7% and 60.3% of the total.

Thus, the Chapman-Richards model was adjusted for stratified volumes by productivity classes of the site, whose results are presented in Table 2. By means of the adjustments high standard errors of the estimate in percentage were observed, 17% and 25%, respectively for classes with lower and higher productivity, which may be related to the variability of the intrinsic volume of local productive capacity and the genetics of individuals. While the high values of the adjusted coefficients of determination, of 0.93 and 0.87, were indicative of efficiency of adjustments.

Table 2: Coefficients and statistics of the Chapman-Richards model for volume of *Eucalyptus* sp., by productivity classes, in Maranhao State.

Productivity Class	Greater	Lower
Sites	I and II	III and IV
Coefficients	θ_1 = 363.21	θ_A = 273.04
	k = 0.361	kc = 0.306
	θ_2 = 2.638	θ_B = 2.553
	$\lambda_{1;2}$ = 0.397	$\lambda_{3;4}$ = 0.603
S_{yx}(%)	17%	25%
R^2_{aj}.	0.93	0.87

The dispersion of values observed along the curves estimated by the fitted equations can be observed in Figure 5. In general, trends of overestimation or underestimation of volume production throughout the period of development of the forest stands were not verified. However, it was noted for the grouped sites (I and II) greater productive capacity (Figure 5a), in relation to the sites (III and IV) (Figure 5b) in *Eucalyptus* sp. stands.

The most appropriate choice of genetic material for each type of local soil, the improvement in the fertilizing, silvicultural practices and control of pests and diseases corroborates the assertion that the younger plantations will certainly have a higher potential for growth in a same rotation time, however new studies should be performed in order to elucidate the growth dynamic in successive intervals of time for each tropical region and genetic material. Only this way, more accurate information and acceding to the data set may be obtained.

Additionally, the zoning of the soil classes with physical and chemical properties more suitable for *Eucalyptus* plantations should precede the definition of viable areas for its expansion in large scale in the tropical environment.

Table 3 shows the values of volumetric productions and the current annual (CAI) and mean annual (MAI) increments in volume for the site classes of higher and lower productive capacity, in addition to the average production estimated by the fitted models, as a function of the plantations age.

The volume production was lower than the observed in *Eucalyptus* sp. stands planted in Para State, in tropical regions of Brazil (Castro *et al.*, 2013). In general, this is due to the low natural site fertility, since the soil management, aiming at high nutritional concentrations occurs in the first two years of the plantations, when the seedlings of *Eucalyptus* exhibit accelerated growth, mainly in height. However, the volumetric increments are reduced after stabilization and adaptation of individuals to local edaphic conditions and, even with deep roots they do not find adequate nutritional availability.

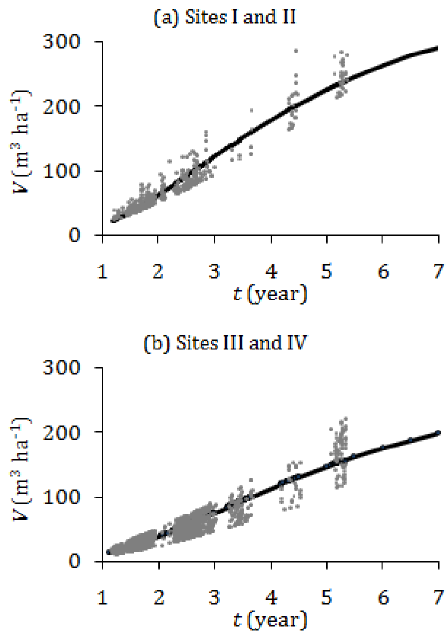

Fig. 5: Volume growth curves for the grouped site classes in *Eucalyptus* sp. stands in Maranhao State.

Table 3: Growth estimates and average production by site classes in *Eucalyptus* sp. stands in Maranhao State.

Age (year)	Average production (m^3 ha^{-1})		
	V	CAI	MAI
1	12	-	11.6
2	47	35.7	23.6
3	93	45.9	31.1
4	138	45.3	34.6
5	178	39.5	35.6
6	210	32.2	35.0
7	235	25.2	33.6
8	255	19.2	31.8
9	269	14.4	29.9
Age (year)	Sites I and II (m^3 ha^{-1})		
	V	CAI	MAI
1	16	-	15.6
2	63	47.3	31.4
3	122	59.3	40.7
4	179	56.5	44.7
5	226	47.5	45.2
6	264	37.3	43.9
7	292	28.1	41.7
8	312	20.7	39.0
9	327	14.9	36.4
Age (year)	Sites III and IV (m^3 ha^{-1})		
	V	CAI	MAI
1	9	-	9.1
2	37	28.0	18.5
3	74	37.1	24.7
4	112	37.9	28.0
5	146	34.2	29.2
6	175	28.8	29.2
7	198	23.3	28.3
8	217	18.3	27.1
9	231	14.1	25.6

Where: *V* = volume per hectare; CAI = current annual increment in volume; and MAI = mean annual increment in volume.

By means of the derivatives of the adjusted biological growth model, it was possible to determine the increments: Current annual (CAI) and mean annual increment (MAI) in volume. Therefore, the curves of increments in volume for the site classes of higher and lower productive capacity, as well as for the estimated average production by the fitted models as a function of plantation ages are presented in Figure 6.

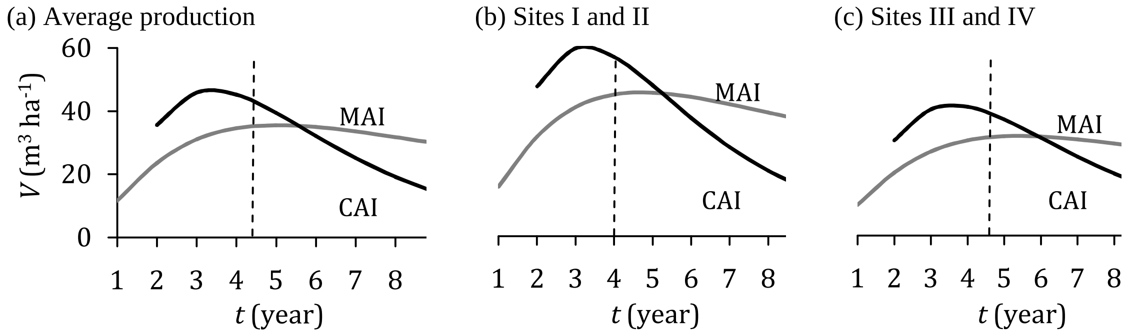

Fig. 6: Curves of mean annual (MAI) and current annual (CAI) increments in volume in *Eucalyptus* sp. stands in Maranhao State, tropical region of Brazil.

The rotation more commonly applied to homogeneous forest stands is that which maximizes the volume productivity per unit of time, using as a criterion the age at which the mean annual increment (MAI) is maximum and equal to the current annual increment (CAI). Therefore, due to its simplicity in the determination of the age of exploitation, the expected speed for the average production of *Eucalyptus* sp. in Maranhao State, Brazil would be around 5.5 years, while it would be to 5.2 years for the more productive sites and 6.0 years for the locations of less productive capacity.

Conclusion:

The fitting of the Chapman-Richards model for the productive capacity of forest sites and for the modeling of growth and yield enable to obtain consistent estimates of local productivity and volume production of *Eucalyptus* sp. in Maranhao State, in tropical region of Brazil.

The modeling of the productive capacity of the sites allows obtaining statistically efficient estimates for the delimitation of four classes, which make up the sites of greater (I and II) and lower (III and IV) productivity for the forest stands of *Eucalyptus* sp.

The shaping of growth and yield stratified by site groups provides adequate estimates with biological realism for volume, average annual and current annual increments, with definition of scenarios that aim to tailor the management practices for *Eucalyptus* sp. stands in tropical regions of Brazil.

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