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Original Article

Forest Management

Dynamics of Eucalyptus Diameter Distribution in the State of Minas Gerais

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ABSTRACT

The aim of this study was to evaluate the effects of age, site, and density factors on the dynamics of eucalyptus diameter distribution. Data were obtained from a continuous forest inventory measured at different occasions, stratified according to the factors evaluated and adjusted by the three-parameter Weibull function using nonthinned clonal plots of eucalyptus stands located in the Central region of the state of Minas Gerais. In order to evaluate the diameter distribution behavior, asymmetry and kurtosis measures and graphical analysis for fitted curves were used. In general, an increase was observed in diameter amplitudes with aging, as well as with improvement of site productivity and higher densities. The number of trees decreased in the lower classes and increased in the upper classes, resulting in diameter distribution curves, being displaced to the right and flattened with aging.

Keywords: probabilistic density function, site productive capacity, average basal area.

1. INTRODUCTION

The industrial sector demand for reforestation wood or commercial plantations of tree species has increased, with higher demands in terms of quality. In this scenario, exotic species of the genus *Eucalyptus* stand out as they constitute much of plantations in Brazil (IBÁ, 2015), especially when it comes to hybrids, which combine the best genetic characteristics of two distinct species. Thus, planning for the use of forest resources, especially related to silvicultural and management procedures is essential to meet regulations and demands of the consumer market.

Diameter distribution characterization is an important tool used to evaluate growth and yield, as well as to understand the dynamics and the potential use of forest plantations. In order to obtain this measurement, plant diameters should be grouped through direct measurements of trees into amplitude classes defined according to the stand characteristics. However, to evaluate growth and yield by diameter class, models that enable detailed yield estimates should be used (Qin & Cao, 2006), facilitating planning under certain situations and obtaining forest multi-products. These models are used to estimate variables of populations and their structure based on probability density functions (Gorgoso et al., 2012).

Probability density functions allow us obtaining the occurrence probability of trees per hectare and per diameter class at previously defined intervals (Scolforo, 2006). In the forest sector, several functions have been used to describe the diameter structure of forests, among which we can highlight the Weibull function, considered as mathematically simpler and more flexible (Bailey & Dell, 1973), and capable of describing a wide range of unimodal distributions (Lei, 2008). In addition, this function has the advantage of not needing numerical integration to calculate the probabilities or proportions of trees within diameter classes (Cao, 2004).

The diameter distribution of even-aged forest stands is characterized by a single modal value (Scolforo, 1998) with different asymmetry and kurtosis degrees, which vary depending on factors such as age, site and density. According to Machado et al. (2006), with the growth in diameter and reduction of the number of trees per hectare, the diameter distribution curves tend to displace to the right and become flatter, in which site is an influencing factor.

Thus, the diameter distribution behavior follows certain characteristics, and understanding them allows knowing the stand structure and stability, enabling the design of silvicultural treatments to control harvesting activities such as type of machinery used and how they work during wood cutting and transport, among other relevant information for decision-making regarding forest management (Gorgoso et al., 2012), especially when it comes to important species for the industrial timber sector such as those of the genus *Eucalyptus*.

In view of the above, the present study considered the hypothesis that the number of trees within larger diameter classes increases and those in smaller classes decrease as forest stands evolve in age, which in turn improves productivity and increases density, resulting in distribution curves displaced to the right and with progressive flattening degree, which become more and more similar as the population reaches maturity and the growth rate decreases.

The aim of this study was to evaluate the diameter structure behavior of clonal eucalyptus stands at different ages, sites, and density classes. Thus, we sought to obtain relevant information to assist the management of forest plantations over the crop rotation.

2. MATERIAL AND METHODS

2.1. Data description

In order to carry out this study, data from nonthinned stands with 20 genotypes (eucalyptus clones) planted in 3 m x 3 m and 3.3 m x 3 m spacing were collected in the Central region of the state of Minas Gerais.

According to Köppen classification, the predominant climate of the region is Cwa, characterized as subtropical dry winter (temperatures below 18°C) and hot summers (temperatures above 22°C), precipitation between 1,300 and 1,600 mm.year^{-1} and altitude between 600 and 1,000 m (Sá et al., 2012; Alvares et al., 2013). Regarding soil type classification, there is a predominance of Latosols and Argisols, both varying from red to yellow-red, and Cambisols (IBGE, 2007).

Data came from 43 permanent plots with area varying between 227.7 and 366.3 m^2, whose measurements were carried out between 2006 and 2012 at ages of 3-8 years.

Diameters were annually measured at 1.30 m of tree height (DBH), along with the total heights (H) of ten trees and heights of dominant trees in each plot. From the total number of sample units, 12 (27.9%) were consecutively measured on six occasions, 21 (48.8%) on five occasions, and 10 (23.3%) on four occasions.

The productive capacity was defined by site indexes established according to the guide curve method for an index age of 5 years using the non-linear Schumacher model (Equation 1), which presented determination coefficient of 0.8347 and relative standard error of 9.74%.

$$Hd = 41.35701 * e^{\frac{27.24102}{t}} \quad (1)$$

Where: Hd = dominant height (m); e = Euler's constant and t = age in months.

Therefore, stands were classified into three site classes, in which class I had site index of 33 m, class II of 27 m, and class III of 21 m. Most measured plots (62.8%) were classified into intermediate productivity class (Class II), while the other plots were classified into site classes I (14%) and III (23.2%).

For density, stands were classified into three classes according to the basal area variable, which indicates the degree of ground occupation by tree stems at height of 1.3 m (Machado & Figueiredo, 2014), and therefore, consists of an appropriate vegetation density indicator. The basal area of the stand ranged from 10.43 to 37.81 $m^2.ha^{-1}$, and the amplitude of these values was used to determine density classes, which were represented by means of the lower and upper limits of each class. Thus, class I presented mean basal area of 33.25 $m^2. ha^{-1}$, class II of 24.12 $m^2. ha^{-1}$ and class III of 14.99 $m^2.ha^{-1}$.

Some descriptive statistics were calculated to assist in the evaluation of the stand's diameter structure. This information was generated for total data and stratified by age, site, and density, evaluating variable diameter at breast height. Moreover, the distribution of trees into diameter classes was also evaluated based on relative frequencies from absolute frequencies observed for each plot and age.

2.2. Fit probabilistic density function

To describe the dynamics and obtain smoother diameter distribution curves, and considering that histograms could present class irregularities, the Weibull probabilistic density function was fitted, being selected for this purpose due to its simplicity and flexibility.

Data were stratified by age, site, and density for fitting the function, and grouped into regular intervals of 2 cm, as recommended by Araújo et al. (2010) for clonal eucalyptus stands. The three-parameter Weibull function was the functional form selected for fits (Equation 2):

$$f(x) = \left(\frac{c}{b}\right)\left(\frac{x-\alpha}{b}\right)^{c-1} e\left[-\left(\frac{x-\alpha}{b}\right)^{c}\right]; x \geq 0; b, c > 0 \quad (2)$$

Where: a, b and c correspond to the location, scale, and shape distribution parameters, respectively.

Non-linear regression by non-linear least squares method with multiple iterations was the selected fit method, according to procedure of Marquardt (1963) and using Table Curve 2d trial version 5.01 software (SSI, 2016), which used the Weibull function in its distribution form and estimated the absolute frequencies in each class using grouped data and initial parameters, as recommended in literature. The probability of occurrence of the number of trees in each class was determined through these frequencies.

2.3. Analysis of age, site, and density factors

After fitting for stratified data, frequency tables by diameter class were constructed and the estimated diameter distribution curves were plotted for different ages, sites, and density classes. These curves were used to evaluate the influence of factors on the diameter distribution behavior over the years.

2.4. Asymmetry and kurtosis

Asymmetry and kurtosis measurements were used to describe the forms and the evolution of observed curves. The degree of symmetry deviation or spacing was evaluated using the Pearson asymmetry coefficient (Equation 3) (Crespo, 2002):

$$A_s = \frac{3(\bar{x} - M_d)}{S} \quad (3)$$

Where: $\bar{x}$ = arithmetic mean; M_d = median and s = standard deviation.

The distribution presented null asymmetry or symmetrical distribution when $A_s = 0$, negative or left asymmetry when $A_s < 0$, and positive or right asymmetry when $A_s > 0$. Asymmetry is considered moderate if $0.15 < |A_s| \leq 1$, and strong if $|A_s| > 1$.

Regarding kurtosis, the flattening coefficient or degree was found according to the relationship between the 10th and 90th percentiles and the quartile deviation, as calculated using Equation 4:

$$C = \frac{Q_3 - Q_1}{2(P_{90} - P_{10})} \quad (4)$$

Where: Q_3 = third quartile; Q_1 = first quartile; P_{90} = 90th percentile and P_{10} = 10th percentile.

The curve was mesokurtic or referential base when K = 0.263; leptokurtic when K < 0.263; and platykurtic when K > 0.263.

3. RESULTS AND DISCUSSION

3.1. Data characterization

Table 1 presents the descriptive statistics and the calculated asymmetry and kurtosis indexes for stratified data, first by age, then by age and site classes, and then

Table 1. Descriptive statistics for stratified data by age, site, and density.

Age (years)	Site Class	Density class	Number of plots	Average number of trees/plot	D_{mean}	D_{min}	D_{max}	s^2	s	A_s	K
3			15	28	13.8	6.4	17.8	2.704	1.644	-0.282	0.211
4			35	29	15.7	6.2	20.7	4.647	2.156	-0.472	0.233
5			43	28	16.8	5.2	22.7	6.149	2.480	-0.334	0.243
6			43	28	17.8	5.3	24.6	7.870	2.805	-0.357	0.256
7			42	28	18.5	5.4	26.3	9.274	3.045	-0.35	0.229
8			39	27	19.2	5.5	27.3	10.184	3.191	-0.268	0.25
3	I		2	28	14.7	8.2	17.8	3.904	1.976	-0.417	0.248
4	I		5	31	16.0	6.5	20.7	6.338	2.518	-0.488	0.266
5	I		6	30	17.3	6.5	22.7	7.989	2.826	-0.711	0.244
6	I		6	30	18.3	7.2	24.6	10.146	3.185	-0.543	0.244
7	I		6	29	19.2	7.8	26.3	12.011	3.466	-0.473	0.252
8	I		2	26	20.9	15	25.3	6.049	2.460	-0.525	0.236
3	II		9	29	13.8	6.4	17.0	2.003	1.415	-0.398	0.199
4	II		21	29	15.9	6.4	20.5	4.107	2.027	-0.444	0.22
5	II		27	28	17.0	5.2	22.4	5.763	2.401	-0.323	0.241
6	II		27	28	18.0	5.3	24.5	7.559	2.749	-0.404	0.237
7	II		27	28	18.8	5.4	26.2	8.975	2.996	-0.418	0.219
8	II		27	28	19.5	5.5	27.3	10.898	3.301	-0.384	0.242
3	III		4	27	13.5	7.4	17.0	3.311	1.820	-0.465	0.262
4	III		9	28	14.9	7.1	18.4	4.035	2.009	-0.465	0.263
5	III		10	27	15.9	7.4	20.5	4.895	2.212	-0.427	0.266
6	III		10	27	16.7	7.4	21.9	5.726	2.393	-0.403	0.266
7	III		9	27	17.3	8.8	23.7	6.272	2.504	-0.337	0.255
8	III		10	27	18.2	8.9	25.2	7.178	2.679	-0.277	0.265
5		I	3	33	17.8	7.9	22.7	5.786	2.405	-0.287	0.256
6		I	11	32	18.3	7.2	24.6	9.305	3.050	-0.458	0.234
7		I	17	31	19.1	7.8	26.3	10.364	3.219	-0.412	0.254
8		I	21	29	19.8	7.1	27.3	10.455	3.233	-0.406	0.247
4		II	21	31	15.9	6.4	20.7	4.522	2.126	-0.372	0.241
5		II	32	28	17.0	5.2	22.4	5.825	2.413	-0.363	0.244
6		II	28	27	17.7	5.3	23.9	6.874	2.622	-0.412	0.252
7		II	23	26	18.2	5.4	26.0	7.842	2.800	-0.288	0.233
8		II	18	25	18.5	5.5	26.8	8.882	2.980	-0.228	0.245
3		III	15	28	13.8	6.4	17.8	2.704	1.644	-0.282	0.211
4		III	14	26	15.2	6.2	20.5	4.509	2.123	-0.461	0.239
5		III	8	25	15.5	7.4	20.5	5.583	2.363	-0.461	0.261
6		III	4	24	16.1	8.8	22.2	6.692	2.587	-0.145	0.293
7		III	2	23	16.7	10.8	24.0	8.181	2.860	0.255	0.283

Where: D_{mean} = mean diameter (cm); D_{min} = minimum diameter (cm); D_{max} = maximum diameter (cm); s^2 = variance (cm^2); s = standard deviation (cm); A_s = asymmetry and K = kurtosis.

by age and density classes. It was observed that the majority of asymmetry index values were negative and the kurtosis values were lower than 0.263, which classified the diameter distribution curves as leptokurtic.

Regarding the concentration of trees into diameter classes, the results showed that the highest concentration of trees corresponded to class with central value of 18 cm (26.67%). It was also observed that the central distribution classes (ranging from 13 to 21 cm) concentrate 81.1% of trees, which is a common fact in planted forests, since most tress are formed by a single species and whose diameter distribution approaches normality, as verified by Lima & Leão (2013) for *Hevea brasiliensis* (*Seringueira*) data.

3.2. Age factor

An increase in the total diameter amplitude with advancing age was observed. The number of trees in smaller classes decreased, while the number in larger classes increased, resulting in the displacement of curves to the right. According to the asymmetry coefficients presented in Table 1, the diameter distribution was classified as negative or left asymmetry for all ages, with moderate asymmetry degree (coefficient between 0.15 and 1). These coefficients showed reduction from 3 to 4 years of age, followed by an increase in values and stabilization tendency.

Regarding kurtosis, all coefficients were lower than 0.263, classifying curves as leptokurtic. The values of these coefficients increased up to 6 years and reduced for the other ages, with stabilization tendency. For ages between 6 and 8 years, the kurtosis coefficients were close to 0.263, indicating that the curves approached normal distribution.

Figure 1 shows the evolution of diameter distribution curves as a function of age. It was observed that the curves did not show symmetry, and they became flatter with age advancement. These effects were also observed by Téo et al. (2011) using data from *Pinus taeda* stands. The authors found flattening of diameter distribution curves over the years and negative asymmetry for all ages, with the exception of age between 8 and 8.9 years.

The shift of curves to the right with increasing age observed in the present study is consistent with Sanquetta et al. (2014), who verified increase of negative asymmetry in the diameter distribution dynamics of *Acacia mearnsii* stands in Rio Grande do Sul - Brazil. Regarding kurtosis, the authors found leptokurtic curves for all ages. Unlike these results, Moraes et al. (2014) found that the diameter distribution was symmetrical and platykurtic when evaluating clonal eucalyptus in two tree component arrangements and ages of 2.5 and 4.5 years.

As for the diameter distribution curve characteristics, Figure 1 shows that the displacement and flattening of curves tended to present greater similarity as stands aged. This was due to the diameter growth stagnation when the forest reached maturity. Such stagnation can be understood as the harvesting moment, thereby finalizing rotation or also as the moment of management intervention to reduce the forest density by thinning to enable the remaining trees to accelerate their growth in diameter (Batista et al., 2014). These considerations lead us to emphasize that the knowledge and identification of diameter growth stagnation influence important decision making regarding forest management.

3.3. Site factor

For Site Class I – 33 m, Figure 2A and the asymmetry and kurtosis coefficients found in Table 1 allowed us characterizing the diameter distribution curves as being negative or left asymmetry with moderate asymmetry and leptokurtic degree, except for the age of 4 years, which is classified as platykurtic. The flattening degree of curves in this Site Class was similar for all ages. The values of asymmetry coefficients showed reduction up to 5 years of age, followed by an increase in values and stabilization tendency. The kurtosis coefficients ranged from 0.236 to 0.266, and were close to 0.263 at the age of 4 years, which indicated that diameters approached normal distribution.

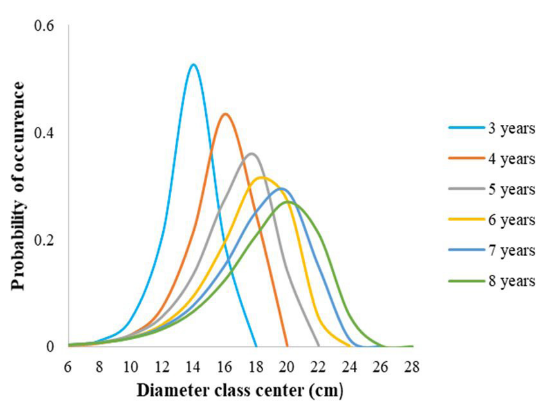

Figure 1. Evolution of diameter distribution curves fitted by the three-parameter Weibull function as a function of age and at ages between 3 and 8 years.

Diameter distribution curves fitted for Site Class II - 27 m were classified as negative or of left asymmetry, with asymmetry degree between 0.15 and 1, considered moderate and leptokurtic with increased kurtosis coefficient values with advancing age, except for 6 and 7 years. The asymmetry coefficients presented similar values at all evaluated ages. Figure 2B shows the displacement of curves to the right and greater flattening degree as stands aged.

For Site Class III - 21 m, the diameter distribution curves also presented negative or left asymmetry and moderate degree (Figure 2C). The coefficients found showed an increasing tendency with advancing ages. Regarding flattening, curves for ages 3 and 7 years were classified as leptokurtic; for four years as mesokurtic; and for ages of 5, 6 and 8 years as platykurtic. The kurtosis coefficient values were very similar for all ages, ranging from 0.255 to 0.266, which indicated that the curves showed diameter distribution very close to normal distribution.

Therefore, the diameter distribution curves for all site classes and ages were of negative asymmetry and of moderate degree, with greater displacement to the right as stands aged and increased the productive capacity of the site. Regarding kurtosis, Site Class II more evidently presented flattening of curves with advancing age. Class I (the most productive site) and Class III (the least productive site) showed more similar curves among ages, with lower evolution in the flattening degree over time.

These results support the hypothesis that tree diameter growth is higher at more productive sites, and are in accordance with observations made by Scolforo & Thiersch (1998). Analyzing *Eucalyptus camaldulensis* data, the authors observed a marked increase in diameter at older ages and more productive sites, which gave rise to more pronounced asymmetries in these cases. Forest development dynamics are slow in less productive and younger sites, which provided distribution forms similar to normal distribution.

Figure 2 also shows an increase in the total amplitude of diameters as a function of age. The number of trees in the lower classes decreased, while those in the upper classes increased, which resulted in displacement of curves to the right. Comparing curves at the same age among the different site classes, it was observed that the diameter amplitude was higher in the most productive site in relation to the others, except for the age of 8 years, which did not present diameters in classes below 13 cm. However, the number of trees in larger classes was higher at this site and age.

This behavior for higher ages can be justified by the onset or increase in competition among trees, which induces mortality in even-aged stands. Places with better productive capacity present lower initial mortality. However, from the moment in which competition begins, mortality will be more intense in more productive sites considering forest density, since trees grow faster in these environments.

Increase in modal diameter was observed with advancing age for all site classes. When comparing the values of this variable among different sites and considering the same age, more productive sites have larger modal diameters.

In general, more productive sites present greater amplitude between the smallest and largest diameter class, which translates into a more intense growth rate of trees. In addition, higher concentration of trees in the lower classes in the less productive site was observed (class III - 21 m) compared to the more productive site

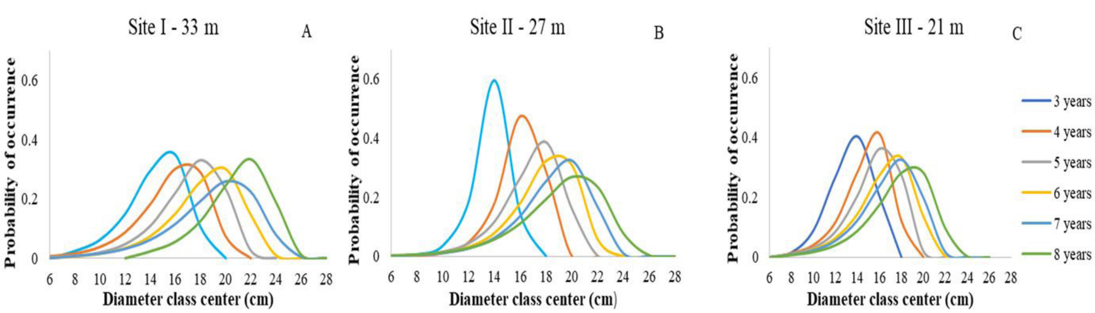

Figure 2. Evolution of diameter distribution curves fitted by the three-parameter Weibull function for Site I – 33 m (A), Site II – 27 m (B) and Site III – 21 m (C) plots at ages between 3 and 8 years.

(class I - 33 m), which presented the highest number of trees in largest diameter classes. These behaviors were also verified by Bartoszeck et al. (2004) for *Mimosa scabrella* Bentham data, at ages ranging from 3.9 to 7.6 years and site indexes of 10.2, 13.5, and 16.8 m at the reference age of 7 years.

3.4. Density factor

Diameter distribution curves were not fitted for all ages. This occurred due to the absence of representative plots for density class I (mean baseline area of 33.25 $m^2.ha^{-1}$) for ages of 3 and 4 years, as well as for density class III (mean baseline area 14.99 $m^2.ha^{-1}$) at 8 years, while class II (mean baseline area 24.12 $m^2.ha^{-1}$) did not present representative plots at the age of 3 years. This behavior was expected, since the possibility of plots with larger mean basal area occurring for lower ages was minimal, as well as for higher ages, for the occurrence of smaller mean basal area plots.

In evaluating the behavior of diameter distribution curves in density class I (33.25 $m^2.ha^{-1}$) based on Figure 3A and asymmetry and kurtosis coefficients found in Table 1, it was possible to characterize them as negative or left asymmetry with moderate asymmetry degree, presenting proximity in coefficient values for ages from 6 to 8 years. Curves were also classified as leptokurtic, with an increasing flattening degree as stands aged. The kurtosis coefficients ranged from 0.234 to 0.256; close to value of 0.263, which characterizes normal distribution.

For density class II - 24.12 $m^2.ha^{-1}$, the diameter distribution curves presented moderate asymmetry, and regarding kurtosis, they were classified as leptokurtic. Asymmetry coefficients tended to reduce up to 6 years and then, values increased for the other ages. On the other hand, kurtosis coefficients were similar to each other, ranging from 0.233 to 0.252, with a more pronounced increase in values at ages from 4 to 6 years. Class III density (14.99 $m^2.ha^{-1}$) presented asymmetric negative curves for ages of 3 to 6 years, and asymmetric positive curves for age of 7 years, in which coefficients tended to decrease up to 5 years, increasing after this age.

Regarding flattening, curves were leptokurtic for ages of 3 to 5 years, with increasing values for coefficients as stands aged until the age of 6 years. The kurtosis coefficient found for 5 years (0.261) was very similar to that characterizing normal distribution (0.263). For ages of 6 and 7 years, curves were classified as platykurtic.

Therefore, the diameter distribution curves presented negative asymmetry for all density classes and ages studied, with the exception of Class III at the age of 7 years, which was characterized as a positive asymmetric curve. The asymmetry degree was moderate in all cases, with curves displacing to the right as stands became older. In relation to kurtosis, curves were classified as leptokurtic, except for the ages of 6 and 7 years in class III. An increase in the flattening degree with advancing age was observed for all density classes.

In addition, the modal diameter and overall diameter amplitude increased with aging. The number of trees tended to decrease in the lower classes and to increase in the upper classes, resulting in curves displaced to the right. Comparing curves at the same age among the different density classes, it was verified that the diameter amplitude is higher in class with mean basal area of 33.2498 $m^2.ha^{-1}$. Regarding modal diameter, classes I and II presented higher values in relation to class III.

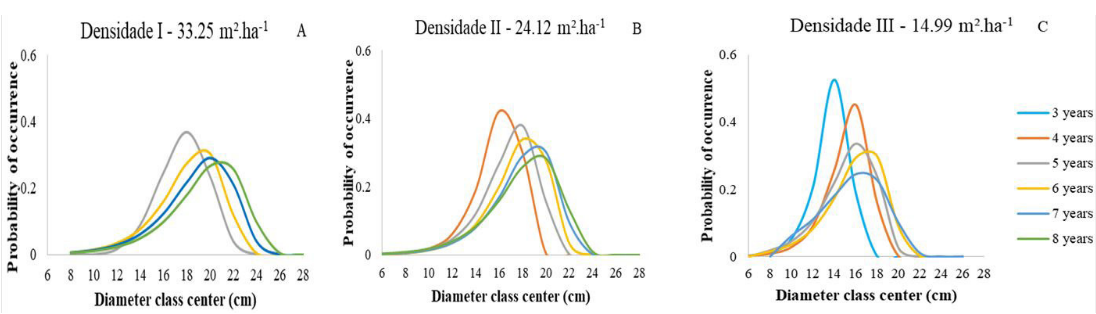

Figure 3. Evolution of diameter distribution curves fitted by the three-parameter Weibull function for Density I – 33.25 $m^2.ha^{-1}$ (A), Density II – 24.12 $m^2.ha^{-1}$ (B) and Density III – 14.99 $m^2.ha^{-1}$ (C) plots at ages between 3 and 8 years.

Figure 3 also shows that the diameter distribution curves for density class III (lower mean basal area per hectare) presented more evident increase in the flattening degree with age advancement compared to higher density classes. It is known that the higher the basal area per hectare, the less vital growth space is, and consequently the lower the increment. Thus, the level of competition among trees in lower density sites is lower, allowing greater increases in diameter, especially in dominant individuals which intensifies the change of trees for successive diameter classes.

Analyzing data from unmanaged *Ocotea porosa* (Nees & Mart.) Barroso stands, Santos et al. (2015) found negative effect of competition on tree growth. These authors reported that the increment decreases with increasing competition and with higher basal area per hectare. This effect was also observed by Silveira et al. (2015), who observed the existence of association between competition and increase in *Trichilia claussenii* C. DC. diameter, concluding that the greater the competition, the lower the tree growth.

The presence of trees with diameter class of 6 and 8 cm was not observed in density class III. This behavior can be justified by the change of trees to successive diameter classes, or by the mortality of individuals. According to Naves et al. (2015), the competition for resources and mortality are higher in smaller diameter classes. Demolinari et al. (2007) verified this relationship based on data of unthinned *Eucalyptus urophylla* x *Eucalyptus grandis* Hybrids.

4. CONCLUSIONS

The behavior of diameter distribution curves of clonal eucalyptus stands of the Central region of Minas Gerais for different ages, sites, and density classes are in accordance with the expected biological development.

In general, an increase in diameter amplitude is observed with advancing age, with improved site productivity and increased density. The number of trees decreases in lower diameter classes and increases in upper classes, shifting curves to the right and increasing the flattening degree with increasing age.

In addition, the diameter distribution curves become increasingly similar as the stand advances in age. This fact is corroborated by the asymmetry and kurtosis indexes found, which tend to stabilize at ages between 6 and 7 years, when stands reach maturity and the growth rate decreases, especially for asymmetry coefficients for more productive and higher density classes.

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