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Dynamics of initial spacing on the diameter of hybrid *Eucalyptus grandis* x *Eucalyptus urophylla* in a systematic design

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Abstract

We evaluated the effect of initial spacing on the distribution of *Eucalyptus grandis* x *Eucalyptus urophylla* tree diameters in a Nelder wheel design. The study area was in west-central Brazil. A Nelder wheel design with three repetitions was used. This design provides 432 planting spots per plot/repetition. Planting density varied from 0.50 m² to 41.25 m². The diameter at breast height was measured for all plants every four months until 36 months of age, totaling eight measurements. The description of the diameter distribution was developed by fitting probability density functions for each spacing and age. The quality of fit was evaluated using the root mean square error percentage, Pearson's correlation coefficient, and the Kolmogorov-Smirnov test ($\alpha < 0.05$). The spacings up to 1.17 m² must be harvested in less than two years, since it is noted that in the third year the increment in diameter is static and the mortality rate increases. The spacing highly affects the diameter structure of the population, impelling the forester to consider different uses for the wood. For wood requiring larger diameters, spacing above 8.69 m² per tree is recommended.

Keywords: Nelder wheel design; Probability Density Function; Spacing experiments and growth; Weibull.
Abbreviations: DBH_diameter at breast height; PDF_probability density functions; S²_variance (cm²); Spa_spacing; N_number of individuals; Nº class_number of diameter classes.

Introduction

Forestry is defined as the art of producing and maintaining a forest (Hawley and Smith, 1962) in order to develop plantation techniques and tree populations conducive to reaching social, economic, and environmental goals. Promoting research on the best forestry practices is necessary in understanding the conditional factors of growth and forestry production, especially in respect of spacing (Balloni and Simões, 1980).

Tree spacing influences the area that the plant has to obtain its resources, affecting its dimension and growth rate (Assmann, 1970; Smith, 1986), as well as the population structure as a whole. Studies on different spacings demand investments in large areas of land and resources for settlement, maintenance, and monitoring. As an alternative, Nelder (1962) developed systematic designs, the most familiar being the Nelder wheel design. This design consists of a system of concentric radii in which the ratio between the inter- and intra-lines (rectangularity) is constant. Aquino (2017) highlights that the main advantage is that it facilitates the evaluation of a large number of possible spacings (including extreme treatments) in smaller experimental areas, reducing the demand on resources and services, which facilitates trial management. Therefore, recent studies have been using this type of design to evaluate different spacings (Santos, 2011; Moraes et al., 2013; Vanclay et al., 2013; Aquino, 2017).

According to Husch et al. (1982), the structure of a forest may be described by the distribution of the plants in each diameter class, which is dynamic, due to plant growth, mortality, or thinning (selection and mechanical). Understanding the diameter distribution of planting is important since it is the initial step in the evaluation of current and future stock and production (Campos and Leite, 2017).

To describe diameter distribution in a forest, systematic monitoring of the forest through permanent sample plots is necessary. After that, individual trees are grouped by diameter class, within the amplitude of known classes, to obtain diameter frequency histograms and enable the fitting of probability density functions (PDFs). The PDFs are mathematical functions that describe the probability of occurrence of the studied variable in a continuous distribution (Campos and Leite, 2017). The rate of occurrence of this variable is given by the integral of the function. Concerning diameter distributions, the PDFs estimate the probability of occurrence of individual trees in a diameter class interval, describing the minimum and maximum limits (Scolforo, 2006).

The most popular PDF's for *Eucalyptus* spp. in Brazil are Weibull (Miguel et al., 2010; Retslaff et al., 2012; Schmidt, 2019), Johnson's SB (Silva et al., 2009), Dagum (Jesus et al., 2017), and Gamma (Araújo Júnior et al., 2013). Even though the Weibull function is the most popular, it is necessary to test different PDFs, since other PDF's may provide a more satisfactory fit and performance of the function may vary depending on the species, site, age, and spacing (Bartoszeck, 2000).

The current study therefore highlights the necessity of research on the spacing and age on diameter distribution of *Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden forests, as well as the use of mathematic tools that describe the structure in a precise and consistent form. The aim of this study was to evaluate the initial effect of spacing on the diameter distribution of *E. urophylla* x *E. grandis* in a Nelder wheel design. It was hypothesized that: i) Different spacings would affect the diameter structure in eucalyptus plantings over time; ii) Density probability functions would describe diameter structure in a distinct way for different spacings at different ages.

Results

Descriptive statistics

Table 1 describes the descriptive statistics stratified for diameter at breast height (DBH) per spacing from 8 to 36 months. The diameters varied from 0.5 to 17 cm, the number of classes was between 3 and 12, and the quantity of specimens measured per spacing and age combination between 73 and 108. It is noted that from the 16th month, the mean DBH was higher at greater spacings than for denser spacings.

This study demonstrated a growth in diameter, number of classes, and total amplitude of the data in all spacings and ages. Regarding the diameter growth, the growth rate was higher at greater spacings (particularly at 19 m², 28.91 m² and 41.25 m²), with mean DBH growth rate between the first and last measurement of 540.9%, 513.9%, and 475%, respectively. Lower growth rates were found at spacings of 0.5 m², 0.77 m² and 1.17 m², with a growth rate of 120.83%, 150%, and 175.86%, respectively.

The spacings with the higher class numbers in the 36th month were 1.17 m² to 3.94 m², and the class number varied from 10 to 12. The intermediate spacings (5.86 m², 8.69 m², and 12.86 m²) presented a lower amplitude of class by the 36th month, when compared to the extremes (thicker and larger), resulting in a lower standard deviation.

In regards to the variation in individual tree number given by the mortality rate, the denser spacings (0.50 m², 0.77 m², and 1.17 m²) presented a higher mortality rate, totaling 32 (30.47%), 14 (13.33%), and 9 (8.41%) specimens, respectively. The spacings of 2.64 m² and 19 m² presented a mortality of only one specimen and the others spacings all survived. Silva (1990) also associated denser spacings with a higher mortality rate.

Fitting the probability density functions

Of the 480 analyses, 425 were not described by the K-S test at a 95% probability rate. The K-S test represented 88.54% of the models and four analyses were not fitted by the Johnson SB PDF.

The Weibull 3p PDF was the only function in which all fits were not represented by the K-S test, followed by the Dagum function (89.69%), Normal (88.65%), Johnson SB (87.5%), and Gama function (77.08%). The fits that were represented occurred in the first year of measurement between the ages of 8 and 12 months.

A better function for each treatment (with a lower score for the eight ages) was obtained using the Johnson's SB function for a spacing of 12.86 m², Dagum for spacings of 5.69 m² and 28.01 m², and the Weibull 3p function for the other spacings.

Table 2 describes the PDF selected and its respective statistical precision and K-S test. For spacings of 0.50 m², 0.77 m², and 1.17 m², the precision of the fit decreased with increasing specimen age. No alteration in the precision of the fit among ages for each planting density was observed in the other spacings.

Analysis of the diameter distribution

The curves of the diameter distribution estimated by the functions with a better performance for each spacing of the *E. urophylla* x *E. grandis* populations from 8 to 36 months are shown in Figs 1 and 2.

In all spacings, we observed an increase in the number of diameter classes in accordance with the age of the population, resulting in the "spread" of the curves of diameter distribution and the displacement of the curves to the right, which indicates growth of all specimens in the experimental design. However, a quicker displacement of the curves for 19 m², 28.01 m², and 41.25 m² spacings occurred, representing a higher growth rate at these less crowded spacings.

It was expected that the theoretical curves of diameter distribution would reduce their maximum probability (DBH class with a higher number of plants) when increasing the age at each spacing, since the number of class increases reduced the number of specimens found in the modal class. Until 36 months, the denser spacings of 0.50 m², 0.77 m², and 1.17 m² confirmed the hypothesis of a "flattening" of the curves.

Another point regarding the stagnation effect was that the changes in class given by the growth of specimens decreased with each measurement. However, this event was more prevalent in the lower classes (smaller DBH), than the higher classes or higher DBH.

Discussion

The highest mean DBH was found in spacings with a larger area per plant. The same result was found in studies by Reiner et al. (2011) and Elerati (2017) who compared eucalyptus plantings at different spacings.

Diameter growth was observed for all spacings, thereby indicating that the spacings were not completely stocked.

Table 1. Descriptive statistics of *Eucalyptus urophylla* x *E. grandis* stratified by spacing and age.

Age (months)	Spc.m^{-2}	DBH min	DBH mean	DBH max	S²	Nº class	N	Age (months)	Esp.m^{-2}	DBH min	DBH mean	DBH max	S²	Nº class	N
8	0.50	0.5	2.4	3.3	0.21	4	105	24	0.50	1.5	4.3	8.1	1.70	8	98
	0.77	1.0	2.8	3.5	0.22	3	105		0.77	1.3	5.6	8.4	1.85	8	103
	1.17	0.5	2.9	3.9	0.36	4	107		1.17	1.1	6.3	8.4	2.31	8	107
	1.76	0.5	3.0	3.9	0.35	4	107		1.76	1.9	7.5	9.5	1.33	9	107
	2.64	1.0	2.9	4.0	0.48	3	107		2.64	4.0	8.4	10.1	0.93	7	106
	3.94	0.5	2.7	3.9	0.4	4	106		3.94	2.5	8.9	10.4	1.65	9	106
	5.86	0.5	2.7	3.8	0.36	4	105		5.86	6.0	9.6	11.7	1.20	6	105
	8.69	0.5	2.5	3.7	0.44	4	108		8.69	5.3	9.9	11.9	1.41	7	108
	12.86	0.5	2.3	3.6	0.39	4	107		12.86	7.9	10.2	12.3	0.78	6	107
	19.00	0.5	2.4	3.5	0.40	4	106		19.00	6.0	10.3	12.5	0.96	7	105
	28.01	0.5	2.3	3.9	0.40	4	106		28.01	5.9	10.1	13.0	1.60	9	106
	41.25	0.5	2.2	3.2	0.34	4	104		41.25	5.2	9.9	12.0	1.70	8	104
12	0.50	0.5	3.0	4.3	0.30	5	104	28	0.50	1.5	4.7	9.8	2.49	9	96
	0.77	1.0	3.5	4.3	0.25	4	105		0.77	2.5	6.2	10.1	2.96	9	102
	1.17	0.5	3.8	5.1	0.46	6	107		1.17	1.6	7.1	9.7	3.44	9	106
	1.76	1.2	4.1	5.3	0.41	5	107		1.76	1.9	8.6	11.1	1.91	11	107
	2.64	2.0	4.2	5.1	0.39	4	107		2.64	4.2	9.5	12.3	1.78	9	106
	3.94	0.5	4.1	5.8	0.58	6	106		3.94	2.6	10.2	12.6	2.58	11	106
	5.86	1.0	4.1	5.9	0.82	5	105		5.86	7.3	11	13.8	1.41	7	105
	8.69	0.5	4.0	5.3	0.66	6	108		8.69	6.5	11.4	13.5	1.45	8	108
	12.86	1.3	4.0	5.7	0.59	5	107		12.86	8.9	11.9	13.7	0.99	6	107
	19.00	1.4	4.1	5.6	0.73	5	105		19.00	7.6	12.4	14.7	1.23	8	105
	28.01	0.5	3.9	5.4	0.84	6	106		28.01	7.6	12.4	15.6	1.78	9	106
	41.25	0.5	3.8	5.9	0.73	6	104		41.25	7.6	12.3	15.3	2.44	9	104
16	0.50	1.5	3.9	6.2	0.95	6	103	32	0.50	1.7	5.1	10.3	2.42	10	75
	0.77	1.3	4.7	6.4	0.78	6	105		0.77	3.2	6.7	10.3	2.63	8	91
	1.17	1.0	5.3	7.0	1.23	7	107		1.17	1.6	7.4	10.3	3.31	10	101
	1.76	1.7	6.1	7.9	0.72	7	107		1.76	1.9	8.9	11.2	2.44	11	107
	2.64	3.7	6.6	7.9	0.53	5	107		2.64	4.3	9.9	12.3	1.66	9	106
	3.94	1.6	6.8	8.4	1.11	8	106		3.94	2.7	10.5	12.7	2.44	11	106
	5.86	4.0	7.1	8.4	0.84	5	105		5.86	7.4	11.4	13.8	1.60	7	105
	8.69	3.4	7.1	9.0	1.04	7	108		8.69	7.0	11.8	14.2	1.59	9	108
	12.86	4.2	7.3	8.9	0.69	5	107		12.86	9.3	12.3	14.2	0.94	6	107
	19.00	3.4	7.4	9.7	0.85	7	105		19.00	8.5	13	15.3	1.23	8	105
	28.01	3.0	7.2	9.2	1.41	7	106		28.01	8.6	13.2	16.4	1.88	9	106
	41.25	3.0	7.0	9.0	1.28	7	104		41.25	8.2	13.2	16.0	2.14	9	104
20	0.50	1.5	4.0	7.7	1.32	7	103	36	0.50	2.2	5.3	10.8	2.79	9	73
	0.77	1.3	5.2	7.4	1.44	7	105		0.77	3.2	7.0	10.8	3.34	8	91
	1.17	1.0	5.8	7.8	1.84	7	105		1.17	2.7	8.0	11.0	3.10	10	98
	1.76	1.9	6.9	8.9	1.07	8	107		1.76	1.9	9.3	12.3	2.83	12	107
	2.64	3.8	7.6	9.1	0.77	7	107		2.64	4.4	10.4	13.2	1.80	10	106
	3.94	2.0	8.1	9.6	1.52	8	106		3.94	2.7	11.1	13.0	2.79	12	106
	5.86	5.0	8.6	10.0	1.02	7	105		5.86	8.1	11.9	13.8	1.42	6	105
	8.69	4.5	8.9	10.7	1.22	7	108		8.69	7.5	12.4	14.9	1.65	8	108
	12.86	6.3	9.1	10.9	0.72	5	107		12.86	9.8	13.1	15.4	0.94	7	107
	19.00	4.5	9.3	11.0	0.96	8	105		19.00	9.1	13.8	16.3	1.33	8	105
	28.01	5.0	9.1	11.4	1.54	7	106		28.01	9.6	14.1	17.0	1.59	8	106
	41.25	4.3	8.8	11.0	1.57	8	104		41.25	8.2	14.1	16.5	2.34	9	104

Note: DBH min: minimum diameter (cm); DBH mean: mean diameter (cm); DBH max: maximum diameter (cm); S²: variance (cm²); Spa: spacing; N: number of individuals; Nº class: number of diameter classes.

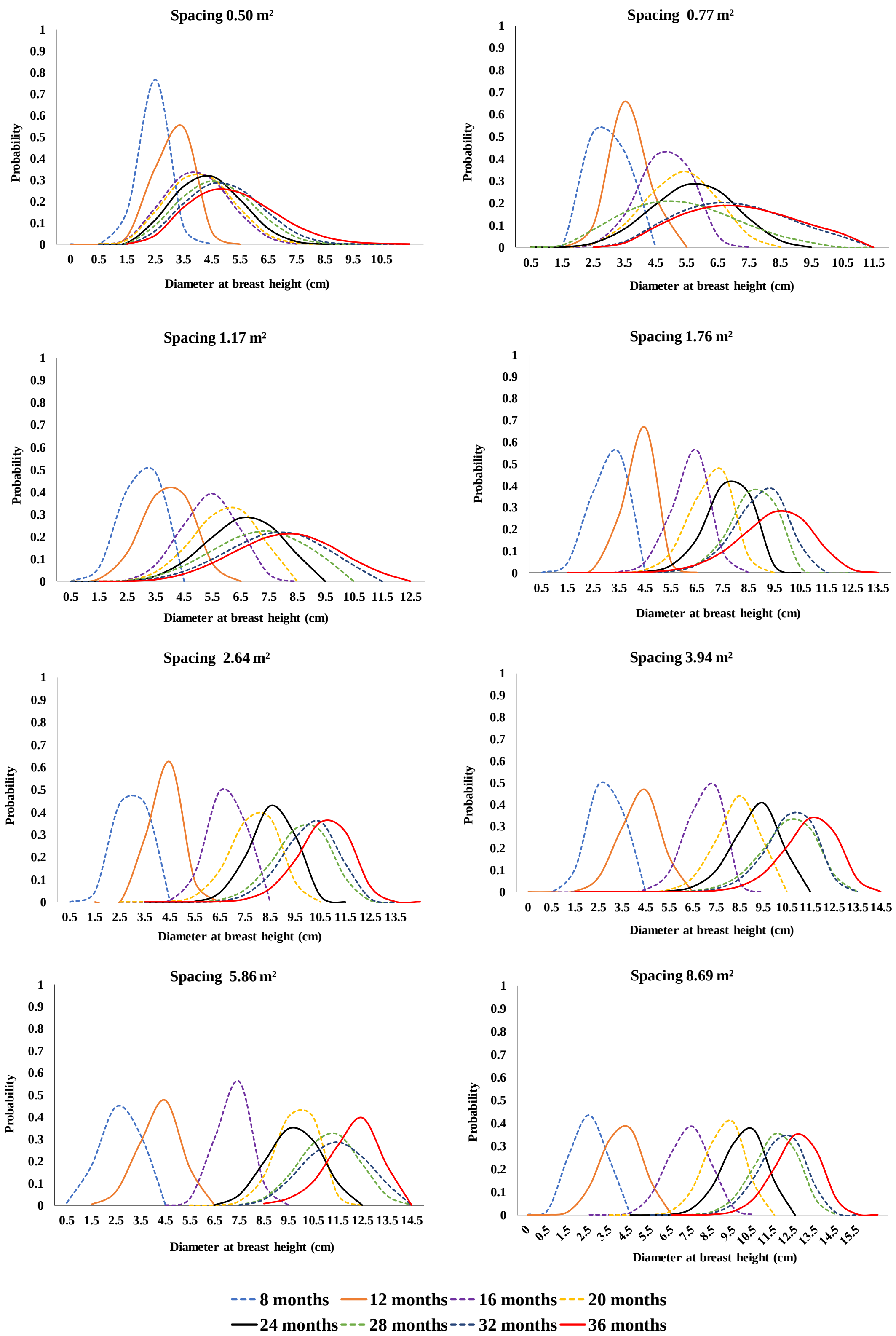

Fig 1. Dynamics of diameter distribution observed in spacings from 1.17 m^2 to 8.69 m^2 in *Eucalyptus urophylla* x *E. grandis* from 8 to 36 months of age. Annual diameter distribution (12th, 24^{th,} and 36th month) is presented as a continuous line and intermediate ages are shown by dotted lines.

Table 2. Parameters and statistical precision of Probability Density Functions selected for each spacing and age.

Spa./PDF	Ag	RMSE	$r_{\hat{y}_i y_i}$	dcal	Spa./PDF	Ag	RMSE	$r_{\hat{y}_i y_i}$	dcal	Spa./PDF	Ag	RMSE	$r_{\hat{y}_i y_i}$	dcal
0.50 m² Weibull 3p	8	5.76	0.99	0.039^{ns}	2.64 m² Weibull 3p	8	13.07	0.77	0.076^{ns}	12.86 m² SB Johnson	8	2.42	0.99	0.021^{ns}
	12	5.24	0.98	0.029^{ns}		12	7.97	0.96	0.056^{ns}		12	0.83	0.99	0.006^{ns}
	16	5.29	0.98	0.026^{ns}		16	6.05	0.98	0.038^{ns}		16	2.18	0.99	0.018^{ns}
	20	3.62	0.98	0.019^{ns}		20	15	0.95	0.097^{ns}		20	5.59	0.98	0.036^{ns}
	24	5.31	0.97	0.024^{ns}		24	9.98	0.94	0.077^{ns}		24	2.03	0.99	0.012^{ns}
	28	24.98	0.90	0.135^{ns}		28	7.21	0.98	0.037^{ns}		28	2.33	0.99	0.017^{ns}
	32	15.94	0.81	0.091^{ns}		32	23.76	0.86	0.048^{ns}		32	1.11	0.99	0.006^{ns}
	36	13.7	0.82	0.097^{ns}		36	23.76	0.86	0.043^{ns}		36	3.82	0.99	0.006^{ns}
0.77 m² Weibull 3p	8	5.76	0.99	0.39^{ns}	3.94 m² Weibull 3p	8	7.65	0.96	0.043^{ns}	19.00 m² Weibull 3p	8	7.39	0.95	0.057^{ns}
	12	9.75	0.98	0.088^{ns}		12	5.89	0.98	0.034^{ns}		12	8.99	0.93	0.082^{ns}
	16	2.27	0.99	0.012^{ns}		16	8.28	0.99	0.043^{ns}		16	5.07	0.99	0.036^{ns}
	20	6.59	0.97	0.047^{ns}		20	9.05	0.97	0.045^{ns}		20	11.84	0.96	0.085^{ns}
	24	3.09	0.99	0.015^{ns}		24	7.93	0.98	0.039^{ns}		24	5.26	0.99	0.049^{ns}
	28	8.93	0.86	0.046^{ns}		28	10.37	0.96	0.046^{ns}		28	2.42	0.99	0.011^{ns}
	32	16.2	0.85	0.083^{ns}		32	8.26	0.99	0.039^{ns}		32	10.09	0.98	0.067^{ns}
	36	15.04	0.78	0.074^{ns}		36	60.87	0.51	0.042^{ns}		36	3.02	0.99	0.067^{ns}
1.17 m² Weibull 3p	8	6.87	0.97	0.038^{ns}	5.69 m² Dagum	8	10.7	0.99	0.077^{ns}	28.01 m² Dagum	8	6.64	0.99	0.055^{ns}
	12	11.59	0.94	0.073^{ns}		12	6.49	0.98	0.053^{ns}		12	7.94	0.99	0.042^{ns}
	16	9.17	0.96	0.058^{ns}		16	8.59	0.97	0.063^{ns}		16	11.28	0.94	0.076^{ns}
	20	9.16	0.95	0.052^{ns}		20	5.43	0.99	0.037^{ns}		20	6.48	0.97	0.054^{ns}
	24	12.25	0.92	0.056^{ns}		24	5.24	0.98	0.039^{ns}		24	2.33	0.99	0.017^{ns}
	28	11.17	0.92	0.049^{ns}		28	3.92	0.98	0.024^{ns}		28	1.79	0.99	0.011^{ns}
	32	11.88	0.86	0.048^{ns}		32	4.74	0.98	0.031^{ns}		32	2.09	0.99	0.011^{ns}
	36	9.73	0.92	0.052^{ns}		36	4.64	0.98	0.031^{ns}		36	2.98	0.99	0.011^{ns}
1.76 4 m² Weibull 3p	8	4.99	0.99	0.028^{ns}	8.69 m² Weibull 3p	8	7.66	0.93	0.052^{ns}	41.25 m² Weibull 3p	8	9.14	0.91	0.065^{ns}
	12	3.14	0.99	0.018^{ns}		12	9.66	0.96	0.061^{ns}		12	8.93	0.94	0.057^{ns}
	16	5.71	0.99	0.046^{ns}		16	5.27	0.99	0.027^{ns}		16	8.35	0.95	0.039^{ns}
	20	7.95	0.97	0.041^{ns}		20	10.71	0.94	0.063^{ns}		20	10.01	0.94	0.057^{ns}
	24	5.93	0.99	0.033^{ns}		24	6.83	0.97	0.051^{ns}		24	7.25	0.96	0.043^{ns}
	28	14.21	0.95	0.075^{ns}		28	4.52	0.99	0.027^{ns}		28	8.01	0.94	0.045^{ns}
	32	21.61	0.91	0.094^{ns}		32	7.21	0.98	0.042^{ns}		32	5.75	0.98	0.029^{ns}
	36	9.11	0.97	0.043^{ns}		36	6.18	0.99	0.042^{ns}		36	16.16	0.99	0.029^{ns}

Note: Spa: spacing; PDF: probability density function; RMSE: root mean square error in percentage; $r_{y_i \hat{y}_i}$:Pearson's correlation coefficient; ns: not significant at the 5% probability, according to the Kolmogorov-Smirnov test.

Table 3. Values of ring interval spacing cross spacing, average spacing, and density of plants of *Eucalyptus urophylla* x *E. grandis* arranged in 12 spacings in a Nelder wheel design.

Spacing	Ring interval spacing	Cross spacing	Average spacing (m²)	Density of plants (ha^{-1})
1	0.80	0.63	0.50	20.000
2	0.96	0.80	0.77	12.987
3	1.17	1.00	1.17	8.547
4	1.41	1.25	1.76	5.682
5	1.71	1.54	2.64	3.788
6	2.07	1.91	3.94	2.538
7	2.50	2.34	5.86	1.706
8	3.03	2.87	8.69	1.151
9	3.66	3.51	12.86	778
10	4.43	4.28	19.00	526
11	5.37	5.22	28.01	357
12	6.49	6.35	41.25	242

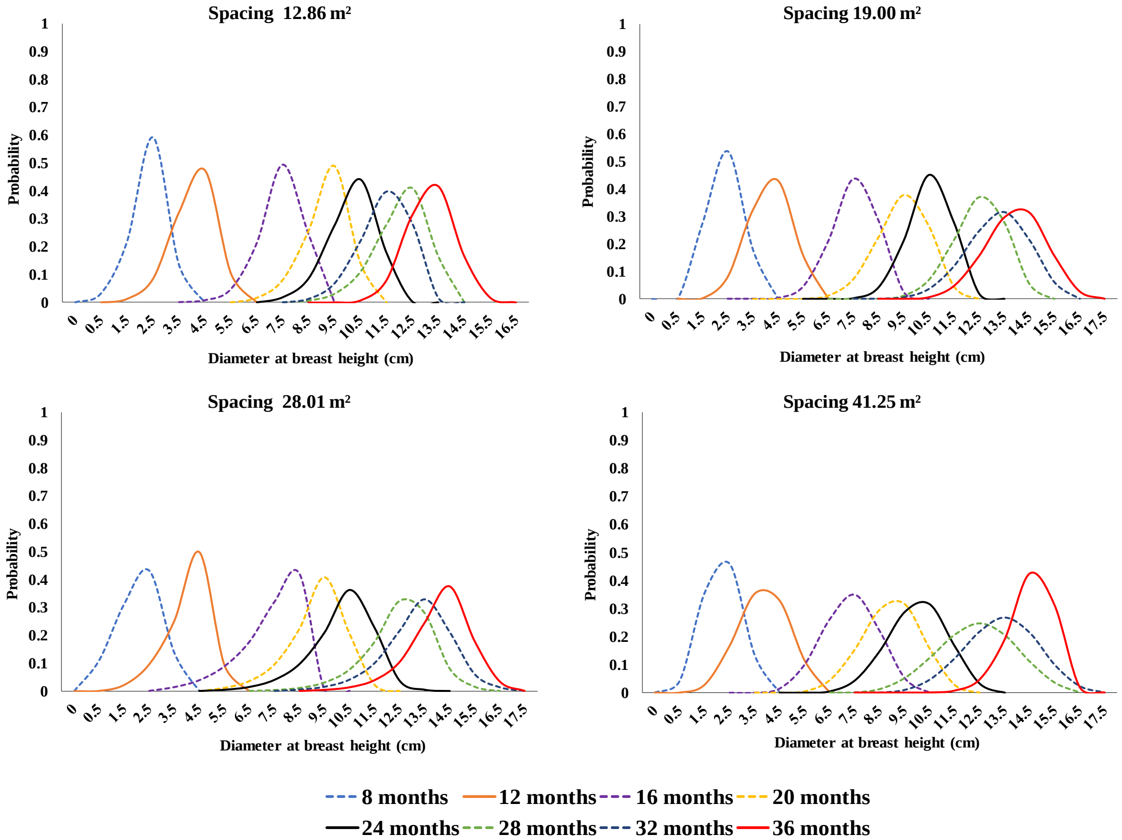

Fig 2. Dynamics of diameter distribution observed in spacings from 8.69 m^2 to 41.25 m^2 in *Eucalyptus urophylla* x *E. grandis* from 8 to 36 months of age. Annual diameter distribution (12th, 24^{th,} and 36th month) is presented as a continuous line and intermediate ages are shown by dotted lines.

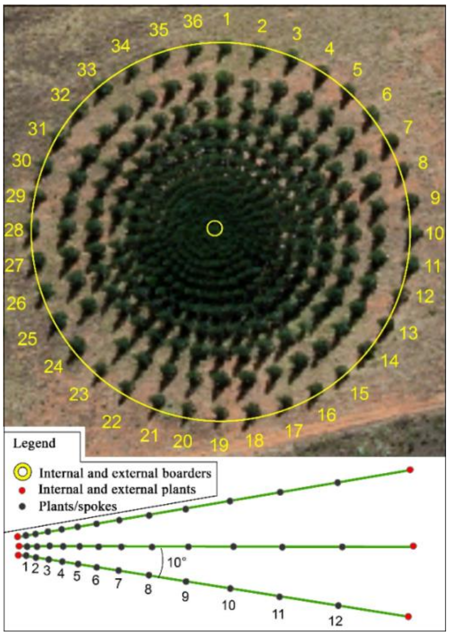

Fig 3. Illustration of planting spots in a Nelder wheel design experiment of 12 spacings (or rings) with 36 plants (spokes) each, giving a total of 432 trees per plot.

This observation was also described by Schmidt (2019) while working with plantings of *E. grandis* x *E. urophylla* at different ages, sites, and densities in the central zone of Minas Gerais, Brazil.

In young tree populations, the diameter amplitude or the number of classes is highly related to the competition for site resources, being either intense or insipient (Baker, 1950; Hawley and Smith, 1962). As other authors explain, resources are scarce due to the high density of the plants, resulting in the deterioration of the planting, causing a large difference in the classes of leaves (dominant, intermediate, and suppressed), and increasing mortality rate. The lack of competition turns the variations in the planting structure into a function of individual behavior and the variations differ with each specimen. In intermediate situations, the competition for resources in the site occurs outside of the extremes, which facilitates regulation of the growth, and greater homogeneity. However, those competition relationships alter with age, with extreme competition for resources obtained at higher ages of smaller and larger spacings.

Extreme inter-specific competition quickens the thinning process, causing the dominance of some specimens and the death of others (Schneider et al., 2015). Knowing the percentage mortality is important because it implies a waste of resources in both cuts sold and the costs of fertilization, soil preparation, and planting. However, a tolerable rate of thinning must be established by the forester. Specimens of *Eucalyptus* spp. tend to be intolerant of competition, quickly segregating into strata (Hillis and Brown, 1978). The level and the speed at which this occurs, varies in accordance with the species, environment, spacing, and the interaction of these factors.

Fitting the probability density function

For some data in this study, it was not possible to use the Johnson's SB function. Schmidt (2019) explains that this function presents more difficulties in reaching a result when the number of classes is equal or lower than the number of parameters.

The Weibull function with two and three parameters describes forestry sites with eucalyptus trees well due to its simple fit and data flexibility for diameters of several plantings. Schmidt (2019) tested the Gama, Beta, Normal, Log-normal, Johnson's SB, and Weibull 3p functions for diameters of the hybrid *E. urophylla* x *E. grandis* in plots of different spacings, ages, and sites and verified that the Weibull 3p function performed the best. Moraes Neto et al. (2014) tested the Log-normal, Weibull 3p, Gamma, and Normal functions for the same hybrid in two arrangements of specimens at the ages of 30 and 54 months and found that the Weibull distribution described the data well for most treatments. Binoti et al. (2014) compared the performance of the Nakagami distribution with a Weibull 3p PDF and concluded that the Weibull 3p function was better in describing the diameter distribution of the plantings.

Other probability density functions are efficient in estimating the diameter distributions of *Eucalyptus* spp. plantings, as seen in this paper and other studies such as Schröder et al. (2016). The latter authors adjusted the Normal, Log-Normal, Gama, and Weibull 2p functions in plantings of *Eucalyptus dunnii* in four spacings (0.87 m x 1.75 m; 1.75 m x 1.75 m; 1.75 m x 3.5 m and 3.5 m x 3.5 m) at the age of four months, and verified that the function that best described the diameter distribution was the Log-Normal PDF for all spacings.

Jesus et al. (2017) tested the Gamma, Beta, Weibull 3p, Normal, Log-Normal, and Dagum functions in describing the diameter structure in a population of a clonal plantings of a hybrid of *E. urophylla* x *E. grandis* in Brasília city (Brazil), and obtained the best results for the Beta, Weibull 3p, and Dagum functions.

The theoretical curves of diameter distribution and the enlarging or flattening of the curves occurred at an age of 36 months because these populations had passed through a stagnation process in diameter growth and this process occurred earlier due to extreme competition (Batista et al., 2014). Nogueira et al. (2006) also described growth stagnation as directly proportional to the rate of growth of the trees.

Materials and methods

Area of study

The study was carried out at the Fazenda Água Limpa (FAL), owned by the University of Brasilia (UnB), in Brasília City, Brazil. The total area is 4.390 ha, and is covered by cerrado (*sensu stricto*) (Brazilian savanna vegetation) and the most common soils is Red Latosoil (Embrapa, 1978). The local climate is classified as Aw, which is a tropical climate, with a dry winter according to the Köppen criteria, and is detailed by Alvares et al. (2013).

Characterization of the experiments, plant materials, and data collection

To conduct this study, the trees were planted in a Nelder wheel design, as proposed by Nelder (1962) and adapted by Namkoong (1966) and Stape (1995). The planting occurred in December 2013 with individuals of *Eucalyptus grandis* x *Eucalyptus urophylla* (clone EAC 1528).

The experiment was installed and conducted as described by Aquino (2017), with 14 rings, each one with 36 spokes (Fig. 3). Each ring is referred to as a distinct spacing and each spoke indicates an individual tree. The first and the last spacings were discarded, since they represent internal and external borders, totaling 12 effective spacings of: 0.50 m², 0.77 m², 1.17 m²; 1.76 m², 2.64 m²; 3.94 m², 5.86 m², 8.69 m², 12.86 m²; 19.00 m², 28,01 m², and 41,25 m². Three Nelder wheel designs were installed as three replications, giving 1296 trees, with 432 individuals per plot.

The plot had an initial radius r_0 (distance from the central point of the circle to the internal border). Each spacing was defined using the ratio of the geometric progression of the radius of the spacing factor (α), the angles (θ), and the area (Ai) of the plants. The values of r_0 = 2.80 m, α = 1.11, and θ = 10º were used to define the values of radius, area per plant, and density of plants for each treatment in the current study (Table 3).

For this study, all individual trees were measured every four months in order to obtain the DBH from the 8th to the 36th month, totaling eight age measurements. All plants were labeled with numbered aluminum plates tied to the trunk. The occurrences of failure and mortality were evaluated.

Data analysis

Firstly, descriptive statistics of DBH variables for data stratified by age and spacing were calculated. To describe diameter distribution, the number of trees per hectare was estimated for each diameter class through fitting PDFs: Normal (Meyer, 1977), Weibull 3p (Bailey and Dell, 1972), Gamma (Nelson, 1964), Dagum (Kleiber and Kotz, 2003), and Johnson's SB (Johnson, 1949), for each of 12 spacings and 8 age classifications. The estimation of model parameters was determined by the maximum likelihood method. EasyFit 5.5 Mathwave (2010) was used to model the functions Normal, Gamma, Dagum, and Johnson's SB, and the Weibull 3p function was modeled using a Microsoft Excel (2016) chart in which the estimates followed the parameters proposed by Barra et al. (2004).

The observed diameter frequencies and the theoretical frequencies from the fitted probability functions for each stratification in spacing and age were compared by the Kolmogorov Smirnov test (K-S), as described by Gibbons and Subhabrata (1992), at a 95% level of probability. This test is defined by the maximum difference between the relative frequencies observed and the relative frequencies estimated, denoted as "Dcal" and the tabled difference is denoted as "Dtab". Therefore, if Dcal < Dtab, the null hypothesis (H_0) is accepted, i.e., the observed diameters follow the modeled probability distribution.

To select the PDF that best described the diameter structure for each spacing, a ranking of 1 to 5 was allocated to each function of the same spacing and age; the function with the lower Dcal received a score of 1 and the higher Dcal received a score of 5. After that, the scores of all ages per spacing were summed and the model that presented the lowest rate was selected. The goodness of fit (root mean square error) was calculated as a percentage (RMSE%), as explained by Murphy and Sternitzke (1979), and the Pearson's correlation coefficient ($r_{y\hat{y}_i}$) was calculated between the absolute observed and estimated frequencies. The dynamic analysis of the diameter distribution was performed by graphics of each spacing with theoretical curves of diameter distribution estimated by the best PDF across all ages.

Conclusions

The spacings that delivered the highest DBH, growth rate, and number of specimens were 19 m², 28.01 m² and 41.25 m². The spacings 0.5 m², 0.77 m², and 1.17 m² obtained the lowest growth rates and a high mortality rate.

A spacing of 12.86 m² was represented best by the Johnson's SB function. Spacings 5.86 m² and 28.01 m² were best represented by the Dagum function, while all other functions were well described by Weibull 3p. While Weibull 3p was not the best for all spacings, it was consistent and precise and could be used for all the spacings evaluated.

The stagnation in the growth of the diameter was higher at spacings of 0.5 m², 0.77 m², and 1.17 m², which are then recommended for early harvesting and wood use.

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