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# Prognosis of growth and production of *Eucalyptus urograndis* planted at different spacings

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**Abstract**

A topic of great interest in forestry research is recognizing the behavior of stands planted at different spacings to optimize the potential of producing multiple products. This study aimed to assess the future production of multiple products from *Eucalyptus* sp. planted at 12 different spacings. The study area was in central Brazil. A Nelder systematic design with three replications was used. This design yielded 432 planting spots per plot per replicate. Diameter at breast height (DBH) and total height were measured for all trees from 4 to 36 months of age. In addition, the volume of five trees for the spacings of 16, 24, and 36 months of age was measured. Subsequently, an equation system was fitted for each area to project the Weibull 3P probability density function parameters: minimum diameter, maximum diameter, and the number of trees. The current and mean annual increments were assessed based on the total volume. Trees of 36 and 48 months of age were compared between the population designed for multiple products (Scenario I) and the population designed for only one product (Scenario II). The results showed that spacing affects the technical harvest age and that 0.77 m² and 1.76 m² are optimal for a short-term regime.

**Keywords:** Nelder wheel desing, Parameter projection, Weibull function, Diameter structure, Diameter distribution.
**Abbreviation:** DBH_Diameter at breast height (cm); RMSE_root mean square error.

**Introduction**

*Eucalyptus* spp. are widely distributed in Brazil due to their fast growth, adaptability, high-quality wood (Santana, 2009), and low production cost compared to species from other countries (Soares et al., 2010). Considering the factors that enable the implementation and development of this species in the national scenario, several species and clones are used in plantations, mostly to provide raw materials for segments such as energy production, paper manufacturing using cellulose, furniture manufacturing, and construction.

The varied usage of wood and variations in price and demand for its material pressure the market to provide a diverse range of products. This behavior affects how producers opt for manufacturing various products from forest plantations. Given this, production planning is fundamental when the forest is intended for multiple products (Retslaff et al., 2012). The most used tool is modeling the diameter variable because it describes the diameter distribution and other forest attributes, enables predictions regarding the multiple products, supports the economic evaluation, and assists the decision-making process (Campos and Leite, 2017). Some studies have shown that eucalyptus forests designed for multiple products are more profitable than those designed for only one use (Soares et al., 2003; Mendonça et al., 2008; Santos, 2010; Lustosa Júnior et al., 2017). During planting, some arrangement and spacing strategies might affect the size and appropriate products, prices, costs, harvests, and culture treatments (Penner et al., 2001), impacting the project's economic viability. According to Pauleski (2010), to establish plant spacing, it is necessary to weigh the pros and cons from the values obtained from the products produced from the forest, defining what is most productive in a region.

However, studies approaching several areas demand significant forest stands, investment costs, and generating challenges in obtaining resources to install, maintain, and assess the experiment (Oda, 2005).

Aiming to overcome the restrictions of the traditional experimental outlines, Nelder (1962) proposed the Nelder wheel design as an alternative used in several forestry research studies over the last years (Oda-Souza et al., 2008; Stape; Binkley, 2010; Santos, 2011; Moraes et al., 2013; Vanclay et al., 2013; Aquino, 2020). Considering this scenario, the following research questions were formulated: Which product combinations are possible for each spacing in young eucalyptus plantations? Which spacing is more promising for short-term use? This study aimed to assess the future production of multiple *Eucalyptus* spp. products in different spacings.

**Results and Discussion**

***Parameters projected by the system of equations***

Table 4 (Supplementary Table) includes the precision of the equations and statistics for the estimates of the number of trees for spacings 1 (0.5 m²), 2 (0.77 m²), and 3 (1.17 m²). A decrease in the correlation coefficient was observed with increasing spacing; however, all were considered to have a high correlation. The inverse result was found for the RMSE (%). It is noteworthy that the prognoses were limited to 48 months due to a lack of information on the mortality rate of older trees.

Campos and Leite (2017) explained that the survival models of trees in a stand are generally non-linear, as they are attributed to biological causes. However, the results demonstrated that the linear equations fitted the database satisfactorily for the very dense spacings evaluated in this study. Therefore, it can be inferred that the linear model is suitable for modeling trees in extra dense spacing, that is, under extreme competition.

Table 5 (Supplementary Table) shows the fitted equations to estimate the beta parameter (β) of the Weibull 3P distribution and its precision statistics for spacings 1–12. The correlations obtained were greater than 0.9 for all spacings, except for spacing 9. The error range for RMSE (%) ranged from 1.18–9.33%; this error range was considered acceptable. The results from this study were an improvement of the findings of Azevedo et al. (2017), who used the same model to estimate the number of *Eucalyptus urophylla* trees up to 72 months of age resulting in a standard error of 11.43% and a coefficient of determination of 0.51. Nogueira et al. (2005), working with a hybrid stand of *E. urophylla* × *E. grandis* subjected to thinning, found an adjusted coefficient of determination of 0.981 for the same model, corroborating the results of this study. The results of the adjustments to obtain the gamma parameter (γ) of the Weibull 3P distribution and its precision statistics for all spacings are listed in Table 6 (Supplementary Table). A high correlation was observed between the observed and estimated gamma data, with higher correlation values ($\boldsymbol{r_{y\hat{y}_i} > 0.99}$) and RMSE (%) values lower than 6.7%.

No studies using this model to project the gamma variable were found. However, some studies used linear relationships to project this variable. Binoti et al. (2015) worked with the projection of the diameter distribution of *E. urophylla* × *E. grandis* in Minas Gerais and found correlation values of 0.917 and an RMSE of 5.33% for the gamma projection equation using the ratio of current and future age as an independent variable and the squared diameter. Table 7 (Supplementary Table) shows the fitting of the maximum diameter projection equations for all spacings. The correlation between the observed and estimated future diameters was considered satisfactory, with values greater than 0.97. The maximum RMSE was 7.09%.

Scolforo's (2006) model proposes inserting the future age and average diameter as input variables. However, the average diameter was replaced by the maximum diameter to improve the fitting. Therefore, the adapted model was suitable for all spacings. Leite et al. (2013) obtained accurate and consistent results when using a linear model with the ratio of current to future age and the maximum diameter as input variables to project the maximum future diameter of a stand of *E. urophylla* × *E. grandis* under an initial spacing of 3.0 x 3.0 m.

Castro et al. (2017) used the same model, hybrid, and planting arrangement in a stand in the Center-East of the State of Minas Gerais and found a correlation coefficient of 0.9455, below that found in the present study.

The correlation between the observed and estimated future minimum diameter variable (Dmin) values was satisfactory. Table 8 (Supplementary Table) presents the adjusted equations for projecting Dmin and the precision statistics for spacings 1–12. The correlation coefficients ranged between 0.809 and 0.9549, and the RMSE ranged between 8.03% and 20.83%. Therefore, it is challenging to estimate the minimum diameter at early ages, regardless of spacing. The minimum diameter growth is associated with suppressed trees, which do not follow general population growth, decreasing the correlation with age. Therefore, the fitting was considered satisfactory.

***Validation of the projection system***

Cumulative theoretical frequencies were projected using estimated beta and gamma values. The alpha values, the curve allocation parameters, were randomly selected from 10–90% of the projected minimum diameter. Table 9 summarizes the performance of the theoretical distributions estimated by the projection equation system for each spacing and age in the K-S test. The values found for Dcal ranged from 0.02–0.158, with adherence accepted by the KS test at 95% probability, except for 20 and 36 months in spacing 9 and at 20 months in spacing 10, which were accepted only at the 99% level of significance. Thus, the projected theoretical curves are equal to the real curves of the diameter distribution, showing the possibility of using the projection system of equations for spacing across the extremes (denser or wider) in eucalyptus plantations at early ages. Leite et al. (2013) explained that the efficiency of the projection system is due to the significant correlation of Weibull 3P distribution parameters with age. The same authors recommend that when estimating a future variable (variable 2), the same variable at previous ages (variable 1) be used in the fitting. Other studies involving a projection system for the prognosis of the diameter distribution of *Eucalyptus* showed accurate and consistent results, as observed by Leite et al. (2005), Lopes (2007), Santos (2008), Binoti et al. (2010), Araújo Júnior et al. (2010), Binoti et al. (2012), Leite et al. (2013), Binoti et al. (2014), Binoti et al. (2015), and Azevedo et al. (2017).

***Projection of volume per diametric class***

Analyzing the accuracy statistics of the hypsometric equations (Supplementary Table 10), the correlation between the observed and estimated heights ranged from 0.912–0.981, and the RMSE (%) was between 8.07% and 13.14%. The very dense spacings (1, 2, and 3) resulted in less precise fittings.

**Table 1.** 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 ($m^2$) | 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 |

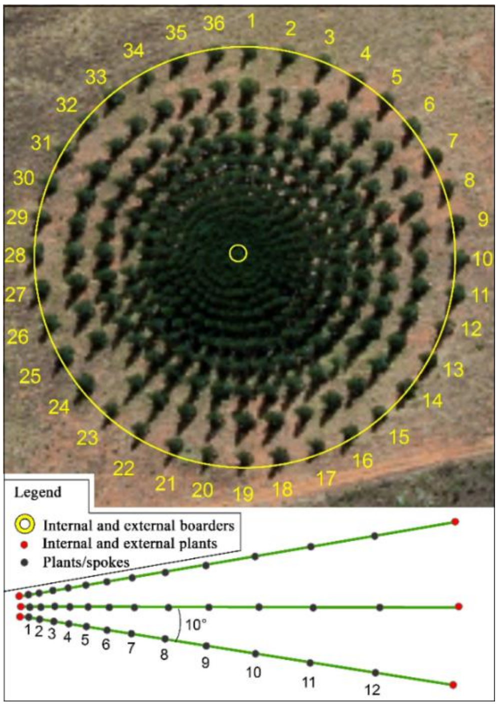


**Fig 1.** Illustration of planting spots in a Nelder wheel design experiment of 12 spacings (or rings) with 36 plants (spokes) each, giving a total of 432 trees per plot (Adopted from Lima et al., 2021).

**Table 2.** System of projection models used for each spacing of a stand of *Eucalyptus urophylla* x *E. grandis*.

| Model | Source | |
|---|---|---|
| $\ln(N_2)=b_0+b_1 d_2+b_2\ln(N_1)+\varepsilon$ | - | (1) |
| $\beta_2=b_0+b_1N_2+b_2 d\,max_2+b_3\beta_1+\varepsilon$ | Azevedo et al. (2016) | (2) |
| $\gamma_2=\gamma_1\left(\frac{Id_1}{Id_2}\right)+b_0\left(1-\frac{Id_1}{Id_2}\right)+\varepsilon$ | Campos and Leite (2017) | (3) |
| $d\,max_2=b_0+b_1Id_2+b_2d\,max_1+\varepsilon$ | Scolforo (2006) adapted | (4) |
| $d\min_2=b_0+b_1Id_2d\min_1+\varepsilon$ | - | (5) |

Note: β1 and β2 are scale parameters of the Weibull distribution at a current and future age, respectively; γ1 and γ2 are shape parameters of the Weibull distribution at a current and future age, respectively; $Id_1$ and $Id_2$ are current and future age, in months, respectively. $N_1$ and $N_2$ are number of trees per hectare at a current and future age, respectively; $dmin_1$ e $dmin_2$ are minimum diameter of DBH at current and future age, respectively; $dmax_1$ and $dmax_2$ are maximum diameter of DBH at current and future age, respectively; $d_2$ is the average diameter of DBH at future age; bi are model parameters to be estimated; ε are independent random errors, with zero average and constant variance.

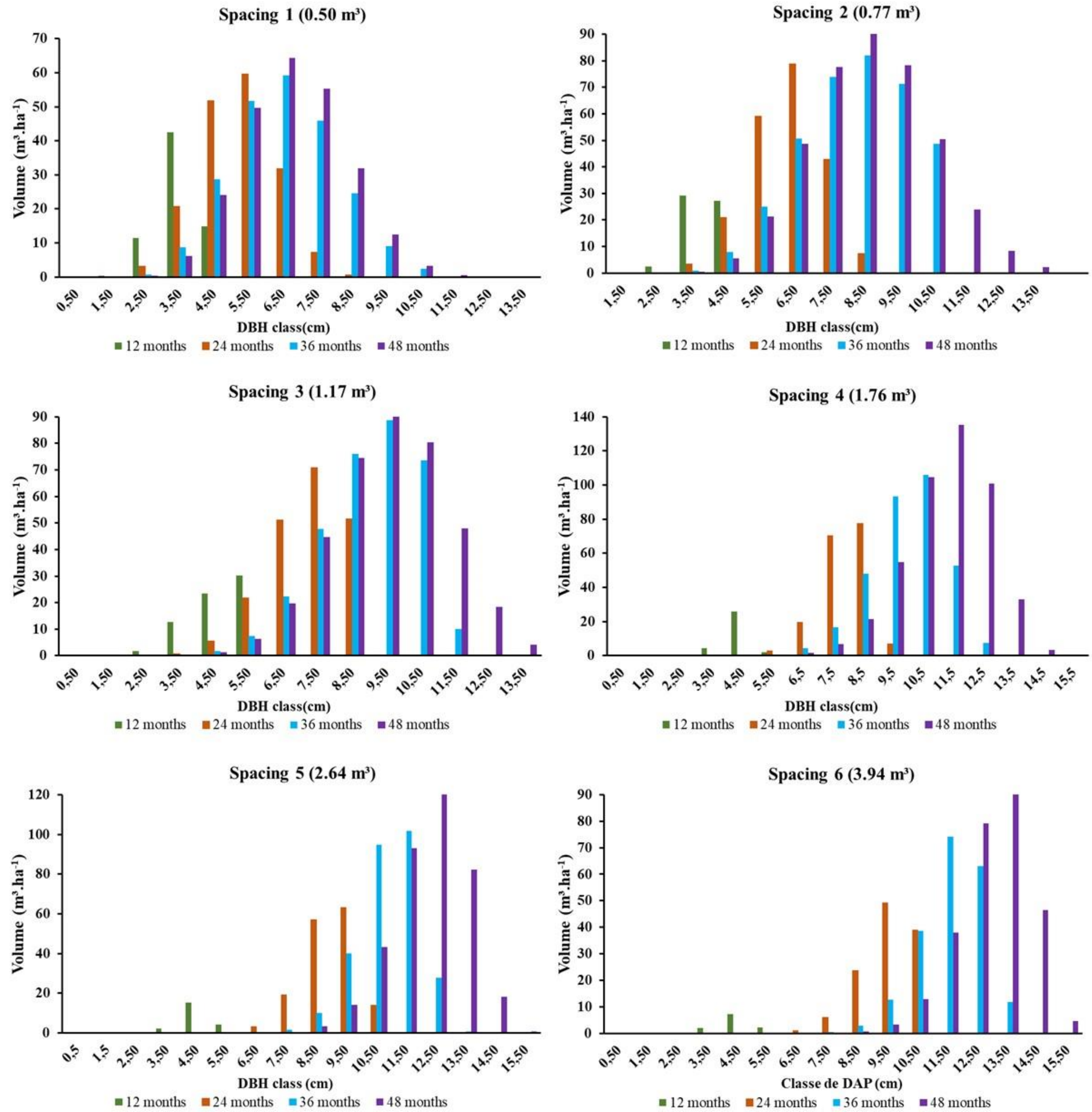


**Fig 2**. Projected volume by diameter class in spacings 1 (0.50m²), 2 (0.77m²), 3 (1.17m2), 4 (1.76m2), 5 (2.64m2) and 6 (3.94m2) of *Eucalyptus urophylla* x *E. grandis* at ages 12, 24, 36 and 48 months.

**Table 3.** Products sold locally, with their measurements.

| Type | Minimum diameter (cm) | Length (m) |
|---|---|---|
| Log stack IV | 5 | 2.2 |
| Log stack III | 8 | 2.2 |
| Log stack II | 11 | 2.2 |
| Log stack I | 14 | 2.2 |
| Fence | 16 | 2.2 |
| Pillar | 16 | 3.2 |

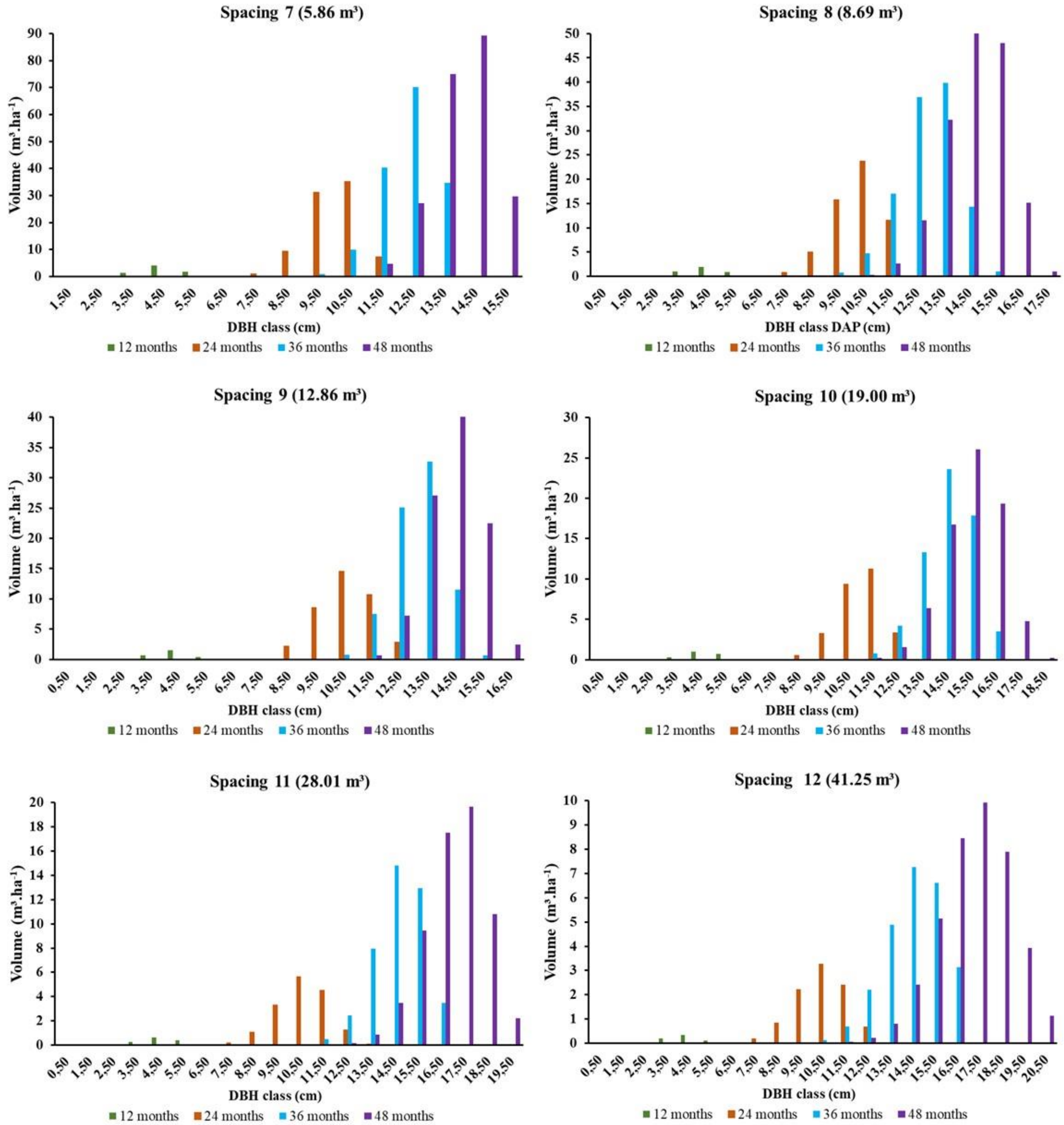


**Fig 3.** Projected volume by diameter class in spacings 7 (5,86m$^2$), 8 (8,69m$^2$), 9 (12,86m$^2$), 10 (19,00 m$^2$), 11 (28,01 m$^2$) and 12 (41,25 m$^2$) of *Eucalyptus urophylla* x *E. grandis* at ages 12, 24, 36 and 48 months.

This drop in performance can be explained by the lower degree of correlation between height and DBH of trees under extreme competition over time. The Trorey model, selected to estimate total height in this study, was also chosen by Miguel et al. (2010) because of the accurate and consistent statistics when estimating the total height of a stand of *Eucalyptus urophylla* in the northern region of the state of Goiás, Brazil. This model also presented satisfactory results in the study by Jesus et al. (2015) when estimating the height of *E. urophylla* × *E. grandis* in a stand at Água Limpa Farm, owned by the University of Brasilia.Azevedo et al. (2017) used the Trorey model to estimate the height of *Eucalyptus urophylla* in a 3.1 x 2.0 m arrangement in the northern state of Goiás, Brazil, and the results were similar to those of this study.

### *Tapering*

The fitting of the taper equations resulted in a coefficient of determination ranging from 0.9725–0.9967 and an RMSE (%) ranging from 4.07–6.59% (Table 11). Compatibility of the Garcia taper model was also observed in the study by Campos et al. (2014), who studied the shape of 7-year-old *E. urophylla*× *E. grandis* trees in a forest area in the state of Minas Gerais, Brazil. The authors found a value of 0.9813 for the coefficient of determination and residuals (errors), with a low bias for the fitted equation.

**Table 9.** The Kolmogorov Smirnov ($p > 0.05$) test of the theoretical distributions estimated by the system of projection equations for each spacing and age.

| Spa (average spacing) | Age (months) | Dcal | Dtab | Spa (average spacing) | Age (months) | Dcal | Dtab |
|---|---|---|---|---|---|---|---|
| 1 (0.50 m³) | 12 | 0.0597$^{ns}$ | 0.1334 | 7 (5.86 m³) | 12 | 0.0840$^{ns}$ | 0.1327 |
| | 16 | 0.0301$^{ns}$ | 0.1341 | | 16 | 0.0836$^{ns}$ | 0.1327 |
| | 20 | 0.0373$^{ns}$ | 0.1341 | | 20 | 0.0816$^{ns}$ | 0.1327 |
| | 24 | 0.0344$^{ns}$ | 0.1374 | | 24 | 0.0590$^{ns}$ | 0.1327 |
| | 28 | 0.0819$^{ns}$ | 0.1388 | | 28 | 0.0852$^{ns}$ | 0.1327 |
| | 32 | 0.1107$^{ns}$ | 0.1571 | | 32 | 0.0668$^{ns}$ | 0.1327 |
| | 36 | 0.1427$^{ns}$ | 0.1592 | | 36 | 0.0722$^{ns}$ | 0.1327 |
| 2 (0.77 m³) | 12 | 0.1155$^{ns}$ | 0.1327 | 8 (8.69 m³) | 12 | 0.1456$^{ns}$ | 0.1309 |
| | 16 | 0.1006$^{ns}$ | 0.1327 | | 16 | 0.0467$^{ns}$ | 0.1309 |
| | 20 | 0.0703$^{ns}$ | 0.1327 | | 20 | 0.0634$^{ns}$ | 0.1309 |
| | 24 | 0.0518$^{ns}$ | 0.1341 | | 24 | 0.0530$^{ns}$ | 0.1309 |
| | 28 | 0.0952$^{ns}$ | 0.1347 | | 28 | 0.0706$^{ns}$ | 0.1309 |
| | 32 | 0.1022$^{ns}$ | 0.1426 | | 32 | 0.0672$^{ns}$ | 0.1309 |
| | 36 | 0.0807$^{ns}$ | 0.1426 | | 36 | 0.0295$^{ns}$ | 0.1309 |
| 3 (1.17 m³) | 12 | 0.1171$^{ns}$ | 0.1315 | 9 (12.86 m³) | 12 | 0.0839$^{ns}$ | 0.1315 |
| | 16 | 0.0578$^{ns}$ | 0.1315 | | 16 | 0.1004$^{ns}$ | 0.1315 |
| | 20 | 0.0732$^{ns}$ | 0.1315 | | 20 | 0.1326$^{ns\ a\ 99\%}$ | 0.1315 |
| | 24 | 0.0719$^{ns}$ | 0.1315 | | 24 | 0.0741$^{ns}$ | 0.1315 |
| | 28 | 0.0492$^{ns}$ | 0.1321 | | 28 | 0.0977$^{ns}$ | 0.1315 |
| | 32 | 0.1164$^{ns}$ | 0.1353 | | 32 | 0.0292$^{ns}$ | 0.1315 |
| | 36 | 0.0581$^{ns}$ | 0.1374 | | 36 | 0.1046$^{ns\ a\ 99\%}$ | 0.1315 |
| 4 (1.76 m³) | 12 | 0.0215$^{ns}$ | 0.1315 | 10 (19.00 m³) | 12 | 0.0632$^{ns}$ | 0.1327 |
| | 16 | 0.0445$^{ns}$ | 0.1315 | | 16 | 0.0391$^{ns}$ | 0.1327 |
| | 20 | 0.0628$^{ns}$ | 0.1315 | | 20 | 0.1582$^{ns\ a\ 99\%}$ | 0.1327 |
| | 24 | 0.0805$^{ns}$ | 0.1315 | | 24 | 0.1239$^{ns}$ | 0.1327 |
| | 28 | 0.0745$^{ns}$ | 0.1315 | | 28 | 0.0203$^{ns}$ | 0.1327 |
| | 32 | 0.1281$^{ns}$ | 0.1315 | | 32 | 0.0794$^{ns}$ | 0.1327 |
| | 36 | 0.0570$^{ns}$ | 0.1315 | | 36 | 0.141$^{ns}$ | 0.1327 |
| 5 (2.64 m³) | 12 | 0.0560$^{ns}$ | 0.1315 | 11 (28. 01 m³) | 12 | 0.0564$^{ns}$ | 0.1321 |
| | 16 | 0.0663$^{ns}$ | 0.1315 | | 16 | 0.0828$^{ns}$ | 0.1321 |
| | 20 | 0.1117$^{ns}$ | 0.1315 | | 20 | 0.0583$^{ns}$ | 0.1321 |
| | 24 | 0.1220$^{ns}$ | 0.1321 | | 24 | 0.0612$^{ns}$ | 0.1321 |
| | 28 | 0.0837$^{ns}$ | 0.1321 | | 28 | 0.0250$^{ns}$ | 0.1321 |
| | 32 | 0.0641$^{ns}$ | 0.1321 | | 32 | 0.0548$^{ns}$ | 0.1321 |
| | 36 | 0.0576$^{ns}$ | 0.1321 | | 36 | 0.1028$^{ns}$ | 0.1321 |
| 6 (3.94 m³) | 12 | 0.0382$^{ns}$ | 0.1321 | 12 (41.25 m³) | 12 | 0.0980$^{ns}$ | 0.1334 |
| | 16 | 0.0585$^{ns}$ | 0.1321 | | 16 | 0.0634$^{ns}$ | 0.134 |
| | 20 | 0.0847$^{ns}$ | 0.1321 | | 20 | 0.0704$^{ns}$ | 0.1334 |
| | 24 | 0.0623$^{ns}$ | 0.1321 | | 24 | 0.0433$^{ns}$ | 0.1334 |
| | 28 | 0.0936$^{ns}$ | 0.1321 | | 28 | 0.0619$^{ns}$ | 0.1334 |
| | 32 | 0.0391$^{ns}$ | 0.1321 | | 32 | 0.076$^{ns}$ | 0.1334 |
| | 36 | 0.0977$^{ns}$ | 0.1321 | | 36 | 0.0859$^{ns}$ | 0.1334 |

Where: Spa is spacing; ns is not significant at the 95% probability for the Kolmogorov-Smirnov test.

***Growth and volume production per diameter class***

Using the prognosis with the system of equations and the general hypsometric and taper integral equations, the ages of 12, 24, and 36 months were adjusted, and the volume distribution by diameter classes for each spacing was predicted at 48 months (Figures 2 and 3). In general, there was volume growth at all ages and spacings. It was also observed that there was a significant reduction in the diameter increment in spacings 1 and 3 for ages 36–48 months. This differs from spacings 11 and 12, which were the sparsest. At 12 months, the highest volume classes were 3.5 cm DBH for spacings 1 and 2, and the others started at 4.5 cm. At 24 months, spacings 8–12 matched the diameter classes, with the largest volume being 10 cm DBH. The denser spacings had different modal volume classes; at 36 months, spacings 10, 11, and 12 had an average of 14.5 cm DBH. Finally, at 48 months, the wider spacing (i.e., 10, 11, and 12) had the highest volumes of 15.5, 16.5, and 17.5, respectively. Figure 4 shows the current annual increment (CAI) and the average annual

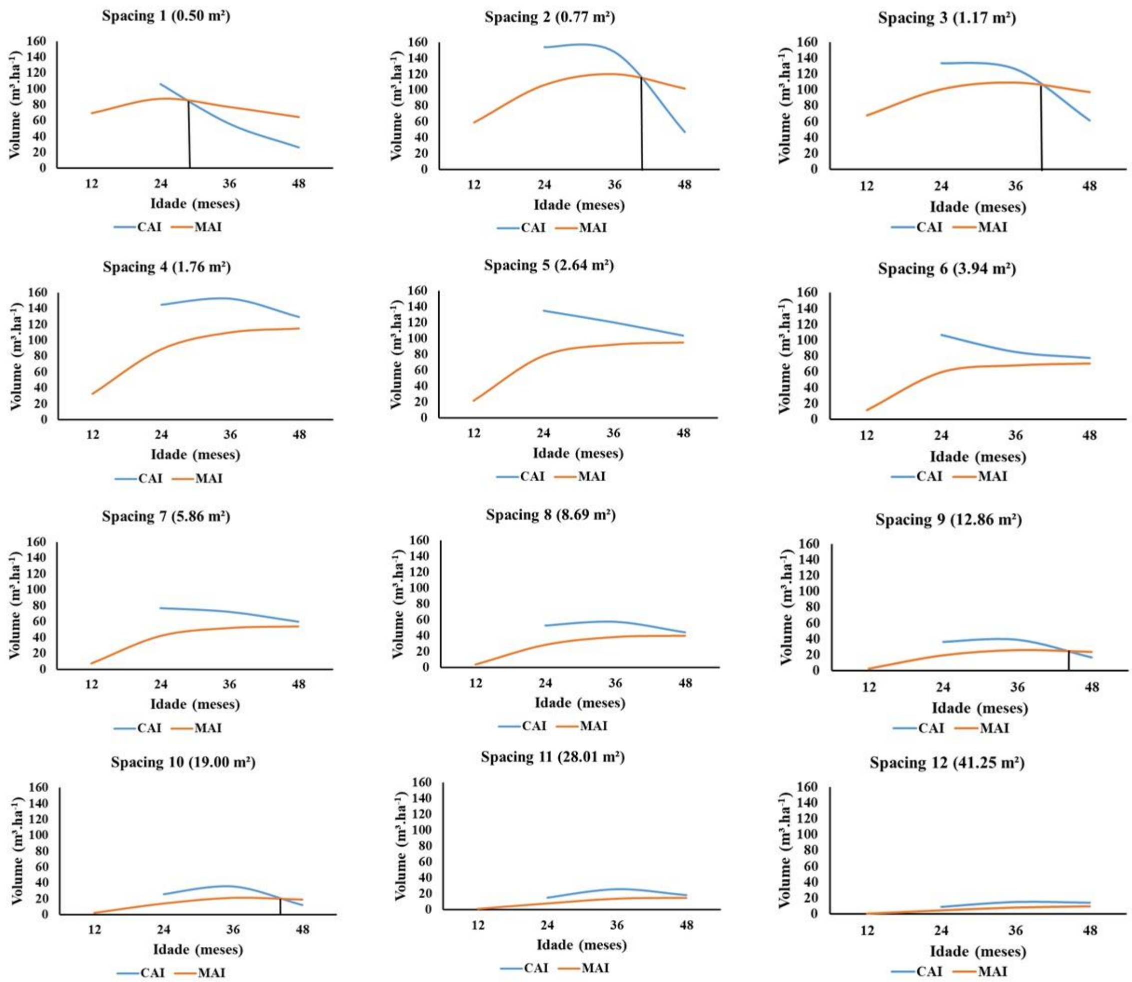


**Fig 4**. The current annual increment (CAI) and the average annual increment (AAI) growth curves for spacings 1 (0.50m²), 2 (0.77m²), 3 (1.17m$^2$), 4 (1.76m$^2$), 5 (2.64m$^2$), 6 (3.94m$^2$), 7 (5.86m$^2$), 8 (8.69m$^2$), 9 (12.86m$^2$), 10 (19.00 m$^2$), 11 (28.01 m$^2$) and 12 (41.25 m$^2$) at ages 12, 24, 36 and 48 months.

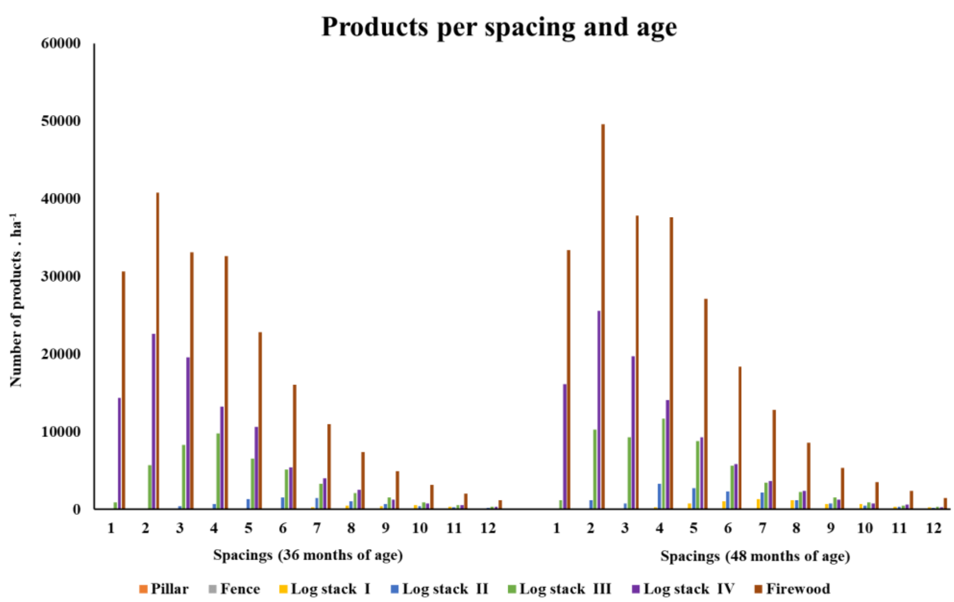


**Fig 1.** Number of products generated for each spacing at ages 36 and 48 months.

**Table 12**. Projected volume (m³. ha-¹) for each spacing at ages 36 and 48 months.

| Spacing | Age (months) | Volume ($m^3.ha^{-1}$) | Residue ($m^3.ha^{-1}$) | Firewood Volume ($m^3.ha^{-1}$) |
|---|---|---|---|---|
| **1** | 36 | 198.66 | 62.93 | 135.73 |
| | 48 | 210.75 | 58.33 | 152.42 |
| **2** | 36 | 294.18 | 49.21 | 244.97 |
| | 48 | 379.86 | 41.76 | 338.10 |
| **3** | 36 | 276.49 | 35.72 | 240.77 |
| | 48 | 295.59 | 33.61 | 261.98 |
| **4** | 36 | 261.33 | 18.69 | 242.64 |
| | 48 | 339.38 | 19.94 | 319.44 |
| **5** | 36 | 225.21 | 10.72 | 214.49 |
| | 48 | 294.05 | 12.42 | 281.63 |
| **6** | 36 | 175.51 | 7.69 | 167.82 |
| | 48 | 230.44 | 7.87 | 222.57 |
| **7** | 36 | 133.91 | 5.74 | 128.17 |
| | 48 | 186.11 | 1.44 | 184.67 |
| **8** | 36 | 99.48 | 4.06 | 95.42 |
| | 48 | 137.53 | 3.79 | 133.74 |
| **9** | 36 | 69.18 | 2.53 | 66.65 |
| | 48 | 88.53 | 2.09 | 86.44 |
| **10** | 36 | 58.03 | 1.86 | 56.17 |
| | 48 | 67.70 | 1.73 | 65.97 |
| **11** | 36 | 36.76 | 1.23 | 35.53 |
| | 48 | 52.89 | 1.11 | 51.78 |
| **12** | 36 | 22.19 | 0.72 | 21.47 |
| | 48 | 34.11 | 0.48 | 33.63 |

increment (AAI)growth curves for each spacing at ages between 12 and 48 months. It was observed that the two curves crossed, just after 24 months for spacing 1, after 36 months for spacings 2 and 3, and close to 48 months for spacings 9 and 10. The point on the curves where CAI equals AAI indicates the maximum volume productivity for a forest stand. From abiological perspective, this is the recommended age for harvesting, also called the silvicultural harvest age or technical harvest age (Campos and Leite, 2017). In this study, the technical harvest age of the stand with spacing 1 was 24 months, spacing 3 was 36 months, and spacings 9 and 10 were 48 months. However, managers must pay attention to the enterprise's sustainability, as short rotation regimes increase nutrient exports, raising the cost of correction and soil fertilization (Zaia and Gama-Rodrigues, 2004). Additionally, a reduction in the harvest cycle increases heavy machinery traffic that can disrupt and compact the soil (Andrade, 2004).
Hawley (1962) reported that overly dense or widely spaced forests are detrimental when timber production is the goal. In a forest with a high tree density, wood production is high at the beginning of the cycle but is distributed among many trees. In the case of wider spacing, trees may not have the physiological capacity to assimilate all available resources, resulting in underutilization of stand potential.

***Assortments***

Figure 5 shows the possible products generated (Scenario I) from each spacing after 36 and 48 months. In general, spacing influenced the number of logs generated from each product for both ages, increasing from the widest to the densest. This can be explained by the density of planted trees, which ranges from 20,000 trees per hectare in the densest to 242 trees per hectare in the broadest, affecting the degree of competition, which accelerates the volume storage process per hectare. Regarding the products generated, firewood was predominant in all spacings in the two periods analyzed because it is a young population, and the firewood product has the smallest dimensions. Table 12 shows the results of Scenario II, showing the volume available for converting the stand into firewood logs for each spacing at age. Larger volume ($m^3$ $ha^{-1}$) in spacings 2 and 4, for the two periods analyzed. The unused wood (residual) decreased from denser to wider spacings and from one age to another. The spacings with the highest percentage of residues were 1 (31.68%), 2 (27.68%), and 3 (16.71%). Scenarios I and II have potentially different uses in the forest. When choosing the best scenario or ideal spacing, the manager or producer must pay attention to market research and carry out an extensive cost analysis. Denser spacings generated larger stock volume. However, high mortality of trees was observed in spacings 1, 2, and 3, amounting to 30.47%, 13.33%, and 8.41%, respectively. This resulted in investment losses due to the cost of seedlings, fertilization, soil preparation, and pesticides. In addition to the high percentage of residues generated and the difficulty of mechanization, this could make a stand unfeasible. Given the analyzed results, the optimal spacing for short-term stands was spacing 4 (1.76 m²).

**Materials and methods**

***Area of study***

This research was conducted at Fazenda Água Limpa (FAL) of the University of Brasília (UnB) in Brasília-DF. Its total area is

4,390 ha, predominantly covered by the Cerrado *stricto sensu* biome, and the most common soil class is Red Oxisol (Embrapa, 1978). According to Köppen (1939), the local climate was classified as Aw and updated by Alvares et al. (2013).

***Characterization of the experiments, plant materials, and data collection***

The data used in this study comes from a Nelder wheel design proposed by Nelder (1962). It is a hybrid clonal planting of *E. urophylla* x *E. grandis* arranged in 14 different spacings (rings), with 36 trees per spacing (Figure 1). The internal and external rings were disregarded, totaling 12 effective spacings.

The present work continues the work of Lima et al (2021), where all the experimental details can be found. The size of the studied spacings, the radial distance, area per plant, and plant density for each treatment are presented in (Table 1).

***Data collection***

To carry out this study, the Diameter at breast height (DBH) and total height (Ht) of all living trees 8–36 months of age, totaling eight ages, were measured every four months. Additionally, trees were scaled, and the diameters were measured in 0.5 m sections from the base of the bole to 5 m in height. Only the 16, 24, and 36 month-old trees were scaled, and five trees per age group and block were selected, totaling 180 trees. The DBH of the selected trees was close to the average DBH of each spacing at the age of 8 months. The same trees were measured during the subsequent survey.

***Prognosis of the diameter distribution***

The prognosis of the diameter distribution was determined using an alternative method of the theoretical redistribution of diameters, as proposed by Nogueira et al. (2005). The method consists of using a system of projection models. The independent variables at the current age are used to project the same variables at a future age, as used by Retslaff et al. (2012) and Leite et al. (2013). In this study, the Weibull 3P distribution was fitted, and its parameters were obtained by Lima et al. (2020).

The beta parameter (β>0) indicates the scale, that is, the amplitude of the theoretical diameter distribution curve. The gamma parameter (γ) represents the shape of the curve, where γ<1 indicates a negative hyperbolic-type curve (inverted-J); if γ=1, the shape of the curve is exponential; if γ= 2, it becomes the Rayleigh form (chi-square distribution); when 1 < c < 3.6, the distribution curve has a normal shape with positive asymmetry; if γ ≈ 3.6, the curve approximates the normal function; and γ> 3.6, the normal shape curve presents a negative asymmetry (Bailey and Dell, 1972; Clutter et al., 1983).

The projection minimum diameter (dmin) and maximum diameter (dmax) define the limits of the diameter distribution curves, and the total amplitude divided by the class amplitude (1 cm) defines the number of classes. In addition, dmin is associated with the alpha parameter (α) of the Weibull 3P distribution, which indicates the beginning of the diameter distribution curve. The fitting of the Weibull 3P distribution was performed using the maximum likelihood method (Lima et al., 2021). Parameter α was obtained independently from the system, with a percentage of dmin assigned, ranging from 0–100%, until the proposed value of α resulted in a combination that was not significant in the Kolmogorov–Smirnov (K-S) adherence test (SCOLFORO, 2006).

The number of trees (N) indicates the survival of the planted population, which can be estimated by a linear or non-linear function or predefined by a percentage of survival. As the survival percentage is influenced by tree density (spacing), it was decided to obtain equations that project mortality. However, equations estimating the future number of trees for spacings 4 (1.76 $m^3$) to 12 (41.25 $m^3$) were not fitted, as mortality was not significant (less than one tree) during the analyzed period.

Thus, the variables used for the projection were the beta (β) and gamma (γ) parameters of the Weibull 3P fitted distribution as described by Lima et al. (2021), minimum diameter (dmin), maximum diameter (dmax), and the number of trees (N). The ordinary least squares (OLS) method was used for fitting, and the projection model system used for each spacing is shown in Table 2.

After the system of equations projected the parameters, the diameter distribution was projected to a future age, always starting from an observed initial distribution, using the parameters of the Weibull 3P distribution according to Nogueira et al. (2005). The quality of the fittings was analyzed using root mean square error (RMSE%) and Pearson's correlation ($r_{y\hat{y}_i}$).

To validate the projection system, the estimated Weibull 3P distribution parameters were used to calculate the theoretical accumulated frequencies and compare them to the observed (current) accumulated frequencies using the Kolmogorov–Smirnov (KS) test (Gibbons and Subhabrata, 1992) at the 95% probability level. After the system of equations was validated, diameter distributions were designed for ages of 12, 24, 36, and 48 months for each of the evaluated spacings.

***Tapering and Hispometric Models***

Using the scaling data, the fitting of the taper model was carried out according to Garcia et al. (1993), using Equation 6 for each of the 12 spacings at ages 16, 24, and 36 months, totaling 45 trees per fitting. The equations allowed the mathematical description of the stem profile, and through its integral (Equation 7), it was possible to obtain the desired tree volumes and assortments (multiple products).

Additionally, using the DBH and total height data of all trees measured in the four-monthly evaluations (eight measurements), Trorey's linear hypsometric model was fitted for each spacing. The models were fitted using the ordinary least squares (OLS) method, and the fitting quality of the taper and hypsometric equations were determined using the root mean square error (RMSE%) and Pearson's correlation ($r_{y\hat{y}_i}$).

***Projection of volume per diametric class***

To estimate the total volume ($m^3 \cdot ha^{-1}$) per diameter class, hypsometric equations were used to estimate the average height in each diameter class, with estimates for ages 12, 24, and 36 months and predicted for 48 months of each spacing. Then, with the center of the diameter classes and the estimated average total height, the integrals of the taper equations were used to calculate the individual average volume of each class, spacing, and age. Finally, the distribution of the total volume was obtained by multiplying the volume per class by the number of trees projected through the parameters of the Weibull 3P distribution. The behavior of the projected volumetric distributions by diameter class for each spacing and age was visually compared using bar graphs.

With the total estimated volumes in hand, the technical cutting age was defined for each spacing by graphically plotting the current annual increment (CAI) and the average annual increment (AAI). The CAI and AAI were calculated using Equations 9 and 10, respectively (Leite and Campos, 2017).

***Used scenarios***

Using the estimated diameter distribution for 36 and the prognosis for 48 months for each spacing, a comparison was made between two scenarios: the population intended for multiple products (Scenario I), and the stand converted to a single product (Scenario II).

In Scenario I, for the conversion of trees into multiple products, the integral of the fitted equation of the general taper for each spacing was used to quantify the products, meeting the specifications of log length and minimum diameter with bark (Table 3). As for Scenario II, the use would be for firewood ($m^3$), with a minimum diameter of 4 cm and in logs of 2 m. A section length with a diameter smaller than 4 cm was considered residual for both scenarios.

**Conclusions**

The hypsometric, taper, and projection equation systems were accurate and consistent for all spacings.

The technical cutting age of the stand of spacing 1 was 24 months, spacings 2 and 3 were 36 months, and spacings 9 and 10 were 48 months. The technical cutting age has not yet been defined in the remaining spacings.

Spacings 2 and 4 were the most suitable for a short-term regime, with a vital area of 0.77 and 1.76 $m^2$ per plant, respectively.

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