Pertanika J. Trop. Agric. Sci. 46 (2): 627 - 645 (2023)

TROPICAL AGRICULTURAL SCIENCE

Journal homepage: http://www.pertanika.upm.edu.my/

Effects of Spacing on Early Growth Rate and Yield of Hybrid *Eucalyptus* Stands

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ABSTRACT

Optimizing tree spacing in a forest plantation is one of the main management techniques to improve stand quality and productivity. Its influence on growth from an early age is an important matter for forest management. This study aims to evaluate the effect of tree spacing on early growth rate and yield over time in *Eucalyptus grandis* × *Eucalyptus camaldulensis* hybrids. The data were obtained from an experiment in Itamarandiba, Minas Gerais, Brazil. The plots were composed of five planting spacing (3.00 m × 0.50 m, 3.00 m × 1.00 m, 3.00 m × 1.50 m, 3.00 m × 2.00 m, and 3.00 m × 3.00 m) measured at the ages of 7, 12, 24, 36, 48, 61, 77, 85, and 102 months. Growth and yield were analyzed by fitting the Gompertz model and a baseline exponential model up to 36 months of age to evaluate the influence of early growth on the harvest age. A Pearson correlation matrix was also generated to find out the relationship between the mean annual increment in the respective treatments during the studied period. It was observed that a positive correlation in the average annual increase in the 3 × 2 and 3 × 3 spacings. It was verified that tree spacing influenced the yielded wood volume and the optimal harvest age. The early growth rate influences the optimal

ARTICLE INFO

Article history:
Received: 08 November 2022
Accepted: 16 January 2023
Published: 18 April 2023

DOI: https://doi.org/10.47836/pjtas.46.2.15

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ISSN: 1511-3701
e-ISSN: 2231-8542

harvest, which may explain a possible loss of yield during the productive cycle of the forest stand.

Keywords: Growth and yield modeling, harvest planning, mean annual increment, optimal harvest age

INTRODUCTION

Brazil is one of the major suppliers of forest products and by-products (da Silva et al., 2017). The Brazilian forest-based industry has been highlighted for presenting the highest productivity with a short-rotation intensive culture (Moreira et al., 2017). *Eucalyptus* is an especially important species in Brazil due to its rapid growth, low-density canopy shape, and multiple uses for its wood (Souza et al., 2020). *Eucalyptus* timber is used for various purposes, such as producing timber plates, plywood, charcoal, wood foils, sawn timber, pulp, furniture, and building purposes (Gonçalves et al., 2008; Instituto Brasileiro de Geografia e Estatística [IBGE], 2021).

The growth rate of a forest stand is determined by factors such as the site`s productive capacity species, number, and spatial distribution of trees. It is also linked to soil conditions, as high salt concentrations can cause reductions in plant growth and productivity, such as for early growth eucalyptus clones (Lacerda, 2016). These characteristics need to be accounted for by the forest manager to select silvicultural treatments and harvest strategies (Clutter et al., 1983).

Mathematical models are often used to predict the growth and yield of a forest stand to aid in the decision-making process. Models are especially useful for reasoning, forecasting, and decision-making and aim to abstract and summarize the problem in real life (Buongiorno & Gilless, 2003). These models must be dependable to describe as precisely as possible the complex dynamics of the nonlinear system that is the growth of forest stands (Porté & Bartelink, 2002). The accuracy of growth estimates directly affects forest planning (Bettinger et al., 2017; Campos & Leite, 2017).

The spacing and spacing arrangement definition directly reflect the silvicultural activities in the stands. These activities influence the availability of resources for plant growth, forest management, wood quality, and production costs (Corrêa et al., 2020; de Oliveira Neto et al., 2003; Moulin et al., 2017).

Some factors must be taken into account to select the best number of trees per unit area: the population density, the local productive capacity, intended wood product, technological aspects (e.g., the equipment to be used for harvesting), silvicultural, ecological, and economic aspects, represented by climate, soil, relief, condition with higher or lower plantation density and management (Campos & Leite, 2017; Salles et al., 2012). At high-density spacings, the growth resources become limited more rapidly, resulting in suppressed individuals and a low population growth rate at relatively young ages (Soares et al., 2004).

In addition, the growth in diameter might also be influenced by the tree spacing, where the larger the spacing, the less competition among the trees and, thus, the greater development in diameter of the trees (Berger et al., 2002; Cockerham, 2004; dos Santos Leles et al., 2001; Pinkard & Neilsen, 2003).

Denser spacings generally provide trees with a smaller diameter and lower survival percentage but higher basal area per hectare and higher total volume per hectare (Stape & Binkley, 2010). However, denser plantations result in smaller trees, shorter rotation, and higher costs of mechanized harvesting, as tree spacing is one factor that defines the trees' growth rate. Meanwhile, the effects of tree spacing on early growth rates and final yields of hybrid *Eucalyptus* stands have not yet been decided. Based on the above, the study aimed to test if the spacing between eucalyptus trees affects the final yield evaluated from the early growth rate (less than 2 years). This study aims to evaluate the effects of spacing on early growth rate and yield over time in *Eucalyptus grandis* × *Eucalyptus camaldulensis* hybrid stands.

MATERIAL AND METHODS

Study Site and Experiment Design

The dataset for the development of the study was from a tree spacing experiment installed in a hybrid *E. grandis x E. camaldulensis* stand in Itamarandiba, in the Jequitinhonha Valley, Minas Gerais, Brazil (17.86° S latitude and 42.86° W longitude). The average annual temperature is 21.2°C, and the climate is tropical altitude with two well-defined seasons. The region has an altitude ranging from 645 to 1,648 m, with an average rainfall of 1,130 mm per year (Alvares et al., 2013).

The experiment started in 2002 and used a randomized block design with five treatments (spacing) and three blocks. Each experimental plot had six planting rows with 28 trees (168 trees) with a distance between rows equal to 3 m. The distance within rows varied according to the treatment and was defined as 0.5, 1.0, 1.5, 2.0, and 3.0 m. A double border was used with 48 measurable trees in each plot (Table 1). The detailed experiment design and dendrometry data by age and treatment in hybrid stands of *E. grandis* × *E. camaldulensis* are shown in Table S1.

Data Collection, Height, and Volume Estimates

The plots were measured at ages 7, 12, 18, 24, 36, 48, 61, 77, 85, and 102 months. In these ages, the circumference at the breast

Table 1
Experiment design and treatments to study the effects of spacing on the early growth rate and yield over time in hybrid Eucalyptus *stands*

Treatment	Spacing (m × m)	Area per tree (m²)	N° of tree in the block	N° of the tree on the border	N° of measurable tree per plot	Plot area (m²)
1	3.00 × 0.50	1.5	168	120	48	72
2	3.00 × 1.00	3.0	168	120	48	144
3	3.00 × 1.50	4.5	168	120	48	216
4	3.00 × 2.00	6.0	168	120	48	288
5	3.00 × 3.00	9.0	168	120	48	432

height of all trees in each experimental plot was measured using a measuring tape. From the age of 48 months onward, the heights of the first 12 normal trees in each plot were measured (Paulino, 2012). A Haglöf hypsometer (Sweden) was used to measure these heights. A hypsometric equation (Equation 1) was fitted to estimate the tree heights that were not measured.

A total of 245 sample trees were scaled by measuring the diameter at every 1-meter section of the stem and calculating their total stem volumes using Smalian's formula. The data from these trees fit the Schumacher and dos Santos Hall (1933) model to estimate the volume for all trees in the plots (Equation 2).

$$LnHt = \beta_0 + \beta_1 Dbh^{-1} + \varepsilon \quad (1)$$

$$LnV = \beta_0 + \beta_1 LnDbh + \beta_2 LnHt + \varepsilon \quad (2)$$

where, V = Volume (m^3); Dbh = Diameter at breast height (cm); Ht = Total height (m); Ln = Natural logarithm; $\beta_0, \beta_1, \beta_2$ = Regression coefficient; and ε = Random error

Growth and Yield Modeling

The growth and yield model were developed using the measurements from 7 to 102 months old stands. The Gompertz model (Gompertz, 1833) (Equation 3) was fitted for each treatment in the experiment. The Gompertz model is the most suitable for analyzing growth as a function of age for eucalypt stands (Reis et al., 2022):

$$Y = \beta_0 e^{-e^{\beta_1 - \beta_2 A}} \quad (3)$$

where, Y = Estimated volume outside bark; $\beta_0, \beta_1, \beta_2$ = Regression coefficients ; and A = Age (months)

The equations to generate the current monthly increment (CMI) and acceleration curves were obtained through the first (Equation 4) and second (Equation 5) derivatives of the Gompertz model, respectively. The curves were created by treatment.

1st derivative of the Gompertz model:

$$Y' = \beta_0 \beta_2 e^{\left(-e^{(\beta_1 - \beta_2 X)} - \beta_2 A + \beta_1\right)} \quad (4)$$

2nd derivative of the Gompertz model:

$$Y'' = \beta_0 \beta_2 (\beta_2 e^{(\beta_1 - \beta_2 A)} - \beta_2) e^{\left(-e^{(\beta_1 - \beta_2 A)} - \beta_2 A + \beta_1\right)} \quad (5)$$

The model was evaluated using the correlation $ry\hat{y}$ between observed and estimated volume (Equation 6), percent root mean square error (RMSE%) (Equation 7), and bias (Equation 8). The scatterplots between observed and estimated values were also analyzed.

$$ry\hat{y} = \frac{n^{-1} \sum_{i=1}^{n} (\hat{Y}_i - \hat{Y}_m)(Y_i - \overline{Y})}{\sqrt{n^{-1} \sum_{i=1}^{n} (\hat{Y}_i - \hat{Y}_m)^2 n^{-1} \sum_{i=1}^{n} (Y_i - \overline{Y})^2}} \quad (6)$$

$$RMSE\% = 100 \overline{Y_i}^{-1} \sqrt{\frac{\sum_{i=1}^{n} (\hat{Y}_i - Y_i)^2}{n}} \quad (7)$$

$$bias = \frac{1}{n} \sum_{i=1}^{n} (\hat{Y}_i - Y_i) \quad (8)$$

where, Y_i and $\hat{Y}_i$ = Observed and estimated volumes, respectively; $\overline{Y}$ and $\hat{Y}_m$ = Mean of the observed and estimated values, respectively; n = Number of cases

Assessment of Early Growth Rate and Yield

The exponential model was fitted for each plot and treatment for the early ages of 7 to 36 months to evaluate the influence of the early growth rate on the mean annual increment (MAI) 6 (MAI 6) and 7 years (MAI 7). The parameter estimates were then related to yield at 6 and 7 years.

$$Y = \beta_0 A^{\beta_1} \quad (9)$$

where, Y = Yield (m^3 ha^{-1} $year^{-1}$); β_0, β_1 = Parameters of the equation; A = Age in months, up to the age of 3 years (36 months)

An exponential reference model, up to 36 months of age, was fitted with a higher early growth rate. Finally, the influence of early growth on the cutting age was evaluated by comparing parameter β_1s with MAI 6 and MAI 7.

A Pearson correlation matrix was generated in R studio (R Core Team, 2020) using the corrplot package (Wei et al., 2021), and the Shapiro-Wilk normality test was performed using the nortest package (Gross & Ligges, 2015) for each treatment to figure out the relationship between MAI in the respective treatments over the studied period. In this way, it was possible to infer in each treatment if the early yield has any positive relationship with the final yield.

RESULTS

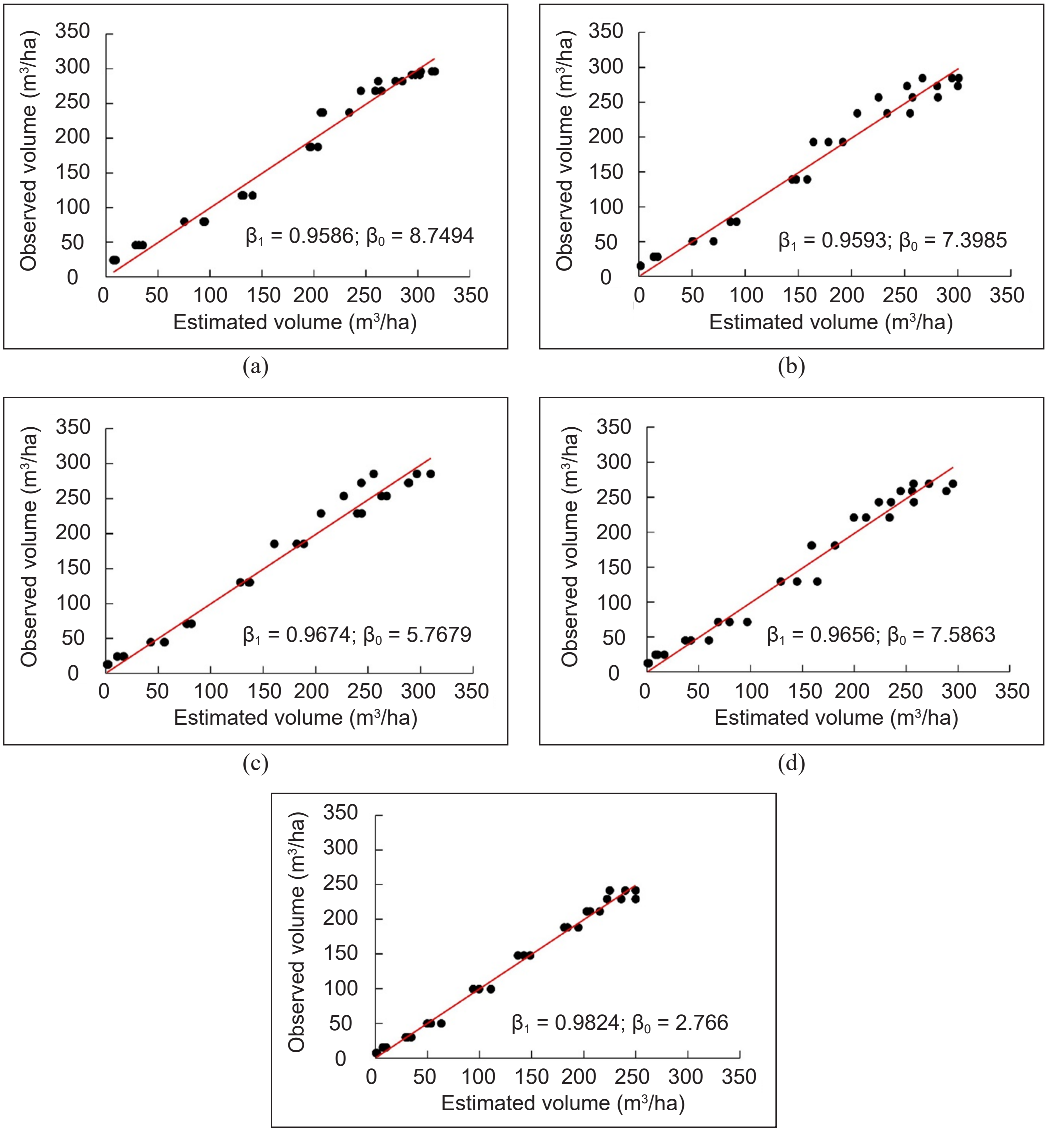
It was observed that all treatments slightly underestimated the total volume. Treatment 4 had the highest bias, and Treatment 2 had the highest RMSE%. The lowest RMSE% was obtained in Treatment 5. All treatments showed a Pearson correlation between observed and estimated volume higher than 98%. The model results and parameters for each treatment can be seen in Table 2, and its distribution graph is in Figure 1.

Figure 2 illustrates the growth curves obtained for the outside bark wood volume as a function of the age in months, the current monthly increment (CMI), mean

Table 2
Parameter estimates and performance statistics for the Gompertz model for each treatment in hybrid eucalypt stands

Treatments	Spacing (m × m)	Parameters					
		β_0	β_1	β_2	Bias	RMSE%	Ryy′
1	3.00 x 0.50	299.3482	1.3215	0.0578	-1.2246	15.2907	0.9896
2	3.00 x 1.00	293.994	1.4198	0.0476	-1.1218	16.2654	0.9878
3	3.00 x 1.50	296.6093	1.467	0.0462	-0.8735	14.9302	0.9898
4	3.00 x 2.00	278.3436	1.4564	0.0479	-1.2320	15.9876	0.9872
5	3.00 x 3.00	252.1766	1.5925	0.0461	-0.6413	7.8878	0.9962

Note. $\beta_0, \beta_1, \beta_2$ = Parameters of the equation $Y = \beta_0 e^{-e^{\beta_1 - \beta_2 A}}$, where Y = volume outside bark (m^3/ha) and A = age (months); RMSE% = Percentage of root mean square error; Ryy′ = Correlation between the observed and estimated volume



(e)

Figure 1. Distribution of observed volumes (m³/ha) on the y-axis and estimated volumes (m³/ha) on the x-axis by treatment for the ages of 7 to 102 months in hybrid eucalypt stands: (a) Treatment 1; (b) Treatment 2; (c) Treatment 3; (d) Treatment 4; and (e) Treatment 5

monthly increment (MMI), and Acceleration curves. The growth acceleration curve is null when the maximum current monthly increment (MCMI) is reached, and they must occur at the same age.

The null hypothesis of normality was not rejected in 33 of 35 cases, with $0.1041 \leq p\text{-value} \leq 0.9869$. In the other three cases, the *p*-values were 0.0289, 0.0308, and 0.0372 (Table S3). The highest positive

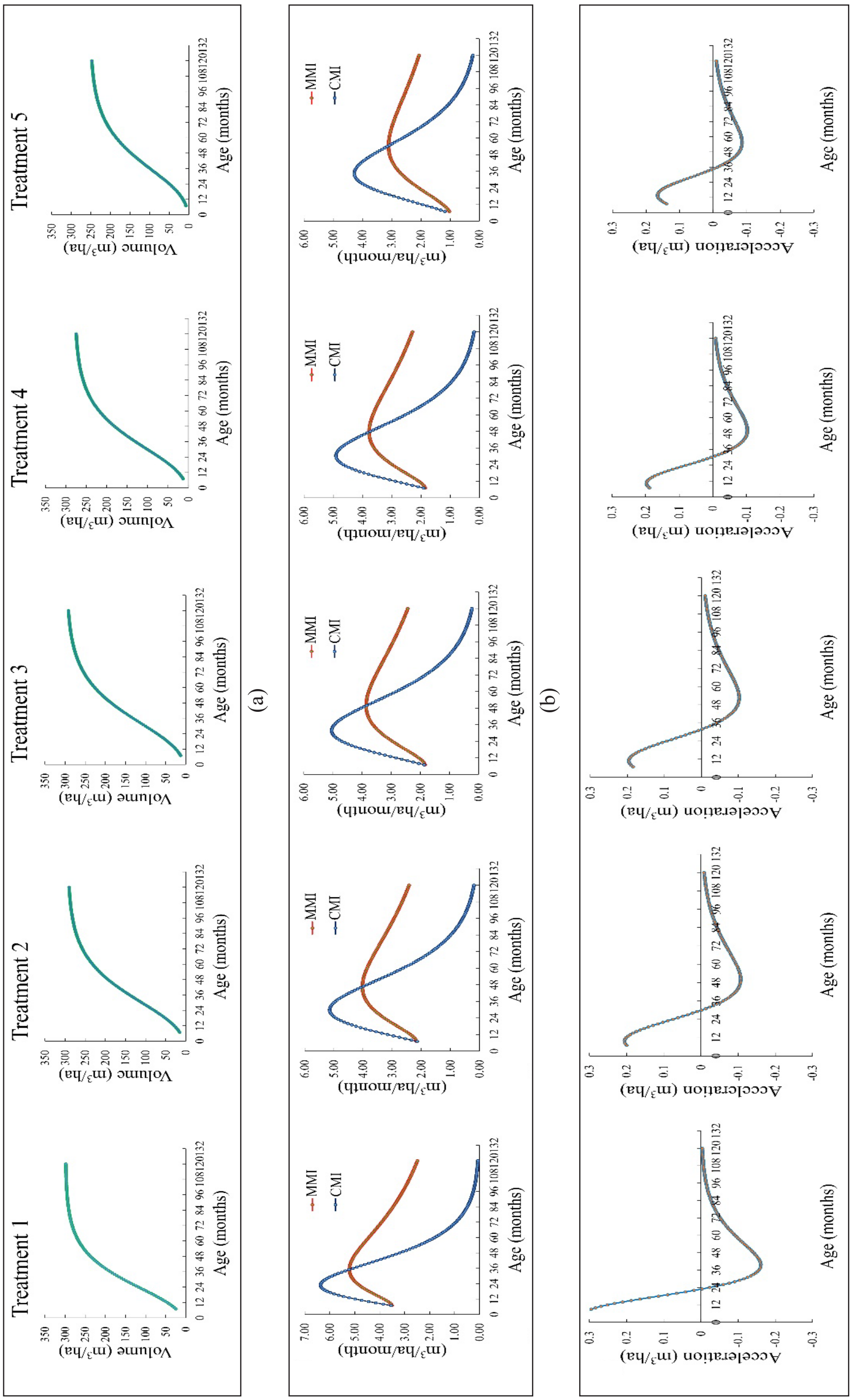


Figure 2. Relationship between growth and yield for each treatment studied in hybrid eucalypt stands: (a) Production; (b) Current monthly increment (CMI), Mean monthly increment (MMI); and (c) Acceleration curves

correlations were observed for Treatments 4 and 5, representing 3 × 2 and 3 × 3-meter spacings (Figure 3).

Table 3 shows the parameter estimates for IMA6 and IMA7. The parameter β_1 of the exponential model indicates the growth rate. Treatment 1 had the lowest parameter value and the highest yield and Treatment 5 had the highest and lowest yield. As shown in Figure 4, the trend was for a lower yield (i.e., lower MAI6 and MAI7) when the parameter β_1 value was higher (i.e., higher early growth rates). This behavior was both for increases at ages 6 and 7.

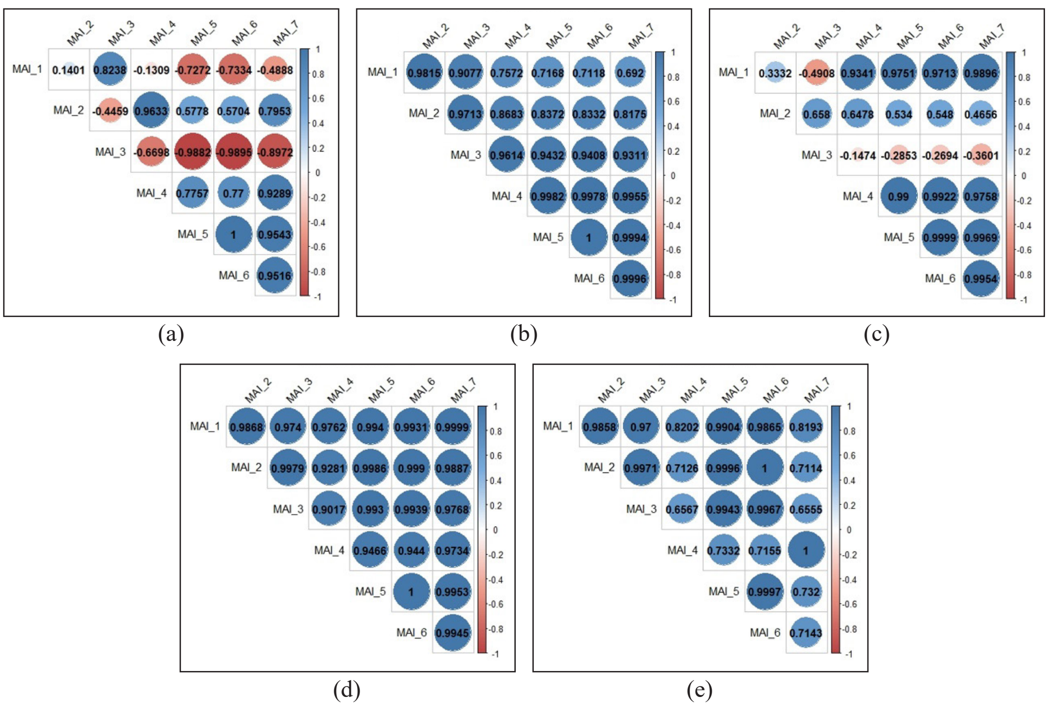


Figure 3. Pearson correlation matrices for mean productivities in the ages of 1 to 7 years in hybrid eucalypt stands: (a) Treatment 1; (b) Treatment 2; (c) Treatment 3; (d) Treatment 4; and (e) Treatment 5

Table 3
Estimation of parameter β_1 of the exponential model and mean annual increment at 6 and 7 years in hybrid eucalypt stands

Treatment	Spacing (m × m)	Plot	β_1	MAI 6	MAI 7
1	3.00 × 0.50	1	0.53	47.5	42.6
1	3.00 × 0.50	6	0.49	43.7	41.5
1	3.00 × 0.50	11	0.54	46.4	42
2	3.00 × 1.00	2	0.7	46.9	42.4
2	3.00 × 1.00	7	0.74	42.9	39.6
2	3.00 × 1.00	12	0.69	37.6	35.6
3	3.00 × 1.50	3	0.76	44.6	40.8

Table 3 *(continue)*

Treatment	Spacing (m × m)	Plot	β_1	MAI 6	MAI 7
3	3.00 × 1.50	8	0.83	43.8	40.7
3	3.00 × 1.50	13	0.7	37.8	34.4
4	3.00 × 2.00	4	0.68	42.9	40.7
4	3.00 × 2.00	9	0.73	39.2	36.1
4	3.00 × 2.00	14	0.75	37.3	34.5
5	3.00 × 3.00	5	0.82	35.9	35.3
5	3.00 × 3.00	10	0.81	34.4	31.4
5	3.00 × 3.00	15	0.89	33.8	33.3

Note. β_1 = Parameter of the equation $MAI_i = \beta_0 A^{\beta_1}$, where *MAI* = Mean annual increment (m³/ha/year) at 6 and 7 years and A = Age in months, up to the age of 3 years (36 months)

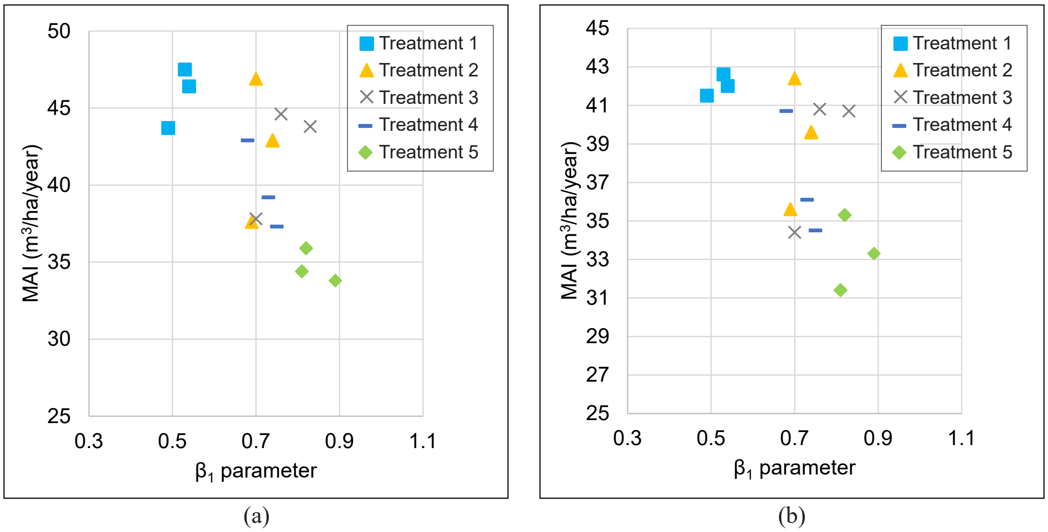


Figure 4. Correlation analysis of parameter (β_1) of the exponential model with mean annual increment (MAI) in hybrid eucalypt stands at (a) 6 and (b) 7 years, respectively

DISCUSSION

This study evaluated the effect of tree spacing on early growth rate and final yield. It was observed that distance within trees in a row influences turnover and yield. Using inventory data in ages lower than two years can lead to inefficiencies in modeling. It, associated with economic issues, reinforces the proposal to carry out a continuous forest inventory of *Eucalyptus* stands from two years of age.

Growth and yield were evaluated by fitting the Gompertz model and found that it was unbiased and allowed the evaluation of the characteristics of each treatment, such as optimal harvest age, zero acceleration age, and MCMI, and to analyze the effect of spacing. Leite et al. (2006), studying

Pinus taeda stands, concluded that spacing influences the volume growth trend per hectare as a function of fertilization and tree spacing; they also observed higher volume yield per unit area at smaller spacings in *E. camaldulensis* stands (de Oliveira Neto et al., 2003). However, Schneider and Schneider (2008) affirmed that the total volume per hectare increases with the number of trees until a certain planting density is reached (critical density), after which the increase in the number of trees causes the reduction of the total volume per hectare due to mortality for competition.

With the increase in tree spacing, it is expected a delay in the optimal harvest age (MMI = CMI). It was observed in Treatments 1, 2, 3, and 5, where the optimal harvest age is about 34 months for Treatment 1, 42 months for Treatment 2, 49 months for Treatment 3, and about 59 months of age for Treatment 5.

Treatment 4 had an unexpected behavior because an ideal harvest age between 49 and 59 months was expected. According to the intersection point of the MMI = CMI curves, the optimal harvest age is 48 months for Treatment 4. On the other hand, Treatment 1 presents the intersection point at 34 months. It may be explained due to the denser spacing in Treatment 1, so the age for harvest tends to be early. More details can be found in Table S2.

Treatments 1, 3, and 5 had an expected behavior where the null acceleration must coincide with the same period of the MCMI. Treatment 1 was at 31 months, Treatment 3 at 32 months, and Treatment 5 at 43 months of age. On the other hand, Treatments 2 and 4 did not have similar behavior. They did not present the same period of null acceleration with the MCMI. Treatment 2 had the maximum increment at 31 months and the null acceleration at 29 months. Whereas, for Treatment 4, the maximum increment was observed at about 29 months and null acceleration at 30 months. Furthermore, relatively low correlations were observed between early yield (1 and 3 years) and yield at 6 and 7 years.

Positive correlations were seen only in Treatments 4 and 5, characterized by spacings 3 × 2 and 3 × 3 meters within rows. It is possible to infer that an increase in the yield at early ages results in an increase in the yield at final ages and, therefore, a reduction in the rotation period. It shows the risk when selecting genotypes based on clonal tests or other types of experiments based on the results of measurements made at early ages, mainly before 3 years.

This trend, however, may not occur in a high-quality site. In this case, the environment supports high growth rates for longer. On the other hand, if the environment is not able to support the early growth rate, there will be a possible reduction in yield at the harvest age (7 years).

Figure 4 shows the estimates for the parameter β_1 in the function of the yield at 7 years, where the higher the value of the parameter (i.e., higher early growth rate), the lower the MAI 7 in relation to the maximum mean annual increment (MMAI) (about 3 years). However, this trend may not occur if the site's quality is extremely high.

Genetic materials with high early growth rates present a greater difference between MMAI and MAI 7 regardless of the tree spacing, with MAI 7 < MMAI. Plots with denser tree spacing tended to have a higher total yield which is also observed in the works of Corrêa et al. (2020) as well as Watzlawick and Carla Benin (2020), with a shorter cutting cycle. Nonetheless, it is important to consider wood use, where a greater total yield does not imply a higher economic return. For instance, a higher total yield may imply higher economic return for energy purposes since there is no effect on wood density and calorific value. Thus, choosing genetic materials with lower early growth rates based on site quality may be an alternative for forest-based companies to reduce yield losses at the end of the cutting cycle.

The growth of a forest stand depends on the genetic material, age, productive capacity, the degree of utilization of the productive potential of the site, silvicultural treatments, and the most relevant environmental factors are the availability of water for the plants throughout the years, temperature, and solar radiation (Campos & Leite, 2017; de Alcantra et al., 2018). The clones developed in Minas Gerais showed a good adaptation to the environmental conditions of the site, with high production (dos Santos et al., 2017).

CONCLUSION

Tree spacing directly affects eucalypt stands growth rates. This study found that distance between trees affects the early growth rate of *Eucalyptus* trees for a fixed distance between rows. It is especially highlighted in early ages (< 2 years) and was noted for the most common tree spacing designs used in eucalyptus plantations. The results suggest that growth and yield models can be affected using datasets collected early in the growth stages. Therefore, forest yield prognosis using only data from early age inventory can have relatively low accuracy. It highlights the importance of continuously collecting inventory data, especially using information from stands older than 2 years to infer the growth and yield of eucalyptus forest plantations.

ACKNOWLEDGEMENTS

This work was carried out with the support of the “Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brasil – CAPES” – Financing Code 001.

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APPENDICES

Supplementary Table 1
Dendrometric data by age and treatment in hybrid eucalypt stands

Treatment	Spacing (m × m)	Age (months)	QMD (cm)	BA (m^2/ha)	Volume (m^3/ha)
1	3.00 × 0.50	7	2.77	4.02	7.85
1	3.00 × 0.50	12	4.00	8.38	31.63
1	3.00 × 0.50	18	5.52	16.00	87.97
1	3.00 × 0.50	24	6.36	21.15	134.51
1	3.00 × 0.50	36	7.08	24.69	199.00
1	3.00 × 0.50	48	7.38	26.92	216.42
1	3.00 × 0.50	61	7.84	29.72	256.37
1	3.00 × 0.50	72	8.04	31.02	275.18
1	3.00 × 0.50	85	8.27	32.77	297.89
1	3.00 × 0.50	102	8.57	33.64	310.96
2	3.00 × 1.00	7	3.04	2.30	1.82
2	3.00 × 1.00	12	4.65	5.68	15.60
2	3.00 × 1.00	18	6.78	12.08	57.47
2	3.00 × 1.00	24	7.65	15.32	88.24
2	3.00 × 1.00	36	8.78	18.91	150.33
2	3.00 × 1.00	48	9.22	21.00	178.31
2	3.00 × 1.00	61	9.82	23.29	231.40
2	3.00 × 1.00	72	10.04	24.56	254.77
2	3.00 × 1.00	85	10.42	25.86	277.71
2	3.00 × 1.00	102	10.83	26.64	287.46
3	3.00 × 1.50	7	3.07	1.66	1.94
3	3.00 × 1.50	12	5.00	4.38	15.04
3	3.00 × 1.50	18	7.33	9.40	51.70
3	3.00 × 1.50	24	8.32	12.08	78.75
3	3.00 × 1.50	36	9.87	16.38	133.90
3	3.00 × 1.50	48	10.60	19.07	177.12
3	3.00 × 1.50	61	11.25	21.05	229.49
3	3.00 × 1.50	72	11.44	21.86	252.46
3	3.00 × 1.50	85	11.92	23.62	273.62
3	3.00 × 1.50	102	12.37	24.32	287.16
4	3.00 × 2.00	7	2.96	1.16	1.15
4	3.00 × 2.00	12	5.16	3.52	11.89
4	3.00 × 2.00	18	7.83	8.08	46.38
4	3.00 × 2.00	24	9.40	11.59	81.63
4	3.00 × 2.00	36	10.91	14.77	146.04
4	3.00 × 2.00	48	11.77	17.23	166.42
4	3.00 × 2.00	61	12.59	19.28	214.90
4	3.00 × 2.00	72	12.85	20.28	238.77

Supplementary Table 1 *(continue)*

Treatment	Spacing (m × m)	Age (months)	QMD (cm)	BA (m^2/ha)	Volume (m^3/ha)
4	3.00 × 2.00	85	13.32	21.59	262.99
4	3.00 × 2.00	102	13.75	21.98	274.70
5	3.00 × 3.00	7	3.31	0.96	0.84
5	3.00 × 3.00	12	5.64	2.79	8.35
5	3.00 × 3.00	18	8.48	6.28	31.55
5	3.00 × 3.00	24	10.07	8.86	55.49
5	3.00 × 3.00	36	12.10	12.31	101.41
5	3.00 × 3.00	48	13.06	14.67	142.68
5	3.00 × 3.00	61	14.07	16.68	186.78
5	3.00 × 3.00	72	14.27	17.00	208.30
5	3.00 × 3.00	85	15.11	18.84	236.13
5	3.00 × 3.00	102	15.52	18.85	238.26

Note. QMD = Quadratic mean diameter; BA = Basal area

Table S2
Table of production for each of the treatments in hybrid eucalypt stands

	Treatment 1				Treatment 2				Treatment 3				Treatment 4				Treatment 5			
Age (months)	Volume (m^3/ha)	MMI (m^3/ha/month)	CMI (m^3/ha)	Acceleration (m^3/ha)	Volume (m^3/ha)	MMI (m^3/ha/month)	CMI (m^3/ha)	Acceleration (m^3/ha)	Volume (m^3/ha)	MMI (m^3/ha/month)	CMI (m^3/ha)	Acceleration (m^3/ha)	Volume (m^3/ha)	MMI (m^3/ha/month)	CMI (m^3/ha)	Acceleration (m^3/ha)	Volume (m^3/ha)	MMI (m^3/ha/month)	CMI (m^3/ha)	Acceleration (m^3/ha)
7	24.54	3.51	3.55	0.31	15.16	2.17	2.14	0.20	12.88	1.84	1.87	0.18	12.94	1.85	1.90	0.19	7.17	1.02	1.18	0.14
8	28.24	3.53	3.85	0.30	17.40	2.18	2.34	0.20	14.84	1.85	2.05	0.19	14.94	1.87	2.09	0.19	8.42	1.05	1.32	0.15
9	32.25	3.58	4.15	0.29	19.84	2.20	2.54	0.21	16.99	1.89	2.25	0.19	17.13	1.90	2.29	0.20	9.81	1.09	1.47	0.15
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31	160.31	5.17	5.79	-0.13	114.09	3.68	5.14	-0.01	105.45	3.40	5.04	0.01	105.30	3.40	4.90	-0.01	77.68	2.51	4.22	0.03
32	166.03	5.19	5.66	-0.13	119.22	3.73	5.12	-0.02	110.50	3.45	5.04	0.00	110.20	3.44	4.89	-0.02	81.92	2.56	4.25	0.02
33	171.62	5.20	5.52	-0.14	124.32	3.77	5.09	-0.03	115.54	3.50	5.04	-0.01	115.08	3.49	4.87	-0.03	86.17	2.61	4.27	0.01
34	*177.07*	*5.21*	*5.38*	*-0.15*	129.39	3.81	5.05	-0.04	120.57	3.55	5.02	-0.02	119.93	3.53	4.84	-0.04	90.44	2.66	4.28	0.01
35	182.37	5.21	5.23	-0.15	134.42	3.84	5.00	-0.05	125.57	3.59	4.99	-0.03	124.75	3.56	4.80	-0.05	94.72	2.71	4.28	0.00
36	187.52	5.21	5.07	-0.16	139.40	3.87	4.95	-0.06	130.55	3.63	4.95	-0.04	129.52	3.60	4.75	-0.05	98.99	2.75	4.27	-0.01
37	192.51	5.20	4.91	-0.16	144.32	3.90	4.88	-0.07	135.48	3.66	4.91	-0.05	134.23	3.63	4.69	-0.06	103.25	2.79	4.25	-0.02
38	197.35	5.19	4.75	-0.16	149.17	3.93	4.81	-0.07	140.36	3.69	4.86	-0.06	138.89	3.66	4.62	-0.07	107.49	2.83	4.23	-0.03
39	202.02	5.18	4.59	-0.16	153.94	3.95	4.74	-0.08	145.19	3.72	4.80	-0.06	143.48	3.68	4.55	-0.07	111.70	2.86	4.19	-0.04
40	206.53	5.16	4.43	-0.16	158.64	3.97	4.66	-0.08	149.95	3.75	4.73	-0.07	148.00	3.70	4.48	-0.08	115.88	2.90	4.15	-0.04
41	210.88	5.14	4.27	-0.16	163.25	3.98	4.57	-0.09	154.64	3.77	4.66	-0.08	152.44	3.72	4.40	-0.08	120.01	2.93	4.11	-0.05
42	215.07	5.12	4.11	-0.16	*167.78*	*3.99*	*4.48*	*-0.09*	159.26	3.79	4.58	-0.08	156.79	3.73	4.31	-0.09	124.09	2.95	4.06	-0.05
43	219.11	5.10	3.95	-0.16	172.21	4.00	4.38	-0.10	163.80	3.81	4.50	-0.08	161.05	3.75	4.22	-0.09	128.12	2.98	4.00	-0.06
44	222.98	5.07	3.80	-0.15	176.54	4.01	4.28	-0.10	168.26	3.82	4.41	-0.09	165.23	3.76	4.13	-0.09	132.09	3.00	3.94	-0.06
45	226.70	5.04	3.64	-0.15	180.77	4.02	4.18	-0.10	172.62	3.84	4.32	-0.09	169.31	3.76	4.03	-0.10	135.99	3.02	3.87	-0.07
46	230.27	5.01	3.49	-0.15	184.90	4.02	4.08	-0.10	176.90	3.85	4.23	-0.09	173.29	3.77	3.93	-0.10	139.83	3.04	3.80	-0.07

Supplementary Table 2 *(continue)*

	Treatment 1				Treatment 2				Treatment 3				Treatment 4				Treatment 5			
Age (months)	Volume (m^3/ha)	MMI (m^3/ha/month)	CMI (m^3/ha)	Acceleration (m^3/ha)	Volume (m^3/ha)	MMI (m^3/ha/month)	CMI (m^3/ha)	Acceleration (m^3/ha)	Volume (m^3/ha)	MMI (m^3/ha/month)	CMI (m^3/ha)	Acceleration (m^3/ha)	Volume (m^3/ha)	MMI (m^3/ha/month)	CMI (m^3/ha)	Acceleration (m^3/ha)	Volume (m^3/ha)	MMI (m^3/ha/month)	CMI (m^3/ha)	Acceleration (m^3/ha)
47	233.69	4.97	3.35	-0.15	188.93	4.02	3.97	-0.11	181.08	3.85	4.13	-0.10	177.17	3.77	3.83	-0.10	143.60	3.06	3.73	-0.08
48	236.96	4.94	3.20	-0.14	192.85	4.02	3.87	-0.11	185.16	3.86	4.03	-0.10	*180.96*	*3.77*	*3.73*	*-0.10*	147.29	3.07	3.65	-0.08
49	240.09	4.90	3.06	-0.14	196.66	4.01	3.76	-0.11	*189.14*	*3.86*	*3.93*	*-0.10*	184.64	3.77	3.63	-0.10	150.90	3.08	3.57	-0.08
50	243.09	4.86	2.93	-0.13	200.37	4.01	3.65	-0.11	193.03	3.86	3.83	-0.10	188.22	3.76	3.53	-0.10	154.43	3.09	3.49	-0.08
51	245.95	4.82	2.79	-0.13	203.97	4.00	3.55	-0.11	196.81	3.86	3.73	-0.10	191.69	3.76	3.42	-0.10	157.88	3.10	3.41	-0.08
52	248.68	4.78	2.67	-0.13	207.47	3.99	3.44	-0.11	200.49	3.86	3.63	-0.10	195.06	3.75	3.32	-0.10	161.25	3.10	3.32	-0.08
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..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
56	258.38	4.61	2.20	-0.11	220.38	3.94	3.02	-0.10	214.20	3.83	3.22	-0.10	207.54	3.71	2.92	-0.10	173.86	3.10	2.98	-0.09
57	260.53	4.57	2.09	-0.10	223.35	3.92	2.92	-0.10	217.37	3.81	3.12	-0.10	210.41	3.69	2.82	-0.10	176.80	3.10	2.89	-0.09
58	262.57	4.53	1.99	-0.10	226.22	3.90	2.82	-0.10	220.45	3.80	3.02	-0.10	213.18	3.68	2.72	-0.10	179.65	3.10	2.81	-0.09
59	264.51	4.48	1.89	-0.10	228.99	3.88	2.72	-0.10	223.42	3.79	2.93	-0.10	215.85	3.66	2.63	-0.09	*182.41*	*3.09*	*2.72*	*-0.08*
60	266.35	4.44	1.80	-0.09	231.67	3.86	2.63	-0.10	226.30	3.77	2.83	-0.10	218.44	3.64	2.54	-0.09	185.09	3.08	2.64	-0.08
61	268.11	4.40	1.71	-0.09	234.25	3.84	2.53	-0.09	229.09	3.76	2.74	-0.09	220.93	3.62	2.44	-0.09	187.69	3.08	2.56	-0.08
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..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
118	298.13	2.53	0.07	0.00	289.59	2.45	0.21	-0.01	291.17	2.47	0.25	-0.01	274.18	2.32	0.20	-0.01	246.85	2.09	0.24	-0.01
119	298.20	2.51	0.07	0.00	289.79	2.44	0.20	-0.01	291.41	2.45	0.24	-0.01	274.37	2.31	0.19	-0.01	247.09	2.08	0.23	-0.01
120	298.26	2.49	0.06	0.00	289.99	2.42	0.19	-0.01	291.64	2.43	0.23	-0.01	274.56	2.29	0.18	-0.01	247.32	2.06	0.22	-0.01

Note: MMI = Mean month increment; CMI = Current month increment; Underlined values = The production at the optimal harvest age

Table S3
Shapiro-Wilk normality test for mean productivity in the ages of 1 to 7 years in hybrid eucalypt stands

Treatment	Period	W	*p*-value
1	MAI_1	1.00	0.89
1	MAI_2	0.90	0.38
1	MAI_3	0.86	0.26
1	MAI_4	0.81	0.14
1	MAI_5	0.95	0.55
1	MAI_6	0.94	0.54
1	MAI_7	1.00	0.87
2	MAI_1	0.88	0.33
2	MAI_2	0.77	0.04
2	MAI_3	0.93	0.50
2	MAI_4	1.00	0.97
2	MAI_5	0.99	0.86
2	MAI_6	0.99	0.84
2	MAI_7	0.99	0.79
3	MAI_1	0.85	0.25
3	MAI_2	0.80	0.10
3	MAI_3	0.86	0.27
3	MAI_4	0.92	0.45
3	MAI_5	0.83	0.18
3	MAI_6	0.84	0.21
3	MAI_7	0.76	0.03
4	MAI_1	0.92	0.45
4	MAI_2	0.98	0.76
4	MAI_3	1.00	0.88
4	MAI_4	0.76	0.03
4	MAI_5	0.97	0.66
4	MAI_6	0.97	0.67
4	MAI_7	0.93	0.47
5	MAI_1	0.83	0.18
5	MAI_2	0.93	0.50
5	MAI_3	0.97	0.65
5	MAI_4	1.00	0.98
5	MAI_5	0.92	0.44
5	MAI_6	0.93	0.49
5	MAI_7	1.00	0.99