Evaluation of different silvicultural management techniques and water seasonality on yield of eucalyptus stands

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Introduction

The adoption of adequate management of factors that influence plant growth provides gains in forest yield, mainly in terms of water availability [Binkley et al., 2017], which depends on rainfall seasonality that reduces forest yield during the dry periods. Few studies have evaluated forest yield every six months to quantify the magnitude of plant growth during the dry and wet periods of the year [Stape et al., 2006, 2010].

Another relevant point is nutritional management. Due to the predominance of eucalyptus plantations in soils with low fertility, the addition of mineral fertilizers has become essential to achieve high yields and reduce the rotation period in a sustainable way [Gonçalves et al., 2013; Carrero et al., 2018]. Thus, studies have investigated the effects fertilization on forest plantations, which may vary according to edaphoclimatic conditions, genetic material, stage of forest development, uniformity level, and management regime adopted, such as first or second rotations [Melo et al., 2015; Silva et al., 2016].

Regarding stand uniformity, regular supply of the correct amount of growth resources results in the greater survival of individual plants, which is essential for uniform planting and reaching attainable plantation yield [Stape et al., 2010; Resende et al., 2016; Soares et al., 2016]. This highlights the importance of these variables in the evaluation of yield gains of forest plantations.

The extent of yield gains of planted forests can be estimated using the concept of production ecology [Lansigan, 1998]. In this sense, plant yield can be divided into potential, attainable, and observed, which considers determination, limitation, and reduction of growth factors involved. Therefore, knowing the yield potential of a region is of great relevance for management practices that control factors that influence yield gains.

This study evaluated the influence of water seasonality, nutritional management, and uniformity on plantation yield. We also estimated the potential, attainable, and observed yield of adult eucalyptus stands.

Materials and Methods

The study was carried out on clonal Eucalyptus stands in six regions (R1; R2; R3; R4; R5 and R6) in the state of Minas Gerais, Brazil [Figure 1, Tables 1 and 2].

The study comprised 284 circular plots installed across six regions. Crop yield was assessed across the 142 plots of the continuous forest inventory (CFI) network of a private enterprise. The plots chosen represent stands across the four age classes (ACL). The first was between 30 to 35 months (ACL1), the second between 42 to 47 months (ACL2), the third between 54 to 59 months (ACL3), and the fourth between 66 to 70 months (ACL4). Each plot consisted of 60 trees with spacing from 4.9 to 9.5 m² per plant. Fifteen clones were evaluated under two management regimes, first and second rotations, respectively (Table 3). The plots where the CFI plots were allocated received operational fertilization (OF) (Table 4) and the best silvicultural practices adopted by the enterprise. Operational fertilization was prescribed based on the nutritional balance method [Barros et al., 2000], calibrated by field experimentation for the edaphoclimatic conditions of the regions.
Figure 1 – Schematic representation of the study sites in the state of Minas Gerais, Brazil.

Table 1 – Characteristics of the study regions.

| Region | Municipalities                  | Latitude (S) / Longitude (W) | Elv. (m) | Climate b | T (°C) | R (mm) | Soil order |
|--------|---------------------------------|-------------------------------|----------|-----------|--------|--------|------------|
| R1     | Três Marias                     | 18°20'59" S 45°22'57" W      | 594      | Cwa       | 21     | 1396   | Oxisols    |
|        | Lassance                        | 17°89'51" S 44°57'93" W      | 554      | Aw        | 21     | 1335   |            |
| R2     | Rio Pardo de Minas              | 15°61'31" S 42°54'12" W      | 796      | Cwa       | 21     | 903    | Oxisols    |
|        | Ibertioga                       | 21°42'94" S 43°36'81" W      | 1021     | Cwb       | 17     | 1555   |            |
|        | São João Del Rei                | 21°13'55" S 44°26'09" W      | 908      | Cwb       | 18     | 1575   |            |
| R3     | Luminárias                      | 21°51'23" S 44°06'61" W      | 946      | Cwb       | 18     | 1594   |            |
|        | Inga                            | 21°40'37" S 44°26'49" W      | 947      | Cwb       | 18     | 1614   | Oxisols and Ultisols |
|        | Nazareno                        | 21°21'77" S 44°61'72" W      | 921      | Cwb       | 18     | 1689   |            |
|        | Santo Antônio do Amparo         | 20°94'62" S 44°11'87" W      | 1008     | Cwb       | 18     | 1709   |            |
|        | Itibiruna                       | 21°14'65" S 44°73'84" W      | 866      | Cwb       | 19     | 1714   |            |
| R4     | João Pinheiro                   | 21°14'65" S 44°73'84" W      | 769      | Aw        | 22     | 1419   | Oxisols and Entisols |
| R5     | Buritizeiro                     | 17°35'94" S 44°95'52" W      | 500      | Aw        | 22     | 1252   | Entisols   |
| R6     | Olhos D’água                   | 17°21'47" S 43°34'28" W      | 866      | Cwa       | 20     | 1232   | Oxisols and Ultisols |
|        | Diamantina                      | 18°24'21" S 43°59'45" W      | 1165     | Cwb       | 19     | 1329   |            |

*Location of the municipalities of the state of Minas Gerais, classification of the Brazilian Institute of Geography and Statistics (IBGE, 2016). Köppen climate classification. Elv. = elevation (m); T = Average annual temperature (°C); R = Rainfall (mm). (Alvares et al., 2013; Meneses et al., 2015).

Table 2 – Precipitation, water surplus and deficit accumulated in the wet and dry periods of the studied regions.

| Region | Wet Period 10/2010 to 03/2011 | 04/2011 to 09/2011 | 10/2011 to 03/2012 | 04/2012 to 09/2012 | 10/2012 to 03/2013 |
|--------|---------------------------------|---------------------|---------------------|---------------------|---------------------|
| R1     | R = 1198                        | 383                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
|        | E = 1618                        | 385                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
|        | D = 997                         | 492                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
| R2     | R = 868                         | 13                  | 0                   | 74                  | 0 0 185             | 455 13 0 28 0 0 596 216 0    |
|        | E = 1618                        | 385                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
|        | D = 997                         | 492                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
| R3     | R = 1515                        | 398                 | 0                   | 157                 | 14 136              | 1737 1051 2 209 2 84 1080 444 38 |
|        | E = 1618                        | 385                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
|        | D = 997                         | 492                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
| R4     | R = 1108                        | 262                 | 22                  | 39                  | 0 362               | 1036 316 63 20 0 534 1223 526 136 |
|        | E = 1618                        | 385                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
|        | D = 997                         | 492                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
| R5     | R = 1520                        | 227                 | 0                   | 203                 | 100 211             | 1481 728 19 84 0 229 864 297 98 |
|        | E = 1618                        | 385                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
|        | D = 997                         | 492                 | 5                   | 73                  | 0 185               | 1254 574 0 85 0 174 1174 528 34 |
| R6     | R = 1160                        | 23                  | 26                  | 82                  | 0 420               | 938 127 60 24 0 523 1055 274 214 |

*Accumulated values or the months Jan, Feb and Mar.
### Table 3 – Spacing, clone, age class (ACL) and the number of plots by region and management regime (first rotation* or second rotation**).

| Spacing | Clone/Region | ACL | Number of plots |
|---------|--------------|-----|-----------------|
| 8.4*    | GG157/R1     | 1   | 4               |
| 8.4*    | GG680/R1     | 1   | 1               |
| 8.4*    | GG100/R1     | 1   | 2               |
| 8.4*    | GG702/R1     | 1   | 1               |
| 8.4*    | GG739/R1     | 1   | 1               |
| 8.4*    | GG100/R1     | 2   | 1               |
| 8.4*    | GG157/R1     | 2   | 2               |
| 8.4*    | GG680/R1     | 2   | 4               |
| 8.4*    | GG100/R1     | 3   | 2               |
| 8.4*    | GG702/R1     | 3   | 5               |
| 8.4*    | GG739/R1     | 4   | 2               |
| 8.4*    | GG100/R1     | 1   | 7               |
| 9.1***  | GG170/R1     | 1   | 1               |
| 9.1***  | GG100/R1     | 2   | 7               |
| 9.1***  | GG157/R1     | 2   | 2               |
| 9.1***  | GG170/R1     | 2   | 2               |
| 9.1***  | GG2335/R1    | 2   | 5               |
| 8.4*    | GG680/R2     | 1   | 2               |
| 8.4*    | GG2335/R2    | 2   | 2               |
| 8.4*    | GG702/R2     | 2   | 1               |
| 8.4*    | GG100/R2     | 3   | 4               |
| 8.4*    | GG702/R2     | 4   | 1               |
| 8.4*    | GG100/R2     | 4   | 3               |
| 8.4*    | GG100/R1     | 1   | 1               |
| 8.4*    | GG100/R1     | 2   | 7               |
| 8.4*    | GG100/R1     | 3   | 5               |
| 8.4*    | GG2335/R2    | 4   | 2               |
| 8.4*    | GG672/R2     | 4   | 1               |
| 8.4*    | GG680/R2     | 4   | 5               |
| 8.4*    | GG702/R2     | 4   | 1               |
| 9**     | GG100/R2     | 4   | 1               |
| 9**     | GG2335/R2    | 4   | 1               |
| 9**     | GG100/R3     | 1   | 1               |
| 9**     | GG2335/R3    | 1   | 5               |
| 6*      | GG680/R3     | 2   | 1               |
| 7.5*    | GG47/R3      | 2   | 1               |
| 7.5*    | GG680/R3     | 2   | 1               |
| 8.4*    | GG680/R3     | 2   | 1               |
| 8.4*    | GG680/R3     | 2   | 2               |
| 6*      | GG100/R3     | 3   | 1               |
| 6*      | GG24/R3      | 3   | 1               |
| 7.5*    | GG157/R3     | 3   | 1               |
| 8.4*    | GG100/R3     | 3   | 1               |
| 8.4*    | GG2335/R3    | 3   | 1               |

ACL1 = age classes between 30 and 35 months; ACL2 = age classes between 42 and 47 months; ACL3 = age classes between 54 and 59; ACL4 = age classes between 66 and 70 months.

To prevent growth limitation due to the availability of nutrients, 142 twin-plots (TP) were installed in addition to the 142 plots of the CFI, as proposed by Stape et al. [2006]. The twin-plots received additional fertilization (AF) at an advanced age to assess the yield attainable in the regions under study. The AF was divided into four applications [Table 5]. The first (AF1) referred to the installation of twin-plots and the others were at 6 (AF2), 12 (AF3), and 18 (AF4) months, respectively. The CFI plots and the respective twins-plots constituted both treatments under study [Figures 2 and 3]. The twin-plots were installed between Mar and May 2011 and five lines were installed after the end of the CFI plot (a border between CFI and AF).

The trees in plots OF and AF were measured in the TP installations every subsequent six months between 2011 and 2013. In each plot, diameter at 1.30 m from the ground (DBH) was measured for all 60 trees as well as the total height (TH) of the first seven trees. The height of the remaining 53 trees was estimated using an artificial neural network (ANN) [Vieira et al., 2018].

To estimate the ANN, age (years) and DBH (cm) were the quantitative input variables, while rotation and genetic material were the categorical input variables and height (m) was the output variable. The trained networks...
were of the multiple layer perceptron type, also known as MLP [Multilayer Perceptron]. An ANN was trained for each treatment (OF and AF) using the software Statistica 10 [Statsoft, 2010], which used 50% of the data for training the networks, 25% for the test, and 25% for validation. The best ANN was selected according to the percentage error dispersion graph and through the root mean square error (RMSE). The percentage error was obtained (Eq. 1).

$$Error_{\%} = \frac{(|\overline{TH} - TH|)}{TH} \times 100$$

where: $\overline{TH}$ the total height estimated and TH the total height observed.

The RMSE assesses the mean quadratic difference between the values observed and estimated. The lower the RMSE, the greater accuracy of the estimate (Eq. 2).

$$RSME_{\%} = 100 \sqrt{\frac{1}{n} \sum_{i=1}^{n} (TH_i - \overline{TH})^2}$$

where: RSME is the root square mean error; $\overline{TH}$ is the average of the total heights observed; n is the total number of observations; $H_i$ is the total estimated height and $H$ is the total observed height.

Based on the DBH and TH values, the individual volumes were estimated for each tree in each plot evaluated, using the Shumacher and Hall (1933) model (Eq. 3).

$$\ln[V] = \beta_0 + \beta_1 \times \ln[DBH] + \beta_2 \times \ln[TH] + \varepsilon$$

where: $\ln$ is the neperian logarithm; V is the volume

Table 4 – Average and standard deviation of nutrients applied through operational fertilization by region.

| Region | n° | N | P2O5 | K2O | CaO | MgO | SO3 | B | Cu | Zn |
|--------|----|---|------|-----|-----|-----|-----|---|----|----|
|        |    | kg ha⁻¹ |      |     |     |     |     |   |    |    |
| First rotation |
| R1     | 71 | 14 (7) | 156 (62) | 177 (50) | 635 (234) | 121 (71) | 22 (14) | 4 (1) | 1 (1) | 3 (3) |
| R2     | 38 | 13 (11) | 107 (68) | 93 (52) | 468 (325) | 208 (206) | 36 (35) | 5 (3) | 1 (1) | 1 (1) |
| R3     | 42 | 9 (5) | 129 (64) | 102 (56) | 325 (256) | 67 (83) | 13 (8) | 3 (1) | 0 (0) | 1 (1) |
| R4     | 43 | 13 (7) | 191 (47) | 191 (30) | 564 (126) | 206 (50) | 18 (11) | 4 (1) | 0 (0) | 7 (1) |
| R5     | 18 | 16 (7) | 181 (49) | 131 (19) | 835 (233) | 119 (38) | 19 (9) | 4 (1) | 1 (1) | 2 (1) |
| R6     | 23 | 10 (5) | 75 (28) | 177 (50) | 428 (232) | 75 (41) | 17 (16) | 5 (1) | 0 (0) | 3 (2) |
| Average | 13 | 140 | 145 | 543 | 133 | 21 | 4 | 1 | 3 |

| Second rotation |
| R1     | 33 | 0 (0) | 125 (43) | 83 (49) | 327 (175) | 71 (35) | 0 (0) | 2 (1) | 0 (0) | 0 (0) |
| R5     | 9  | 0 (0) | 102 (46) | 64 (68) | 129 (59) | 28 (17) | 1 (4) | 1 (1) | 0 (0) | 0 (0) |
| Average | 0 | 114 | 74 | 228 | 50 | 1 | 2 | 0 | 0 |

n° = Number of compartments. Values in parentheses refer to standard deviation, because each compartment where the plot was established received a specific fertilization prescription.

Table 5 – Nutrients applied for additional fertilization (AF).

| Fertilizers | Applied dose | N | P2O5 | K2O | CaO | MgO | SO3 | B | Cu | Zn | Fe | Mn | Mo |
|-------------|--------------|---|------|-----|-----|-----|-----|---|----|----|----|----|----|
|             | kg ha⁻¹ |      |     |     |     |     |     |   |    |    |    |    |    |
| MAP         | 538         | 48 | 258 |    |     |     |     |   |    |    |    |    |    |
| Rima Limestone | 839  | -   | -   | 0   | 447 | 101 | -   | -   | -   | -   | 30  | 5   | -   |
| Magnesite   | 249         | -   | -   | -   | 199 |     |     | -   | -   | -   | -   | -   |    |
| Gypsum      | 2268        | -   | 5   | -   | 680 | -   | 401 | -   | -   |    |    |    |    |
| KCl + 1%B   | 403         | -   | -   | 218 |     | -   | 4   | -   | -   |    |    |    |    |
| NH₄SO₄     | 627         | 132 | -   | -   | 144 | -   | -   | -   |    |    |    |    |    |
| Borogran    | 10          | -   | -   | -   | -   | 144 | -   | -   | -   |    |    |    |    |
| CuSO₄       | 30          | -   | -   | -   | -   | -   | -   | 3   | -   |    |    |    |    |
| ZnSO₄       | 270         | -   | -   | -   | -   | -   | 27  | -   |    |    |    |    |    |
| MnSO₄       | 6           | -   | -   | -   | -   | 1   | -   | -   | 2   |    |    |    |    |
| Ammonium Molybdate | 0.9 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | 0.3 |    |

MAP = monoamonic phosphate; KCl = potassium chloride; NH₄SO₄ = ammonium sulphate; CuSO₄ = copper sulphate; ZnSO₄ = zinc sulphate; MnSO₄ = manganous sulphate. AF1 was applied in the establishment of the twin-plots and the others were applied a 6 (AF2), 12 (AF3), and 18 (AF4) months later.
where:

$P_{\text{var}50}$ is the Cumulative percentage of the dendrometric variable of interest for the 50% smallest trees planted; $X$ is the dendrometric variable of interest to parcel $i$ at age $j$; $n$ is the number of trees planted in order (from lowest to highest).

The Optimal Uniformity Interval (OUI) for DBH was used to verify stand uniformity (Eq. 6).

$OUI_{ij} > x_{ij} - 1 * s_{ij}$

where: $OUI$: Optimal Uniformity Interval of the plot $i$ at age $j$; $x$ = average of the dendrometric variable of the plot $i$ at age $j$; $s_{ij}$ = standard deviation of the mean of the dendrometric variable of the plot $i$ at age $j$.

These intervals were calculated using ACL [1, 2, 3, and 4] for the initial age [age of stands upon experiment installation] and for the final age [age of stands at the experiment end].

Potential, attainable, and observed productivity were estimated using the average annual increase at seven years of age (AAI7). The observed and attainable yield were obtained by AAI7 of treatments OF and AF, respectively. Potential productivity (PP) was estimated by extrapolating the yield of six rainy months through the treatment received by AF to the other 12 months of the year (Eq. 7).

$$V = \frac{a}{1 + b * e^{-cx}}$$

where: $V$ is the volume (m$^3$ ha$^{-1}$); $x$: Age (year); $t$: OF or AF; $a$, $b$, and $c$: model coefficients.
where: $PP$ is the Potential productivity (m$^3$ ha$^{-1}$ yr$^{-1}$); $AAI_7$ is the average annual increase estimated at seven years of age for treatment AF (m$^3$ ha$^{-1}$ yr$^{-1}$); $X$ is the average yield percentage in the rainy season; 2 is the factor to extrapolate yield from six rainy months to 12 months of the year.

Data was processed using the software Statistica 10 (Statsoft, 2010).

**Results**

In the first year after applying the treatments, the proportion of average growth was 64 % (OF) and 69 % (AF) in the $P_w$, regardless of R or ACL (Table 6). There was a regional effect with a growth variation in $P_w$ from 62 to 74 % (AF) and from 51 to 71 % (OF). In the analysis using ACL, the greatest yield in $P_w$ occurred at younger ages, ranging from 61 (ACL4) to 73 % (ACL1) for OF and from 68 (ACL4) to 72 % (ACL1) for AF. The reverse behavior was observed for the dry periods.

In the second year between 18 and 24 months after the application of the treatments, the average proportions of yield in $P_w$ were obtained for the stands in the first and second rotations. In the first rotation, the average proportion of the independent production of R and ACL was 73 % for OF and AF, respectively (Table 7). Higher yields were observed in R1, with 81 % for OF and 83 % for AF. In the ACL analysis, the variation between the production areas was 70 to 74 % (OF) and 71 to 76 % (AF). In the second rotation, the proportions of yield in $P_w$ were 68 and 69 % for OF and AF respectively. In this regime, there was also a regional effect with higher yield in R1 of 71 % (OF) and 74 % (AF).

The uniformity indices [Pvar50 %] for DBH in R1 for the first and second rotation stands are shown in Table 8. It appears that for the initial age in the first rotation plantations, the rates ranged from 37 to 47 % (OF) and 42 to 48 % (AF) in ACL1, from 26 to 47 % (OF) and 30 to 47 % (AF) in ACL2, from 36 to 46 % (OF) and 34 to 46 % (OF) in ACL3 and 41 to 48 % (OF) and 42 to 47 % (AF) in ACL4. As for the final age, the rates ranged from 37 to 47 % (OF) and 39 to 47 % (AF) in ACL1, from 30 to 46 % (OF) and 32 to 46 % (AF) in ACL2, from 36 to 46 % (OF) and 33 to 45 % (OF) in ACL3 and from 41 to 48 % (OF) and 41 to 47 % (AF) in ACL4. For the second rotation stands, the Pvar50 % at the initial age ranged from 13 to 40 % (OF) and 25 to 40 % (AF) in ACL1 and from 23 to 41 % (OF) and 18 to 44 % (AF) in ACL2. For the final age, this variation was 16 to 40 % (OF) and 24 to 39 % (AF) in ACL1. In ACL2, it was 22 to 40 % (OF) and 19 to 42 % (AF).
Table 6 – Production in the dry ($P_d$) and wet ($P_w$) periods of the OF and AF treatments of stands in the first rotation in the first year after the application of the treatment.

| Region ACL | $I_0$ | CAI | Dry Period | Wet Period |
|------------|-------|-----|------------|------------|
|            |       | OF  | AF         | OF         | AF         |
|            | year  | m$^3$ ha$^{-1}$ yr$^{-1}$ | %         |            |            |
| CAI        |       |     |            |            |            |
| First rotation |
| R1        | *     | 44  |
| R2        | *     | 26  |
| R3        | *     | 2  |
| **        | 2.5   | 63  |
| **        | 4.5   | 39  |
| R1        | 1.5   | 52  |
| R2        | 4.5   | 31  |
| R3        | 2.5   | 50  |
| R1        | 3.5   | 43  |
| R2        | 4.5   | 55  |
| R3        | 3.5   | 70  |
| R1        | 4.5   | 29  |
| R2        | 3.5   | 31  |
| R3        | 5.5   | 22  |
| OF = Operational fertilization; AF = Additional fertilization at advanced age; CAI = Annual current increase; $I_0$ = Stand age class at the beginning of the experiment; ACL = Age class: ACL1 (30 to 35 months), ACL2 (42 to 47 months), ACL3 (54 to 59 months); ACL4 (66 to 70 months); *Age independent analysis by age. **Age independent analysis by region.

The OUI for stands in the first rotation regime of their initial age was established with a lower limit of 39 % (OF and AF), 36 % (OF), and 38 % (AF), 40 % (OF and AF) and 42 % (OF and AF) for ACL1, ACL2, ACL3, and ACL4, respectively [Figure 4]. For the final ages, the lower limit was 35 % (OF) and 40 % (AF) in ACL1, 37 % (OF) and 38 % (AF) in ACL2, 40 % (OF), and 39 % (AF) in ACL3 and 42 % (OF and AF) in ACL4. The upper limit for all treatments and evaluated ages was 50 %.

In the stands under the second rotation regime, the OUI for the initial ages showed a lower limit of 24 % (OF) and 29 % (AF) for the ACL1 and 26 % (OF) and 25 % (AF) for ACL2. For the final ages, the limits were 29 % (OF) and 26 % (AF) in ACL1 and 24 % (OF), and 23 % (AF) in ACL2, respectively [Figure 5].

The equations to estimate volume (m$^3$ ha$^{-1}$) as a function of age (year) by rainfall and treatment class in both the first and second rotation stand regimes showed a good adjustment, according to their determination coefficients ($R^2$) (Table 9), which were used to calculate potential, attainable and observed productivity through the average annual increase at seven years of age (AAI).

The average proportion of production in $P_w$ encompassing the two years measured was approximately 67 % (OF) and 70 % (AF) for the first rotation, which were considered capable of estimating potential yield by rainfall class. In the second rotation, the yield proportion used was obtained for the second year of response due to the restriction of data from $P_w$ for the first year of measurements.

In the first rotation, the potential yield per class of rainfall resulted in the following order: P3, P4, and P2 with AAI of 75, 62, and 50 m$^3$ ha$^{-1}$ yr$^{-1}$, respectively [Table 10]. The attainable yield for the three classes was 40 % lower than the potential. The observed yield was 40, 47, 58, and 44 % lower than potential yield, respectively, for P1, P2, P3, and P4. The attainable yield was lower than the potential yield of 38 % for both classes, while the observed yield was lower than the potential yield of 67 % [P2] and 84 % [P4].

### Discussion

Forest yield is usually measured at 12 to 24 months intervals to assess the growth of stands, which are useful for monitoring forest development as well as forest planning and regulation (Oliveira et al., 2009; Vescovi et al., 2020). However, this type of measurement does not explain growth differences between the dry and wet periods of the same year. Few studies have measured eucalyptus stands every six months for dry and humid
periods [Stape et al., 2006, 2010]. Water availability and rainfall seasonality significantly influence eucalyptus production [Binkley et al., 2020; Costa et al., 2020; Soares et al., 2020]. In the State of Minas Gerais, most rainfall is concentrated between Oct and Mar (Table 2). The increase in $P_{W}$, on average, corresponds to 67 % of the annual yield in stands with OF and 70 % when AF was performed, regardless of region, clone, and age (Tables 6 and 7). Stape et al. [2010] assessed the effect of rainfall seasonality on annual yield for different eucalyptus clones in four Brazilian states and reported an average of 73 % of yield for $P_{W}$ corroborating the results in our study.

The values $P_{\text{var}50}$ % for variable DBH demonstrates that stands in the first rotation tend to present greater uniformity than stands in the second

![Figure 4](image-url)  
**Figure 4** – The Optimal Uniformity Interval (OUI) of $P_{\text{DBH}}$ 50 % of the initial (I$_{0}$) and final (I$_{f}$) ages for OF (Operational Fertilization) and AF (Additional Fertilization) in each age class (ACL) for stands in the first rotation. The ACL Age classes are as follows: ACL1 (30 to 35 months), ACL2 (42 to 47 months), ACL3 (54 to 59 months) and ACL4 (66 to 70 months).

![Figure 5](image-url)  
**Figure 5** – The Optimal Uniformity Interval (OUI) of $P_{\text{DBH}}$ 50 % of the initial (I$_{0}$) and final (I$_{f}$) ages for OF (Operational Fertilization) and AF (Additional Fertilization) for each age class (ACL) for stands under the second rotation. The ACL Age classes are as follows: ACL1 (30 to 35 months), ACL2 (42 to 47 months), ACL3 (54 to 59 months) and ACL4 (66 to 70 months).
Table 8 – Uniformity index (Pvar50 %) of the DBH variable referring to the OF and AF treatments in the initial and final ages of stands under first and second rotations.

| ACL Plot | Pvar50 (%) | I₀ | I₁ |
|----------|------------|----|----|
|          | OF         | AF | OF | AF |
| First rotation |
| 1        | 4          | 47 | 44 | 47 |
| 1        | 5          | 40 | 42 | 39 | 40 |
| 1        | 27         | 48 | 47 | 47 | 47 |
| 1        | 29         | 45 | 46 | 45 | 46 |
| 1        | 32         | 46 | 43 | 46 | 42 |
| 1        | 39         | 47 | 47 | 43 | 43 |
| 1        | 48         | 42 | 42 | 41 | 42 |
| 1        | 70         | 42 | 39 | 40 | 39 |
| 2        | 1          | 43 | 45 | 44 | 45 |
| 2        | 7          | 42 | 40 | 40 | 40 |
| 2        | 11         | 47 | 46 | 45 | 42 |
| 2        | 14         | 47 | 45 | 46 | 43 |
| 2        | 23         | 46 | 41 | 44 | 40 |
| 2        | 29         | 45 | 44 | 44 | 44 |
| 3        | 1          | 43 | 45 | 44 | 45 |
| 3        | 4          | 45 | 45 | 42 | 42 |
| 3        | 7          | 46 | 45 | 46 | 44 |
| 3        | 11         | 47 | 46 | 45 | 44 |
| 3        | 14         | 47 | 45 | 46 | 43 |
| 3        | 23         | 46 | 41 | 44 | 40 |
| 3        | 29         | 45 | 44 | 44 | 44 |
| 4        | 1          | 43 | 45 | 44 | 45 |
| 4        | 4          | 45 | 45 | 42 | 42 |
| 4        | 7          | 46 | 45 | 44 | 44 |
| 4        | 11         | 47 | 46 | 45 | 44 |
| 4        | 14         | 47 | 45 | 46 | 43 |
| 4        | 23         | 46 | 41 | 44 | 40 |
| 4        | 29         | 45 | 44 | 44 | 44 |
| Second rotation |
| 1        | 3          | 36 | 32 | 36 | 30 |
| 1        | 10         | 25 | 16 | 24 | 25 |
| 1        | 44         | 32 | 29 | 32 | 32 |
| 1        | 45         | 36 | 36 | 35 | 36 |
| 1        | 58         | 34 | 34 | 33 | 33 |
| 2        | 4          | 13 | 26 | 15 | 16 |
| 2        | 11         | 42 | 40 | 40 | 39 |
| 2        | 14         | 44 | 31 | 32 | 25 |
| 2        | 19         | 40 | 35 | 39 | 35 |
| 2        | 4          | 39 | 39 | 39 | 39 |
| 2        | 7          | 39 | 37 | 39 | 39 |
| 2        | 2          | 23 | 20 | 21 | 20 |
| 2        | 6          | 27 | 26 | 26 | 26 |
| 2        | 15         | 30 | 32 | 34 | 32 |
| 2        | 25         | 38 | 38 | 37 | 37 |
| 2        | 4          | 32 | 32 | 32 | 32 |
| 2        | 8          | 27 | 22 | 26 | 26 |
| 2        | 10         | 31 | 33 | 33 | 33 |
| 2        | 14         | 30 | 30 | 30 | 30 |
| 2        | 22         | 32 | 32 | 32 | 32 |

Table 9 – Coefficients of volume equations and coefficients of determination according to rainfall class and treatment in stands in the first and second rotations.

| Rainfall class (mm) | First rotation | OF | AF |
|---------------------|----------------|----|----|
| P1 = Rainfall < 1000 mm; P2 = 1200 < Rainfall < 1400 mm; P3 = 1400 mm < Rainfall < 1600 mm and P4 = Rainfall > 1600 mm, R² = Coefficient of determination; OF = Operational fertilization; AF = Additional fertilization at advanced age; Coefficients of volume equations.

| Rainfall class (mm) | a            | b            | c            | R² |
|---------------------|--------------|--------------|--------------|----|
| P1                  | –1199.6      | –43.6        | 0.3          | 0.99 |
| P2                  | 290.7        | 13.7         | 0.6          | 0.99 |
| P3                  | 2498461809.8 | 652397675.7  | 0.3          | 0.97 |
| P4                  | 311.9        | 47.0         | 1.0          | 0.99 |

| Rainfall class (mm) | Second rotation | OF | AF |
|---------------------|----------------|----|----|
| OF                  | 207.1          | 10.5 | 0.6 | 0.97 |
| AF                  | 159.5          | 24.6 | 1.0 | 1.00 |

| Rainfall class (mm) | P2 | P4 |
|---------------------|----|----|
| P2                  | 238.4 | 15.7 | 0.97 |
| P4                  | 213.2 | 34.9 | 1.00 |

Table 10 – Potential, attainable, and observed yield and its relative differences by rainfall class for tall shaft and coppice stands.

| Rainfall class | Yield Potential Attainable Observed
|---------------|-------------------|-------------------|-------------------|
| mm            | m³ ha⁻¹ yr⁻¹ %    | m³ ha⁻¹ yr⁻¹ %    | m³ ha⁻¹ yr⁻¹ %    |
| First rotation |
| P1            | 51              | 100              | 37                | 40                |
| P2            | 50              | 100              | 36                | 40                |
| P3            | 75              | 100              | 54                | 40                |
| P4            | 62              | 100              | 44                | 40                |
| Second rotation |
| P2            | 42              | 100              | 30                | 25                |
| P4            | 41              | 100              | 30                | 22                |

*Relative difference of attainable and observed productivity in relation to potential. P1 = Rainfall < 1000 mm; P2 = 1200 < Rainfall < 1400 mm; P3 = 1400 mm < Rainfall < 1600 mm and P4 = Rainfall > 1600 mm.

According to Hakamada et al. [2015], when Pvar50 % of the studied variable is closer to 50 %, the population is more uniform. Stands in the second rotation show P DBH values 50 % lower, reaching 13 % (OF) in ACL1 and 18 % (AF) in ACL2 for the initial ages.

The OUI (Figures 1 and 2) shows that 88 % of the plots in ACL1 and ACL2 for the first rotation are within the limits, both for the initial and the final ages. For ACL3 and ACL4, these values are 91 and 90 %, respectively. For the second rotation, 88 % of the plots are within the OUI in ACL1 for both OF and AF. Nevertheless, in ACL2, the percentage of installments within the OUI...
was 76 and 92 % for OF and AF, respectively. For both management regimes, most plots are within the OUI. However, stands under the second rotation showed higher amplitude than the OUI of stands in the first rotation due to lower values of PVar 50 % for the second rotation. This indicates less uniformity in these stands. More heterogeneous plantations are less productive since the number of dominating individuals is larger, which is less efficient in terms of capturing resources [Ryan et al., 2010; Stape et al., 2010; Resende et al., 2016; Soares et al., 2016]. In our study, the lower yield observed in stands under the second rotation may be associated to lower uniformity of the stands, among other things.

Potential yields estimated for rainfall classes remained between 50 and 75 m³ ha⁻¹ yr⁻¹ for the stem of stands in the first rotation (Table 10). Stape et al. [2010] estimated that the potential average of stem yield was 51 m³ ha⁻¹ yr⁻¹ for Brazil. However, if water availability does not limit growth, this yield could reach 65 m³ ha⁻¹ yr⁻¹. In the first rotation, the highest potential yields were obtained for rainfall classes P3 and P4 at 75 and 61 m³ ha⁻¹ yr⁻¹, respectively. These are the classes with the highest average precipitation high values, which could explain these values. In general, the highest yield occurred in regions with greater water availability (Table 10) [Binkey et al., 2017, 2020; Costa et al., 2020; Rocha et al., 2020].

According to the authors, besides water availability, other elements influence the yield of the eucalyptus forest, such as genotype, temperature, vapor pressure deficit, water deficit in the soil, leaf area index, among other things. However, it was not possible to measure those variables in this study, because the data were collected in an experimental area in a forestry company, which did not plan collection of these data. Nevertheless, it is possible to analyze the results using the highest precipitation rate from the database available.

In our study, there was an increase in quantities of fertilizers used, in addition to those applied operationally, which allowed to eliminate the nutritional limitation of stands, estimate the potential yield, and obtain the average attainable yield. These yields are limited by the genetic plant characteristics and climatic conditions in the region [Silva et al., 2016]. Studies on potential yield of eucalyptus forests in Brazil have increased in recent years [Stape et al., 2006, 2010].

Potential yield increased by up to 84 % in relation to the yield observed in the second rotation (Table 10). The potential yield was estimated for classes P2 and P4, with an average of approximately 41.5 m³ ha⁻¹ yr⁻¹. The wide difference in yield between the two silvicultural regimes of 33.5 m³ ha⁻¹ yr⁻¹ suggests that silvicultural practices used in the second rotation are likely to limit yield.

The difference between potential and observed yields show that in the first rotation, the P3 class [1400 to 1600 mm] had the greatest difference, where the effect of the additional fertilization together with water provided a 58 % gain in yield. For class P1 (< 1000 mm), there was no effect on AF, where the attainable yield was approximately equals to the observed yield. These results demonstrate that response to fertilization is strongly dependent on water availability. Irrigating forests is not an objective in a country with large land tracts as Brazil; thus, the adoption of conservationist practices that enhance water permanence in the site can greatly increase yield. In addition, the use of a standard fertilization method for different edaphoclimatic conditions is not recommended. Precision forestry has increasingly shown a high potential for the return on investments.

**Conclusion**

Water seasonality strongly influences annual yield with the drier semester producing approximately 30 % of the current annual increase.

Eucalyptus stands under the second rotation tend to have less uniformity than stands under the first rotation.

Potential yield varied according to the rainfall intensity, which ranged from 50 to 75 m³ ha⁻¹ yr⁻¹ for stands in the first rotation and from 41 to 42 m³ ha⁻¹ yr⁻¹ for stands in the second rotation.

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**Authors’ Contributions**

**Conceptualization:** Silva, L.G.; Santana, R.C. **Data acquisition:** Gomes, F.S. **Data analysis:** Silva, L.G.; Oliveira, M.L.R.; Santana, R.C. **Design of methodology:** Gomes, F.S.; Oliveira, M.L.R. **Writing and editing:** Silva, L.G.; Santana, R.C.

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