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

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ABSTRACT: Appropriate management of factors that influence forest development is essential to increase yield of forest plantations. The objective of this study was to evaluate the influence of water seasonality, nutritional management, and uniformity on yield of eucalyptus plantations and estimate the potential, attainable, and observed yield of adult eucalyptus stands. We evaluated *Eucalyptus* clonal stands in six regions of Minas Gerais State, Brazil, in a system of first and second rotation across four age classes using the twin-plots method (TP). In the study, 142 TPs were allocated alongside 142 plots in a continuous forest inventory (CFI) network of a private enterprise. The CFI received operational fertilization and additional fertilization was carried out in the TP. The trees were measured at the beginning of the experiment and at every six months to quantify the production in the wet (P_W) and dry (P_D) periods of the year. Uniformity of plantations was evaluated using Pvar 50 % and the optimal uniformity index. Potential, attainable, and observed yields were estimated using the average annual increase at seven years of age. The P_W showed higher plant yield. There was an effect due to water availability and nutrient level on the yield of the stands. The driest semester of the year produces approximately 30 % of the current annual increase. The stands under the second rotation tend to have less uniformity than the in the first rotation. Potential yield varied depending on rainfall intensity where wetter regions had the highest yield.
Keywords: forest fertilization, precipitation, silviculture, twin-plots method, uniformity

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.

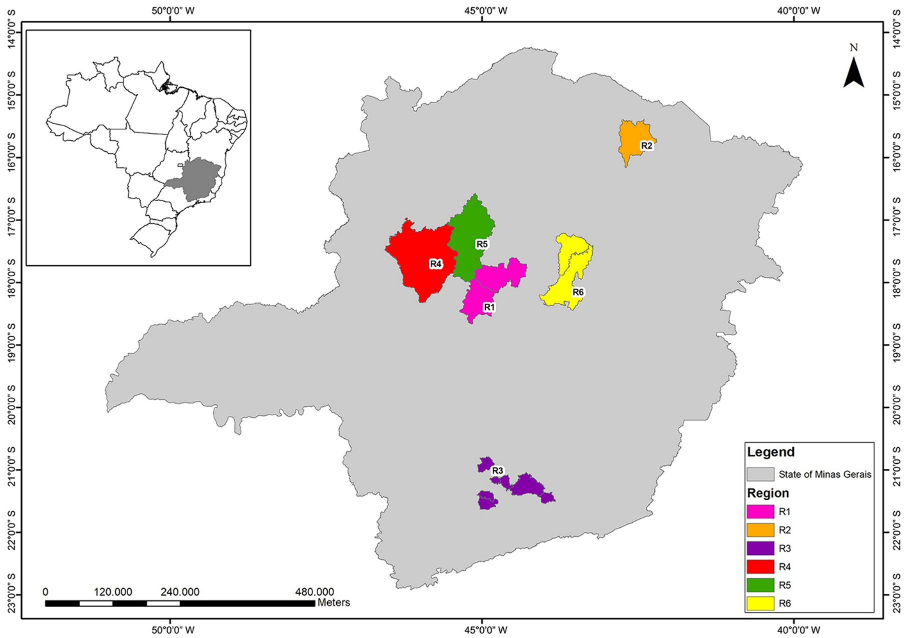

Figure 1 – Schematic representation of the study sites in the state of Minas Gerais, Brazil.

Table 1 – Characteristics of the study regions.

Region	Municipalities	Latitude (S) / Longitude (W)[a]	Elv.	Climate[b]	T	R	Soil order
			m		°C	mm	
R1	Três Marias	18°20'59" S 45°22'57" W	594	Cwa	21	1396	Oxisols
	Lassance	17°89'513" 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
R3	Ibertioga	21°42'94" S 43°96'81" W	1021	Cwb	17	1555	Oxisols and Ultisols
	São João Del Rei	21°13'55" S 44°26'09" W	908	Cwb	18	1575	
	Luminárias	21°51'23" S 44°90'61" W	946	Cwb	18	1594	
	Ingaí	21°40'37" S 44°92'249" W	947	Cwb	18	1614	
	Nazareno	21°21'77" S 44°61'72" W	921	Cwb	18	1689	
	Santo Antônio do Amparo	20°94'62" S 44°91'87" W	1008	Cwb	18	1709	
	Ibituruna	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°23'47" 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	

[a]Location of the municipalities of the state of Minas Gerais, classification of the Brazilian Institute of Geography and Statistics (IBGE, 2016). [b]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			Dry Period 04/2011 to 09/2011			Wet Period 10/2011 to 03/2012			Dry Period 04/2012 to 09/2012			Wet Period 10/2012 to 03/2013		
	R	E*	D*	R	E	D	R	E	D	R	E	D	R	E	D
	mm														
R1	1198	383	5	73	0	185	1254	574	0	85	0	174	1174	528	34
R2	868	13	0	74	0	0	455	13	0	28	0	0	596	216	0
R3	1515	398	0	157	14	136	1737	1051	2	209	2	84	1080	444	38
R4	1108	262	22	39	0	362	1036	316	63	20	0	534	1223	526	136
R5	1520	227	0	203	100	211	1481	728	19	84	0	229	864	297	98
R6	1160	23	26	82	0	420	938	127	60	24	0	523	1055	274	214

R = Accumulated rainfall; E = Accumulated water surplus; D = Accumulated water deficit *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
m² per plant		month	
8.4*	GG157R1	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*	GG702/R1	2	1
8.4*	GG680/R1	3	2
8.4*	GG100/R1	3	5
8.4*	GG702/R1	3	4
8.4*	GG157/R1	4	2
8.4*	GG702/R1	4	1
9.5*	GG680/R1	4	1
8.2*	GG100/R1	4	1
8.2*	GG680/R1	4	1
8.4*	GG100/R1	4	3
8.2*	GG100/R1	4	1
9.1**	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**	GG2333/R1	2	1
9.1**	GG2334/R1	2	1
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	3	1
8.4*	GG100/R2	4	1
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*	GG62/R3	2	1
7.5*	GG680/R3	2	1
8.4*	GG68/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
8.4*	GG100/R3	4	2
8.4*	GG157/R3	4	2
8.4*	GG2335/R3	4	1
4.9*	GG2333/R4	1	1
4.9*	GG2335/R4	1	2
8.4*	GG100/R4	1	1
8.4*	GG2335/R4	1	2
8.4*	GG680/R4	1	2
8.4*	GG702/R4	1	1
8.4*	GG702/R4	1	1
8.4*	GG100/R4	2	1
8.4*	GG680/R4	2	3
8.4*	GG702/R4	2	2
8.4*	GG100/R4	3	5
8.4*	GG680/R4	3	1
8.4*	GG100/R5	3	2
8.4*	GG2335/R5	3	1
8.1*	GG100/R5	4	1
8.4*	GG100/R5	4	1
8.4*	GG680/R5	4	1
9.1**	GG100/R5	1	1
9.1**	GG157/R5	1	1
9.1**	GG2335/R5	1	1
9.1**	GG100/R5	2	2
9.1**	GG50/R5	2	1
8.4*	GG2335/R6	1	3
8.4*	GG100/R6	2	1

Continue...

Table 3 – Continuation.

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

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

Region	n°	N	P_2O_5	K_2O	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 apsplied for additional fertilization (AF).

Fertilizers	Applied dose	N	P_2O_5	K_2O	CaO	MgO	SO_3	B	Cu	Zn	Fe	Mn	Mo
	kg ha^{-1}												
							AF1						
MAP	538	48	258	-	-	-	-	-	-	-	-	-	-
Rima Limistone	839	-	-	0	447	101	-	-	-	-	30	5	-
Magnesite	249	-	-	-	-	199	-	-	-	-	-	-	-
Gypsum	2268	-	5	-	680	-	401	-	-	-	-	-	-
KCL + 1%B	403	-	-	218		-	-	4	-	-	-	-	-
NH_4SO_4	627	132	-	-	-	-	144	-	-	-	-	-	-
Borogram	10	-	-	-	-	-	-	1	-	-	-	-	-
$CuSO_4$	30	-	-	-	-	-	-	-	3	-	-	-	-
$ZnSO_4$	270	-	-	-	-	-	-	-	-	27	-	-	-
$MnSO_4$	6	-	-	-	-	-	1	-	-	-	-	2	-
Ammonium Molybdate	0.9	-	-	-	-	-	-	-	-	-	-	-	0.3
							AF2, AF3 and AF4						
MAP	377	34	181	-	-	-	-	-	-	-	-	-	-
KCl	403	-	-	218	-	-	-	-	-	-	-	-	-
NH_4SO_4	696	146	-	-	-	-	160	-	-	-	-	-	-

MAP = monoamonic phosphate; KCl = potassium chloride; NH_4SO_4 = ammonium sulphate; $CuSO_4$ = copper sulphate; $ZnSO_4$ = zinc sulphate; $MnSO_4$ = 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.

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).

$$Error_{(\%)} = \left(\widehat{TH} - TH\right)\Big/TH * 100 \tag{1}$$

where: $\widehat{TH}$ 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).

$$RSME_{(\%)} = 100/\overline{H}\sqrt{\left(H_i - \widehat{H}_i\right)^2 / n} \tag{2}$$

where: RSME is the root square mean error; $\overline{H}$is the average of the total heights observed; n is the total number of observations; $\widehat{H}$ 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).

$$Ln(V) = \beta_0 + \beta_1 * Ln(DBH) + \beta_2 * ln(TH) + \varepsilon \tag{3}$$

where: Ln is the neperian logarithm; V is the volume

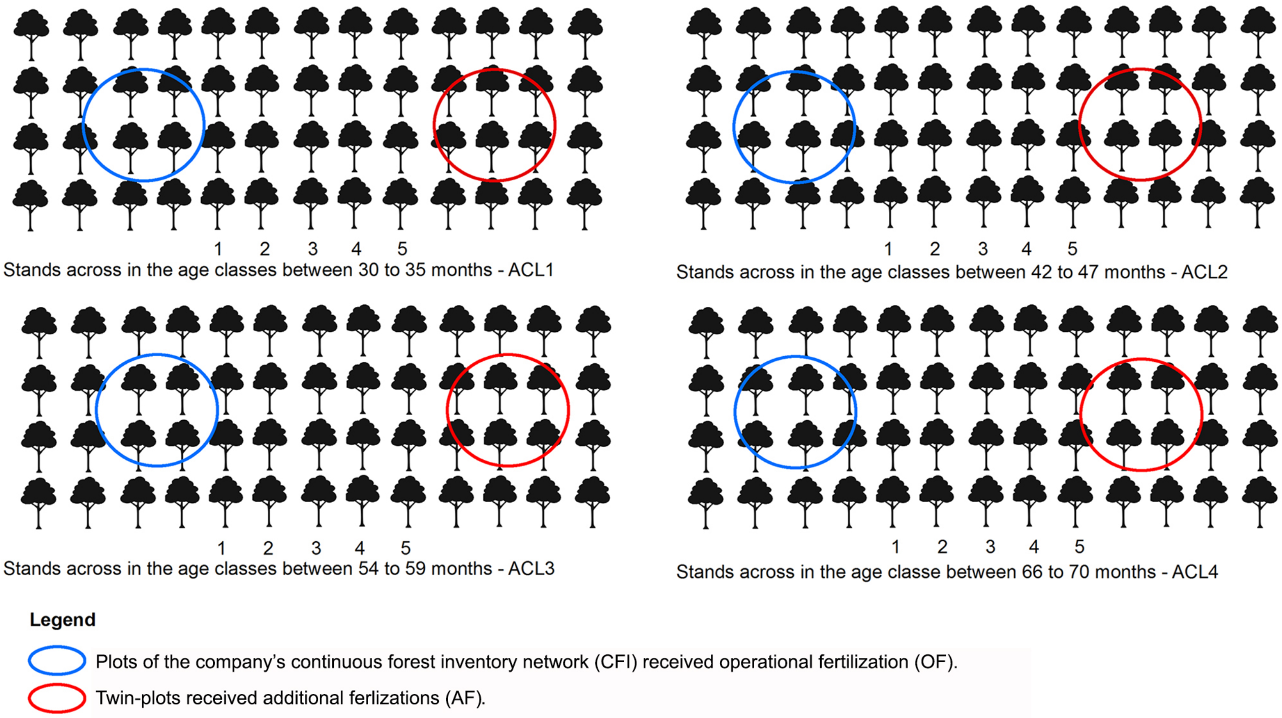

Figure 2 – Schematic representation of the plots allocated according to four age classes. ACL1: stands between 30 and 35 months age, ACL2: stands between 42 and 47 months age, ACL3: stands between 54 and 59 months age, ACL4: stands between 66 and 70 months age.

per tree; β_0, β_1 and β_2 is the model parameters; *DBH* is the diameter at 1.30 m from the ground; *TH* is the total height of trees; ε is the random error.

The volume estimate for the wet (P_W) and dry (P_D) periods was carried out by selecting the plot inventories measured in the months of Apr and Oct, respectively (Table 2). Depending on the average annual rainfall in each region, the plots were grouped into the following rainfall classes (mm): P1 – rainfall < 1000, P2 – between 1200 and 1399, P3 – between 1400 and 1599 and P4 – rainfall > 1600. Next, the average of volumes (m^3 ha^{-1}) for OF and AF were calculated by rainfall class and age, using the logistic model (Eq. 4).

$$V_t = a\Big/\left(1 + b * e^{(-cx)}\right) \quad (4)$$

where: *V* is the volume (m^3 ha^{-1}); *x*: Age (year); *t*: OF or AF; *a*, *b* and *c*: model coefficients.

Only the plots included in R1 were selected to assess uniformity of OF and AF plots, since they comprised stands in the four age classes and two management regimes (first and second rotation). Their uniformity was assessed by the accumulated percentage of the variable of interest, in this case the DBH of the 50 % smaller trees planted (Pvar50 %), in accordance with the methodology proposed by Hakamada et al. (2015). For that, the DBH of trees in the plots was put in ascending order for each age class and thus calculating the Pvar 50 % (Eq. 5).

$$Pvar50 = \frac{\sum_{k=1}^{n/2} X_{ij}}{\sum_{k=1}^{n} X_{ij}} \quad (5)$$

where: *P*var50 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).

$$OUI_{ij} > \bar{x}_{ij} - 1 * s_{ij} \quad (6)$$

where: *OUI*: Optimal Uniformity Interval of the plot *i* at age *j*; $\bar{x}$ = 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 (AAI_7). The observed and attainable yield were obtained by AAI_7 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).

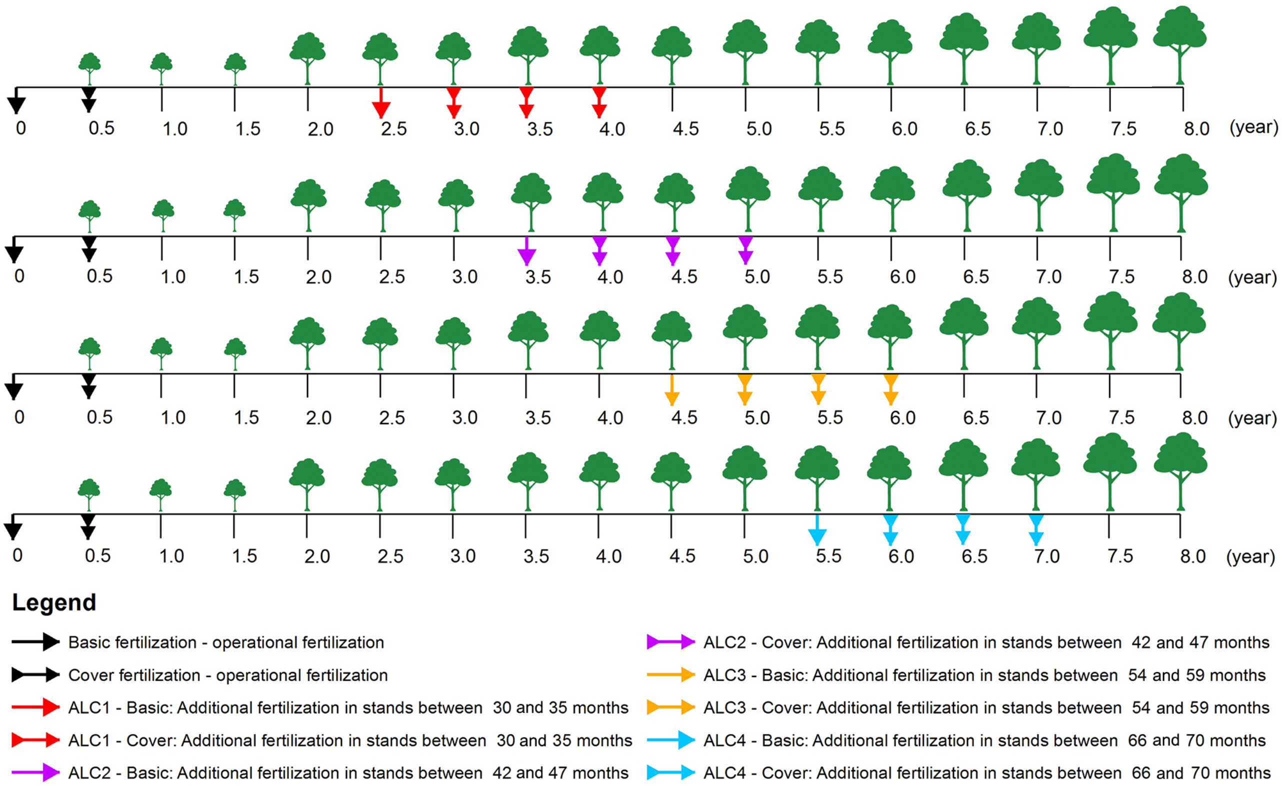

Figure 3 – Schematic representation of additional fertilization (AF) applied to the twin-plots in the stands in the four age classes.

$$PP = (AAI_7 * X) * 2 \tag{7}$$

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, 36 to 47 % (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	OF	AF
		year	— m^3 ha^{-1} yr^{-1} —		————— % —————			
First rotation								
R1		*	44	45	34	26	66	74
R2		*	26	28	49	38	51	62
R3		*	70	87	30	31	71	69
**	1	2.5	63	87	28	28	73	72
**	2	3.5	58	64	36	31	64	69
**	3	4.5	39	43	40	33	60	67
**	4	5.5	38	38	39	32	61	68
R1	1	2,5	52	64	32	28	68	72
R1	2	3.5	50	48	30	25	70	75
R1	3	4.5	43	46	34	22	66	78
R1	4	5.5	29	20	39	30	61	70
R2	2	3.5	31	35	49	43	51	57
R2	3	4.5	22	25	46	35	54	65
R2	4	5.5	24	24	52	37	48	63
R3	1	2.5	74	110	23	28	77	72
R3	2	3.5	93	108	29	26	71	74
R3	3	4.5	52	59	40	41	60	59
R3	4	5.5	62	70	26	29	74	71

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.

Table 7 – Production in the dry (P_D) and wet (P_W) periods of the OF and AF treatments of stands under the first and second rotations in the second year after the application of the treatment.

Region	ACL	I_0	CAI		Dry Period		Wet Period	
			OF	AF	OF	AF	OF	AF
		year	— m^3 ha^{-1} yr^{-1} —		————— % —————			
Firts rotation								
R1		*	34	36	19	17	81	83
R3		*	60	75	34	35	66	65
**	1	2.5	54	64	30	29	70	71
**	2	3.5	45	48	26	24	74	76
**	3	4.5	40	50	27	28	73	72
R1	1	2.5	38	39	18	16	82	84
R1	2	3.5	37	39	16	13	84	87
R1	3	4.5	28	30	23	21	77	79
R3	1	2.5	70	88	41	41	59	59
R3	2	3.5	70	78	39	38	61	62
R3	3	4.5	55	72	24	25	76	75
R3	4	5.5	43	62	31	35	69	65
Second rotation								
R1		*	34	49	30	27	71	74
R5		*	28	52	38	39	63	62
**	1	2.5	31	53	33	36	67	64
**	2	3.5	31	48	35	29	66	71
R1	1	2.5	35	54	34	32	66	68
R1	2	3.5	32	44	25	21	75	79
R5	1	2.5	27	52	31	40	69	60
R5	2	3.5	29	51	44	37	56	63

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 ACLI2. 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_7).

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_7 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

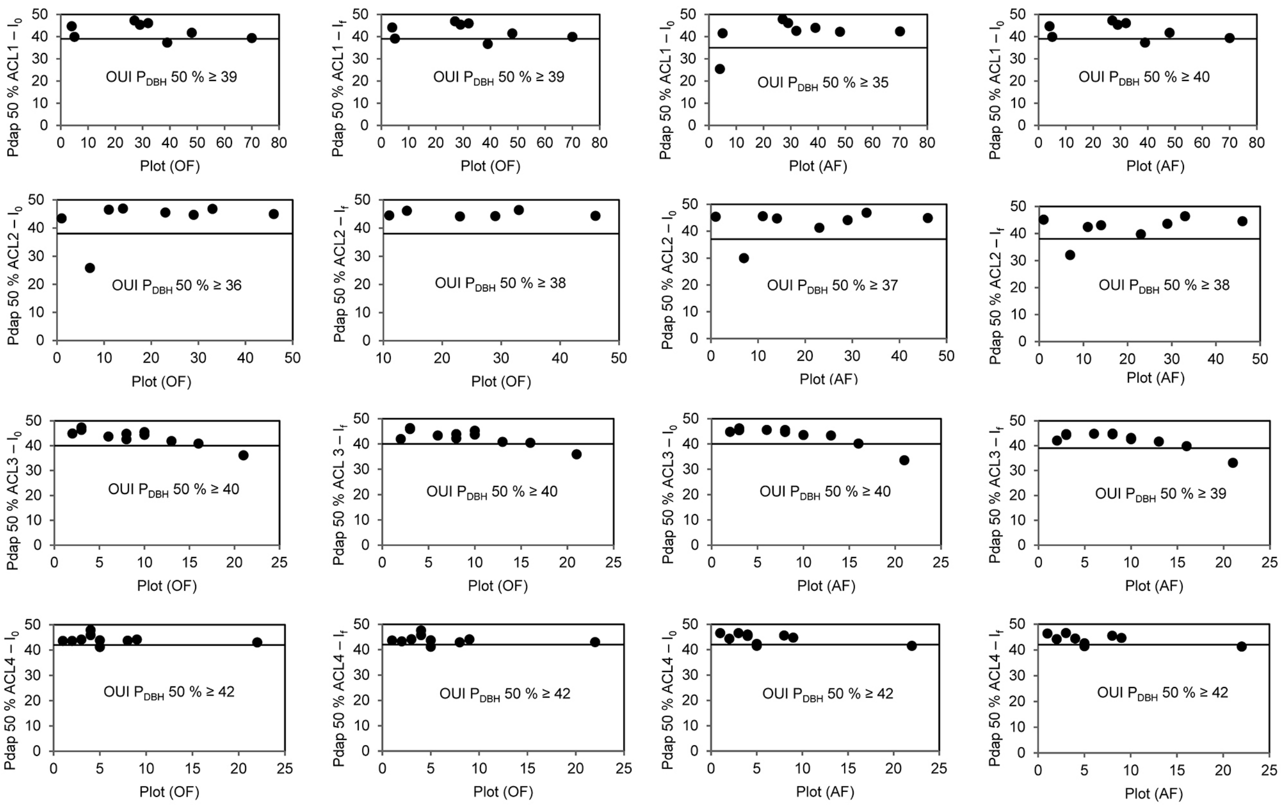

Figure 4 – The Optimal Uniformity Interval (OUI) of P_{DBH} 50 % of the initial (I_0) and final (I_F) ages for OF (Operational Fertilization) and AF (Additional Fertilization) in each age class (ACL) for stands in the first rotation. The ACL Age classes are as follows: ACL1 (30 to 35 months), ACL2 (42 to 47 months), ACL3 (54 to 59 months) and ACL4 (66 to 70 months).

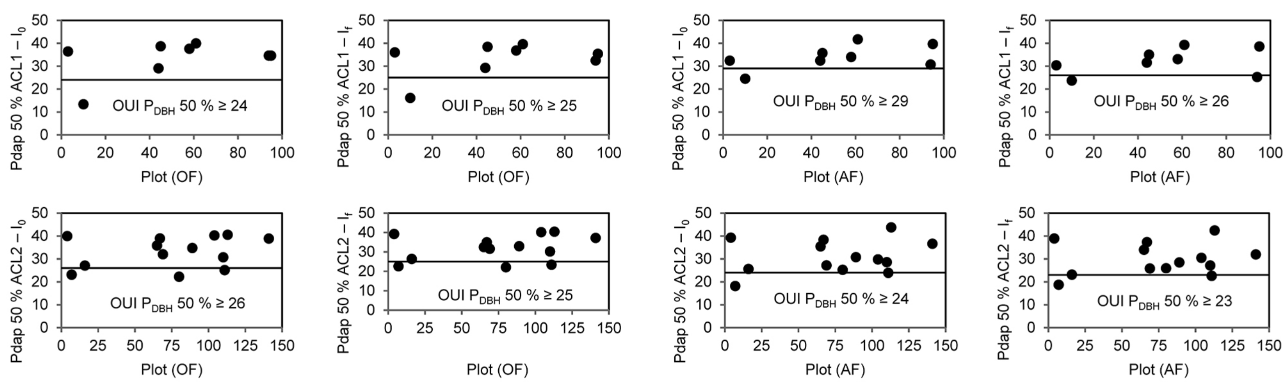

Figure 5 – The Optimal Uniformity Interval (OUI) of PDBH 50 % of the initial (I_0) and final (I_F) ages for OF (Operational Fertilization) and AF (Additional Fertilization) for each age class (ACL) for stands under the second rotation. The ACL Age classes are as follows: ACL1 (30 to 35 months), ACL2 (42 to 47 months), ACL3 (54 to 59 months) and ACL4 (66 to 70 months).

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 Pvar50 % for variable DBH demonstrates that stands in the first rotation tend to present greater uniformity than stands in the second

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 (%) I_0 OF	I_0 AF	I_f OF	I_f AF
First rotation					
1	4	45	47	44	47
1	5	40	42	39	40
1	27	47	48	47	47
1	29	45	46	45	46
1	32	46	43	46	42
1	39	37	44	37	43
1	48	42	42	41	42
1	70	39	42	40	39
2	1	43	45	44	45
2	7	26	30	30	32
2	11	47	46	45	42
2	14	47	45	46	43
2	23	46	41	44	40
2	29	45	44	44	44
2	33	47	47	46	46
2	46	45	45	44	45
3	2	45	45	42	42
3	3	46	45	46	44
3	3	47	46	46	45
3	6	44	46	43	45
3	8	43	46	42	45
3	8	45	45	44	45
3	10	44	44	44	43
3	10	45	44	45	43
3	13	42	43	41	42
3	16	41	40	40	40
3	21	36	34	36	33
4	1	44	47	44	46
4	2	44	44	43	44
4	3	44	47	44	47
4	4	48	45	48	44
4	4	46	46	46	46
4	5	44	42	44	43
4	5	41	42	41	41
4	8	44	46	43	46
4	9	44	45	44	45
4	22	43	42	43	41
Second rotation					
1	3	36	32	36	30
1	10	13	25	16	24
1	44	29	32	29	32
1	45	39	36	38	35
1	58	38	34	37	33
1	61	40	42	40	39
1	94	35	31	32	25
1	95	35	40	35	39
2	4	40	39	39	39
2	7	23	18	23	19
2	16	27	26	26	23
2	65	36	35	32	34
2	67	39	38	35	37
2	69	32	27	32	26
2	80	22	25	22	26
2	89	35	31	33	28
2	104	40	30	40	30
2	110	31	29	30	27
2	111	25	24	23	23
2	113	41	44	40	42
2	141	39	37	37	32

OF = Operational fertilization; AF = Additional fertilization at advanced age; I_0 = Stand age class at the beginning of the experiment; I_f = Average age of stands in the last measurement; ACL = Age class: ACL1 (30 to 35 months), ACL2 (42 to 47 months), ACL3 (54 to 59 months), ACL4 (66 to 70 months).

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)	a	b	c	R^2
First rotation				
OF				
P1	–1199.6	–43.6	0.3	0.99
P2	290.7	13.7	0.6	0.99
P3	2498461809.8	65239767.5	0.3	0.97
P4	311.9	47.0	1.0	0.99
AF				
P1	–307.7	–9.3	0.2	0.99
P2	330.3	11.8	0.5	0.99
P3	6361837331.4	173515685.9	0.3	0.96
P4	319.5	37.3	1.0	0.99
Second rotation				
OF				
P2	207.1	10.5	0.6	0.97
P4	159.5	24.6	1.0	1.00
AF				
P2	238.4	15.7	0.7	0.97
P4	213.2	34.9	1.1	1.00

P1 = Rainfall < 1000 mm; P2 = 1200 < Rainfall < 1400 mm; P3 = 1400 mm < Rainfall < 1600 mm and P4 = Rainfall > 1600 mm, R^2 = Coefficient of determination; OF = Operational fertilization; AF = Additional fertilization at advanced age; Coefficients of volume equations.

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	$m^3\ ha^{-1}\ yr^{-1}$	%	$m^3\ ha^{-1}\ yr^{-1}$	%*	$m^3\ ha^{-1}\ yr^{-1}$	%*
First rotation						
P1	51	100	37	40	37	40
P2	50	100	36	40	34	47
P3	75	100	54	40	48	58
P4	62	100	44	40	43	44
Second rotation						
P2	42	100	30	38	25	67
P4	41	100	30	38	22	84

*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.

rotation. 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 m^3 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 m^3 ha^{-1} yr^{-1} for Brazil. However, if water availability does not limit growth, this yield could reach 65 m^3 ha^{-1} yr^{-1}. In the first rotation, the highest potential yields were obtained for rainfall classes P3 and P4 at 75 and 61 m^3 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 m^3 ha^{-1} yr^{-1}. The wide difference in yield between the two silvicultural regimes of 33.5 m^3 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 m^3 ha^{-1} yr^{-1} for stands in the first rotation and from 41 to 42 m^3 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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