Original Article

Silviculture

Fertilization of Eucalyptus Stands at Advanced Ages in Minas Gerais, Brazil

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ABSTRACT

This study evaluated the response to fertilization at advanced ages in Eucalyptus stands. Fertilization at advanced ages (FA) was applied in stands managed according to tall shaft and coppice regimes. All stands received operational fertilization from the company. It was used as the basis to the network of continuous forestry inventory plots (P-IFC) of the company. Connected to the P-IFC, twin-plots received FA throughout four age classes, 30 to 35, 42 to 47, 54 to 59 and 66 to 70 months. The FA presented a biological response and provided volumetric gains of 17 and 51% for stands with tall shaft and coppice, respectively. The most significant responses to the FA was seen at younger ages of the forest in the tall shaft regime. Despite the biological response, the volumetric gains did not provide financial returns in either regime due to the elevated doses applied.

Keywords: silviculture, forest nutrition, forest management.

1. INTRODUCTION

In recent decades in Brazil the average gains in productivity of wood from 10 to 39 m³ha⁻¹year⁻¹ in *Eucalyptus* stands have been observed. These gains are mainly attributed to an evolution in forestry practices and to genetic improvements (Gonçalves et al., 2008). According to Stape et al. (2010), the use of mineral fertilizers corresponds, on average, to 30% of the gains in productivity.

Fertilization in *Eucalyptus* plantations is normally carried out between the pre-planting phase and the canopy closure. After two years of age, fertilization is reduced or stopped completely (Silva et al., 2013). A direct relation between biomass production and nutrient accumulation was observed by Santana et al. (2008). These authors observed that 70% of the total nutrient demand of *Eucalyptus* plantations in Brazil is accumulated up until 4.5 years of age. Between planting and the maximum leaf area index, the stand shows high levels of nutrient absorption and elevated metabolic activity, factors that explain the greater response to fertilization at a younger age (Gonçalves et al., 2013). After the canopy closure phase, the biochemical cycle becomes gradually more established and tends to meet part of the nutritional demand of the stand. The nutrient cycling associated with the fertilization applied during the initial years is considered adequate to satisfy the total demand of the stand because soluble and relatively insoluble fertilizers are used with the intention of providing nutrients throughout the whole cycle. Consequently, it is expected that the plantations are not responsive to the application of nutrients at advanced ages.

Despite this, studies seeking to analyze the nutritional limitations and potential productivity of *Eucalyptus* have shown a response to fertilization at ages older than two years when very elevated doses of nutrients are applied (Stape et al., 2006; Ferreira & Stape, 2010; Silva et al., 2016). According to the cited authors, the increase in productivity due to fertilization at advanced ages is influenced, amongst other factors, by the stage of development of the forest, soil and climatic conditions, genetic material and type of forestry management adopted. The knowledge of the probability of response to fertilization and its economic viability (Ferreira & Stape, 2010) and the classification of responsive and non-responsive sites (Fisher & Binkley, 2000) are important factors to be considered in making forestry management decisions.

Different to management by tall shaft regime, there have been very little studies on the responses to fertilization in coppice regimes. Generally, the initial fertilization of the stand in coppice regimes takes place after sprout thinning between eight and eighteen months post-harvest. During the phase prior to fertilization, the growth of the stand depends on the nutrient cycling of forest debris, ground cover and the nutrients available in the soil. Reports regarding a drop in productivity during the second rotation in comparison with the first are common (Miranda et al., 1998a, b). Part of the loss of productivity of the stands in the second rotation is attributed to the management adopted in sprout thinning and later fertilization.

Given this, this study aims to evaluate the response to fertilization at advanced ages of *Eucalyptus* stands under tall shaft and coppice regimes in the state of Minas Gerais.

2. MATERIALS AND METHODS

The present study was realized in clonal stands of *Eucalyptus,* planted in six regions (R1; R2; R3; R4; R5; and R6) in the state of Minas Gerais (Table 1).

To evaluate the potential for response to fertilization at advanced ages (FA), 142 twin-plots were planted (Stape et al., 2006) connected to the 142 plots of the network of the continuous forestry inventory (P-IFC). The plots chosen represented stands in four age classes (CLI). The first was between 30 and 35 months, the second between 42 and 47 months, the third between 54 and 59 months, and the fourth between 66 and 70 months. The study evaluated 244 circular parcels, with 60 trees per parcel, planted in spaces varying from 4.9 to 9.5 m² per plant, with 15 clones under two management regimes, tall shaft and coppice (Table 2).

The twin-plots were planted between March and May of 2011, set in five rows at the end of the continuous forestry inventory, with the same soil type and slope.

The evaluated treatments were organized in the following way: Control (C) – operational fertilization (Table 3) represented by the plots of continuous forestry inventory, which received the best forestry practices of the company; fertilization at advanced

Table 1. The main characteristics of the study area.

Region	City	Latitude (S) Longitude (W)[a]	Elv. (m)	Climate[b]	T (°C)	R (mm)	Soil order
R1	Três Marias	45°15'16" S 18°12'32"O	735	Cwa	21	1396	Oxisols
	Lassance	17°53'13"S 44°34'36"O	790	Aw	21	1335	
R2	Rio Pardo de Minas	15°36'36"S 42°32'23"O	900	Cwa	21	903	Oxisols
R3	Ibertioga	21°25'52"S 43°57'58"O	1099	Cwb	17	1555	Oxisols and Ultisols
	São João Del Rei	21°8'82"S 44°15'40"O	1007	Cwb	18	1575	
	Luminárias	21°30'40"S 44°54'11"O	1027	Cwb	18	1594	
	Ingaí	21°24'30"S 44°55'19"O	963	Cwb	18	1614	
	Nazareno	21°13'00"S 44°36'41"O	935	Cwb	18	1689	
	Santo Antônio do Amparo	20°56'47"S 44°55'69"O	969	Cwb	18	1709	
	Ibituruna	21°9'80"S 44°44'51"O	892	Cwb	19	1714	
R4	João Pinheiro	17°44'34"S 46°10'31"O	680	Aw	22	1419	Oxisols and Entisols
R5	Buritizeiro	17°21'10"S 44°57'29"O	658	Aw	22	1252	Entisols
R6	Olhos D'água	17°23'47"S 43°34'28"O	866	Cwa	20	1232	Oxisols and Ultisols
	Diamantina	18°14'40"S 43°36'10"O	998	Cwb	19	1329	

[a]Location of the municipal and district headquarters of the state of Minas Gerais, classification of the Institute of Applied Geosciences (IGA, 2015). [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. Spacing, clone, age class (CLI) and number of plots per region and management regime.

Spacing (m² tree⁻¹)	Clone/Region	CLI (month)	Number of plots
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

*tall shaft. **coppice. CLI = age classes between 30 and 35 months; CLI2 = age classes between 42 and 47 months; CLI3 = age classes between 54 and 59; CLI4 = age classes between 66 and 70 months.

Table 2. Continued...

Spacing (m² tree⁻¹)	Clone/Region	CLI (month)	Number of plots
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
9.0*	GG100/R2	4	1
9.0*	GG2335/R2	4	1
9.0*	GG100/R3	1	1
9.0*	GG2335/R3	1	5
6.0*	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
6.0*	GG100/R3	3	1
6.0*	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

*tall shaft. **coppice. CLI = age classes between 30 and 35 months; CLI2 = age classes between 42 and 47 months; CLI3 = age classes between 54 and 59; CLI4 = age classes between 66 and 70 months.

ages (FA) – recommended to eliminate possible nutritional limitations, applied on the twin-plots that had already received the operational fertilization, in stands in tall shaft and coppice regimes, and in the CLI 1, 2, 3 and 4, according to the proposal of Stape et al. (2006). The FA was divided into four applications, the first (FA1) in the establishment of the twin-plots and the others 6 (FA2), 12 (FA3), and 18 (FA4) months later (Table 4).

The trees of the plots (C and FA) were measured in the twin-plots installations every six months subsequently,

between 2011 and 2013. In each plot, the diameter at 1.30 m from the ground was measured (DBH) for all 60 trees as well as the total height (HT) of the first seven trees. The height of the remaining 53 trees was estimated using artificial neural networks – ANNs (Özçelik et al., 2013).

To estimate the ANNs, the quantitative entry variables were considered to be age (years) and DBH (cm), the categorical entry variables were the rotation and genetic material and the output variable was the HT (m). The trained networks were of the multiple

Table 3. Average and standard deviation of the nutrients applied in the operational fertilization by region.

Region	nº	N	P_2O_5	K_2O	CaO	MgO	SO_3	B	Cu	Zn
		--kg ha^{-1}--								
Tall shaft										
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
Coppice										
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

nº = Number of compartments. Values in parentheses refer to standard deviation, because each compartment in which the plot was established received a specific fertilization prescription.

Table 4. Nutrients applied in the fertilization at advanced age (FA).

Fertilizers	Dose	N	P_2O_5	K_2O	CaO	MgO	SO_3	B	Cu	Zn	Fe	Mn	Mo
		---kg ha^{-1} ---											
FA1													
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
FA2, FA3 e FA4													
MAP	377	34	181	-	-	-	-	-	-	-	-	-	-
KCL	403	-	-	218	-	-	-	-	-	-	-	-	-
NH_4SO_4	696	146	-	-	-	-	160	-	-	-	-	-	-

MAP = monoamonic phosphate; KCl = potassium chloride; NH_4SO_4 = ammonium sulphate; CuSO4 = copper sulphate; $ZnSO_4$ = zinc sulphate; $MnSO_4$ = manganous sulphate. FA1 was applied in the establishment of the twin-plots, and the others 6 (FA2), 12 (FA3) and 18 (FA4) months later.

layer *perceptron* type, also known as MLP (Multilayer Perceptron). An ANN was trained for each treatment (C and FA) utilizing the software Statistica 10 (Statsoft, 2010), which used 50% of the data to train the networks, 25% for the test and 25% for validation.

Based on the DBH and HT values, the individual volumes were estimated (V – Equation 1) for each tree, in each parcel evaluated, utilizing the Shumacher & Hall (1933) model,

$$Ln(V) = \beta_0 + \beta_1 * Ln(DBH) + \beta_2 * \ln(HT) + \varepsilon \qquad (1)$$

in which: *Ln* is the Naperian logarithm; *V* the volume per tree (m³); β_0, β_1 and β_2 the model parameters; *DBH* the diameter at 1.3 m from the ground (cm); *HT* the total height of the trees (m); and ε the random error.

To obtain the initial twin character between the plots C and FA, plots whose volumes were statistically equal according to T-paired test analysis were chosen, with a level of significance of 0.05 (Figure 1) (Stape et al. 2006).

In each treatment (C and FA) the volumetric gain (GV – Equation 2), was expressed by the difference between the volume obtained in the last and first measurements:

$$GV = Vf_i - V0_i \qquad (2)$$

In which: *GV* is the volumetric gain (m³ ha⁻¹); *V* the volume (m³ ha⁻¹); *f* the last measurement; 0 the first measurement; and *i* the treatment.

The response to FA, independent of R and CLI, was evaluated by comparison with the GV between the treatments C and FA. For this, the T-paired test was applied, with a level of significance of 0.05 utilizing the Statistic 10 software (Statsoft, 2010). The response to FA (Equation 3) by R and CLI was evaluated using descriptive statistics, obtaining an average of the GV for each treatment (C and FA) and comparing them according to the relative difference between the average of GV of the FA in relation to the average of the volumetric gain of C:

$$RFA = GV_{FA} - GV_C \qquad (3)$$

in which: *RFA* is the response to FA in m³ ha⁻¹; and *GV* is the volumetric gain (m³ ha⁻¹).

To evaluate the economic viability of the GV stemming from the FA, a cost benefit analysis according to Kimberley et al. (2004) was carried out for two situations: general analysis (independent of R and CLI) and analysis by CLI. The costs per hectare included expenses for fertilizer and labor (F1 – R$ 3,618.9; F2 – R$ 2,090.0; F3 – R$ 2,090; F4 – R$ 2,090). For the calculation of the income, the value of sales of standing wood was considered to be R$ 55.0 m⁻³. The current values of the costs were deflated according to the General Price Index – internally available at the Fundação Getúlio Vargas (FGV, 2017) as suggested by Nascimento et al. (2016).

The probability of the response to FA, by the GV, was analyzed using five classes according to the frequency of response by plot. The class (CL) was distributed according to the average ($\bar{X}$) and the standard deviation (S): CL1 – R < $\bar{X}$ − 2S; CL2 − $\bar{X}$ − 2S < R < $\bar{X}$ − 1S; CL3 − $\bar{X}$ − 1S < R < $\bar{X}$ + 1S; CL4 − $\bar{X}$ + 1S < R < $\bar{X}$ + 2S; and CL5 − R > $\bar{X}$ + 2S.
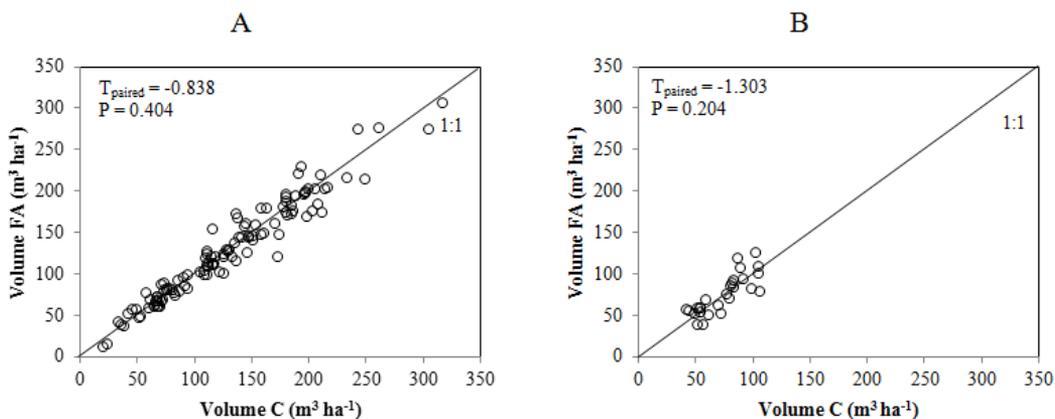

Figure 1. The twin character between the initial volumes of the control (C) and the fertilization at an advanced age (FA) in the stands in tall shaft (A) and coppice (B) regimes.

3. RESULTS

Stands in a tall shaft regime presented, respectively, volumes (m³ ha⁻¹) initial averages and mean annual increment – MAI (m³ ha⁻¹ year⁻¹) – of 128 and 34 for C and 129 and 36 for FA, and for the coppice regime 73 and 26 for C and 76 and 33 for FA.

The FA provided a positive response in terms of volumetric production in both management regimes (Figure 2). The volumetric gain, independent of age and region, was 17% greater in the tall shaft (FA = 77 m³ ha⁻¹; C = 66 m³ ha⁻¹) and 51% in the coppice (FA = 95 m³ ha⁻¹; C = 63 m³ ha⁻¹).

Considering the tall shaft regime, the greatest gain was observed in R6 (39%) and the least in R2 (6%) (Table 5). The response to the FA was different depending on the age at the time of application. Stands in the CLI 1 showed volumetric gains of 21% and those in the CL4 of 11%. In the coppice regime, gains were above those of the tall shaft regime with values reaching 57% in the R5 and 62% in the CLI 1.

The cost for the FA was the same in all evaluated situations (Table 6). It can be observed that the GV with FA did not present an economic return for stands in tall shaft and coppice regimes, independent of R and CLI, given that income obtained was much less than
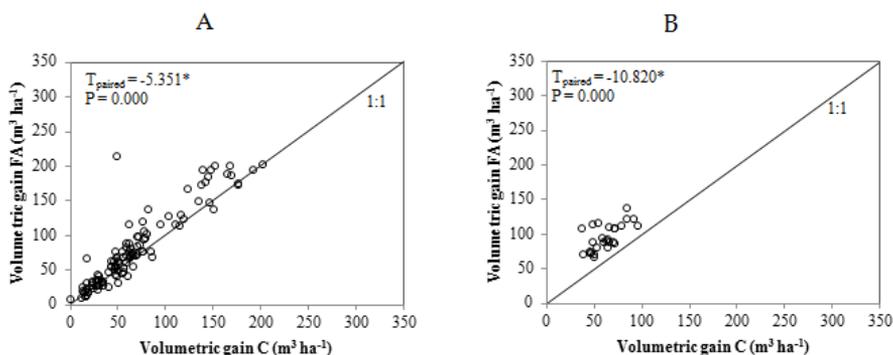
Figure 2. Relationship between the volumetric gains of the control (C) and fertilization at advanced age (FA) in stands with tall shaft (A) and coppice (B) regimes.

Table 5. Average volumetric gains of the control (C) and the fertilization at advanced age (FA) for stands in tall shaft and coppice regimes.

Region	CLI	I_0	I_f	N	Volumetric gain C	Volumetric gain FA	D_i	CV C	CV FA
		---month---			----m³ ha⁻¹----			------%------	
Tall shaft									
R1	*	*	*	38	54	59	8	49	53
R2	*	*	*	22	30	31	6	50	51
R3	*	*	*	23	121	152	25	43	35
R4	*	*	*	22	70	76	9	58	55
R5	*	*	*	6	62	82	33	39	36
R6	*	*	*	4	50	70	39	45	28
**	1	30	54	30	87	106	21	58	53
**	2	42	66	25	87	97	11	58	62
**	3	54	78	30	60	71	18	46	53
**	4	66	80	30	34	38	11	78	90
Coppice									
R1	*	*	*	21	62	93	49	22	22
R5	*	*	*	6	64	100	57	37	16
**	1	30	55	11	61	99	62	26	21
**	1	42	66	16	64	92	44	25	20

C = control; FA = fertilization at advanced age; CV = coefficient of variation; I_0 = Stands age class at the beginning of the experiment; I_f = Average age of stands in the last measurement; N = Number of plots; D_i = Difference in percentage between the mean volumetric gains of the FA in relation to the C at the end of the experiment. *Age independent analysis by age. **Age independent analysis of the region.

Table 6. Cost of fertilization at advance age (FA) and income obtained from volumetric gains derived from FA in stands with tall shaft and coppice regimes.

Type of analysis	Cost	Income	
		Tall shaft	Coppice
		--------------------------------------R\$ ha^{-1}--------------------------------------	
General*		605	1760
CLI 1**		1045	2090
CLI 2**	13,375	550	1540
CLI 3**		605	-
CLI 4**		220	-

*Independent of region and age classes. **Analysis of age classes (CLI): CLI1 between 30 and 35 months; CLI2 between 42 and 47 months; CLI3 between 54 and 59 months; and CLI4 between 66 and 70 months.

A

B
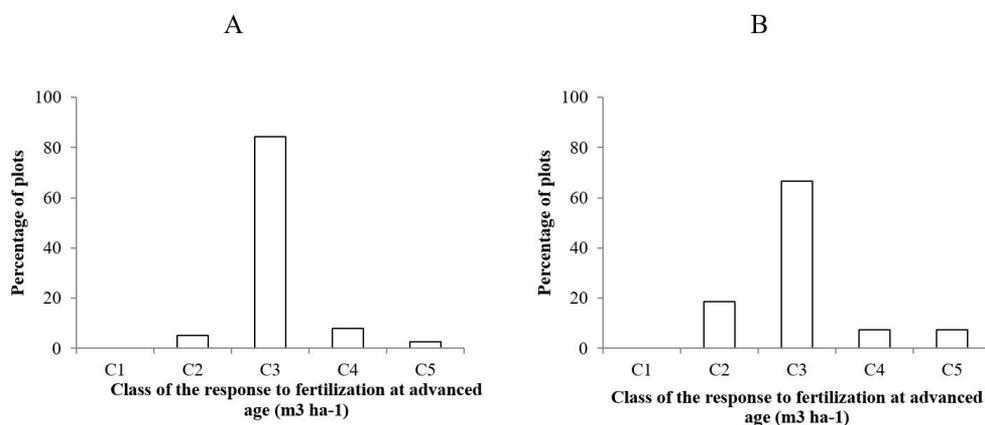
Figure 3. Distribution of the response to fertilization at advanced age of all the parcels, by response class (R): $CL1 - R < \bar{X} - 2S$; $CL2 - \bar{X} - 2S < R < \bar{X} - 1S$; $CL3 - \bar{X} - 1S < R < \bar{X} + 1S$; $CL4 - \bar{X} + 1S < R < \bar{X} + 2S$; and $CL5 - R > \bar{X} + 2S$, for the stands in tall shaft (A) and coppice (B) regimes.

the cost. In analyses only using CLI, it can be observed that the stands that received the FA at younger ages were those presenting the greatest additional incomes.

The probability of the response to FA tended toward normal distribution in the stands in tall shaft and coppice regimes (Figure 3). In the tall shaft regime, the average gain was 11 m³ ha⁻¹ with a standard deviation of 22 m³ ha⁻¹. In percentage terms, 38% of the plots presented responses above the average and 19% presented more than twice the average. In the coppice regime, the average was 32 m³ ha⁻¹ with a deviation of 15 m³ ha⁻¹. In this regime, 37% of the plots showed responses above the average and 7% were more than twice the average.

4. DISCUSSION

The response to FA in terms of GV showed an average of 11 m³ ha⁻¹ in tall shaft regimes (Figure 2). Studies carried out in the state of São Paulo agree

with these observations. The average gains of 10 and 8.1 m³ ha⁻¹ year⁻¹ were observed, respectively, by Stape et al. (2006) and Ferreira & Stape (2010). In both studies, the same FA utilized in the present study was used. The operational fertilization utilized was based on the nutritional balance method. This method was developed to achieve desired productivity and guarantee the sustainability of the forestry sites (Gonçalves et al., 2008) with fertilization generally focusing on the first two years of life to guarantee growth until nutrient cycling was established.

Despite the biological response observed with FA, it did not lead to economic viability, given that the additional income derived from GV presented values well below the cost of the fertilizer and the labor for its application (Table 6). Considering the cost benefit analysis by CLI, it was found that the additional income was greater in stands that received FA at a younger age (CLI 1). This fact agrees with the observations

of Santana et al. (2008) and Gonçalves et al. (2013) where a greater demand for nutrients during younger phases of forest development was demonstrated with a consequent greater potential for response to its application at younger ages. It is underlined that the economic returns from FA were not expected since it was primarily recommended to guard against nutritional shortfalls in the stands.

The average of the MAI in the coppice regime was 23% lower than the tall shaft regime for operational fertilization. However, a much greater biological response to FA in terms of the tall shaft regime was observed, despite not observing an economic benefit. Probably the unviable economic outcome occurred due to the elevated doses of fertilizers applied in the FA. The use of high doses aimed to avoid growth restrictions due to nutrient shortfalls. This indicates that studies with fertilizer doses in FA in the coppice regime have a greater potential to achieve economic viability.

The operational fertilization in the coppice regime is only carried out after sprout thinning, which occurs at 12 months post-harvest, applying quantities of nutrients well below those of the tall shaft regime (Table 3). This marked reduction of the doses applied, associated with stress caused by the sprout thinning, eliminating between 50% and 70% of the biomass produced, is one of the factors that could explain the drop in productivity and the greater biological response to FA. Less productivity tends to present more significant responses to fertilizations in *Eucalyptus* stands (Ferreira & Stape, 2010; Silva et al., 2016). Studies in stands managed according to a coppice regime have shown lower productivity in relation to the tall shaft regime (Miranda et al., 1998a, b; Faria et al., 2002). The authors argue that part of the drop in productivity of these stands results from nutritional deficiencies generated by the exportation of nutrients. These nutritional limitations can be minimized if the harvest is restricted to the wood, leaving all the residue in the area (Santana et al., 2002).

When comparing the two extremes of response to the same FA by region, in the tall shaft regime we can infer that greater water availability favors production (Tables 1 and 5). To demonstrate this effect, regions R2 and R3 were selected, since they possess all the age classes evaluated. A greater response to fertilization in regions with greater water availability is widely reported in the literature (Smethurst et al., 2003; Stape et al., 2010; Silva et al., 2016).

Greater responses to the FA was observed during development in forests with tall shaft regimes, in other words, the younger the age, the greater the response observed. Stands with 2.5 years (CLI 1) are nearer to the canopy closure stage. This stage tends to show a greater leaf area index (Smethurst et al., 2003; Laclau et al., 2010), consequently, there is a greater demand for nutrients. The lower response to FA at more advanced ages can be attributed to the establishment of nutrient cycling (Santana et al., 2008; Gonçalves et al., 2013) and of operational fertilization that adopted the nutritional balance model where one does not expect nutritional restrictions. Some authors report greater responses to FA at advanced ages in studies with twin-plots (Stape et al., 2006; Ferreira & Stape, 2010; Silva et al., 2016) where nutritional restrictions were observed using limited quantities of nutrients applied during operational fertilization.

The probability of the response to the FA can be employed to classify the stands with greater or lesser potential for response (Fisher & Binkley, 2000). In the present study, approximately 37% of the plots presented a greater potential for biological response to the FA in both regimes evaluated (Figure 3). This highlights that applying the same fertilization indiscriminately without considering regional quality may not generate the best outcomes. It is common in Brazilian *Eucalyptus* cultivation to apply similar quantities of nutrients in locations with distinct potentials in the response, a fact that can compromise economic returns.

The FA applied at advanced ages where operational fertilization was established employing the nutritional balance method shows that starting from 2.5 years of age there was no economic benefit, despite the biological response. To better exploit the potential of this type of fertilization, its application, taking into account different levels and dosages in a sequence of ages between six and 30 months, can demonstrate the viability or not of the response to fertilization at advanced ages.

5. CONCLUSION

- Fertilization at advanced age presented a biological response and provided volumetric gains for stands managed according to tall shaft and coppice regimes.

- Stands with a coppice regime possess greater potential for biological response to fertilization at an advanced age.

- Despite the biological response, the volumetric gains did not provide a financial return in either regime due to the elevated doses applied.

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