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ORIGINAL ARTICLE

Effect of sprouting rate and number of stems on the productivity of a *Eucalyptus grandis* plantation coppiced for three rotations

Número de fustes, falhas e necessidade de compensação na condução da terceira rotação de uma plantação de *Eucalipto grandis*

José Henrique Tertulino Rocha[1*], Alexandre de Vicente Ferraz[2], Rildo Moreira e Moreira[3], Gustavo Jaske da Conceição[4], Graziela Baptista Vidaurre[4], Arthur Vrechi[5], José Henrique Bazani[5], Eduardo Moré de Matos[5], José Leonardo de Moraes Gonçalves[3]

[1]*Sylvamo, Mogi Guaçu, SP, Brasil*
[2]*Instituto de Pesquisa e Estudos Florestais – IPEF, Piracicaba, SP, Brasil*
[3]*Escola Superior de Agricultura "Luiz de Queiroz" – ESALQ, Universidade de São Paulo – USP, Piracicaba, SP, Brasil*
[4]*Universidade Federal do Espírito Santo – UFES, Jerônimo Monteiro, ES, Brasil*
[5]*GEPLANT Tecnologia Florestal, Piracicaba, SP, Brasil*

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***Corresponding author:** rocha.jht@gmail.com
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ABSTRACT

The ability of a coppice system to sustain the same productivity as a high forest depends primarily on silvicultural management (e.g., harvester efficiency, fertilization regime, and weed control) and the maintenance of plant populations under similar climatic conditions. To test this hypothesis, we conducted a trial in a *Eucalyptus grandis* plantation managed under a coppice system for three successive rotations in São Paulo state, Brazil. We evaluated the effects of stump survival rate and stem number per hectare on wood productivity and quality. The productivity at age seven for the first (R1, high forest), second (R2), and third rotations (R3) was 43 m^3 ha^{-1} $year^{-1}$, 53 m^3 ha^{-1} $year^{-1}$, and 56 m^3 ha^{-1} $year^{-1}$, respectively. At the beginning of each rotation, failure compensation (maintenance of two stems per stump adjacent to a non-sprouting stump) enhanced canopy cover and increased wood volume. Wood volume production declined with decreasing survival rates but increased with a higher number of stems per hectare. However, at seven years in the third rotation, no significant differences ($p = 0.151$) in wood volume were observed among treatments. An increase in the number of stems per hectare reduced individual tree volume by 50% and wood basic density by 3%. Thus, maintaining more than one stem per stump may shorten the optimal harvest age but does not affect total wood volume at seven years while potentially reducing wood quality of R3.

Keywords: *Sprout conduction; Coppice; Silvicultural system; Failure compensation.*

RESUMO

A capacidade da talhadia em manter a mesma produtividade da reforma depende, primordialmente, do manejo silvicultural (e.g., eficiência da colheita, regime de fertilização e controle de plantas daninhas) e da sobrevivência, sob condições climáticas semelhantes. Para testar essa hipótese, foi conduzido um experimento em um plantio de *Eucalyptus grandis* manejado sob sistema de talhadia por três rotações sucessivas no estado de São Paulo, Brasil. Foi avaliado o efeito da sobrevivência das cepas e do número de fustes por hectare sobre a produtividade e a qualidade da madeira. A produtividade aos sete anos de idade na primeira (R1, alto fuste), segunda (R2) e terceira rotações (R3) foi de 43 m^3 ha^{-1} ano^{-1}, 53 m^3 ha^{-1} ano^{-1} e 56 m^3 ha^{-1} ano^{-1}, respectivamente. A compensação de falhas (manutenção de dois fustes por cepa adjacente a uma cepa sem brotação) promoveu maior fechamento do dossel e aumento do volume de madeira no início do ciclo. A produção de madeira diminuiu com a redução da taxa de sobrevivência das cepas, porém aumentou com o maior número de fustes por hectare. Entretanto, aos sete anos de idade na terceira rotação, não foram observadas diferenças significativas ($p = 0{,}151$) no volume de madeira entre os tratamentos avaliados. O aumento do número de fustes por hectare reduziu o volume individual das árvores em 50% e a densidade básica da madeira em 3%. Dessa forma, a manutenção de mais de um fuste por cepa pode reduzir a idade ótima de corte, mas não afeta o volume total de madeira aos sete anos, embora possa comprometer a qualidade da madeira na terceira rotação.

Palavras-chave: *Condução de brotação; Talhadia; Sistema silvicultural; Compensação de falhas.*

1. INTRODUCTION

Eucalyptus plantations are extensively regenerated through coppicing, particularly in even-aged stands established in tropical and subtropical regions, due to their high sprouting capacity following clear-cutting and the cost-effectiveness of the system (Andrade, 1961; Reis & Reis, 1997; Gonçalves et al., 2013; Arthur Junior et al., 2015; Little & du Toit, 2002). Although coppiced plantations exhibit faster initial growth, they generally achieve similar productivity to high forests at the end of the rotation (~7 years), provided that climatic conditions remain consistent across rotations (Gonçalves et al., 2014; Little & Gardner, 2021).

Despite numerous studies confirming that coppice productivity matches that of high forests (Gonçalves et al., 2014), many Brazilian forestry companies assume that productivity in coppiced stands is approximately 10% to 20% lower (Arthur Junior et al., 2015). This perceived reduction is often attributed to factors such as lower nutrient availability in subsequent rotations (Rocha et al., 2019), mechanical damage to stumps during harvesting (Santana et al., 2000), and a decline in plant populations due to stump mortality post-harvest (Reis & Reis, 1997). The overall reduction in productivity has led to a cautious approach to coppicing, resulting in underutilization of the system. Among vertically integrated forestry companies in Brazil, coppicing is used in only 0% to 50% of reestablished areas for the second rotation, and none maintain coppice systems beyond three rotations (Arthur Junior et al., 2015). Since 2015, no further benchmarking studies on coppice have been published; however, the available evidence indicates that the these values remain essentially unchanged.

Another factor influencing coppice adoption is its increased utilization during economic downturns. For instance, in 2008, only 5% of the *Eucalyptus* plantation area in Brazil was reestablished through coppice. However, following the 2008 financial crisis, this figure surged to 25% in 2009 (Associação Brasileira de Produtores de Florestas Plantadas, 2013). Coppicing is a strategic cost-saving measure, reducing reestablishment expenses by 40% to 50%. Nevertheless, economic downturns often coincide with reduced silvicultural standards, including suboptimal weed control and fertilization, which can negatively impact productivity.

There is no evidence of reduced plant vigor with successive coppice cycles, at least up to the sixth rotation (Andrade, 1961; Reis & Reis 1997). This suggests that the ability of coppiced stands to maintain productivity comparable to high forests is primarily dependent on effective silvicultural management and the maintenance of an adequate plant population. To test this hypothesis, we conducted a study in a *Eucalyptus grandis* plantation managed under a coppice system for three successive rotations. Our objective was to assess the effects of stump survival rate and the number of stems per hectare on wood productivity and quality.

2. MATERIAL AND METHODS

2.1. Study site

The study was conducted at the Itatinga Forest Science Experimental Station of the University of São Paulo (ESALQ/USP) in Brazil (23° 06' S, 48° 36' W, and 857 m above sea level). The region is classified as humid subtropical (Cfa) according to the Köppen climate classification, with a mean annual temperature of 19.4 °C [ranging from 15.6 °C in the coldest month (July) to 22.3 °C in the hottest month (January)] and a mean annual rainfall of 1319 mm, with 75% of rainfall concentrated between October and March (Alvares et al., 2013).

The topography of the area is flat to undulating, and the soil is a deep Ferralsol (International Union of Soil Sciences, 2015), classified as Latossolo Vermelho-Amarelo distrófico típico in the Brazilian Soil Classification System and Oxisol in the USDA Soil Taxonomy. The soil is developed from Cretaceous sandstone, with a clay content ranging from 17% in the A horizon to 20% in deeper layers. Its mineralogy is dominated by quartz, kaolinite, and aluminum and iron oxyhydroxides. The soil is acidic (pH ~4.3 in water), with low exchangeable cations (0.4, 3.1, and 2.3 mmolc kg^{-1} of K, Ca, and Mg, respectively) and limited P (3.1 mg kg^{-1}) and S (3.8 mg kg^{-1}) availability. The original vegetation was Cerrado *stricto sensu* (Brazilian savannah) (Ribeiro & Walter, 1998). The site has been used for *Eucalyptus* plantations since 1940.

2.2. Site management

The experimental site was initially planted (R1) in September 2000 with clonal *Eucalyptus grandis* seedlings at a 3 × 2 m spacing as part of a commercial pulpwood plantation. The first harvest occurred in September 2007, after which the coppice sprouts were managed (R2). Twelve months post-harvest, sprout thinning was conducted to maintain one stem per stump. In April 2014, the site was harvested again, and the trial for the third rotation (R3) was established. The productivity of R1 (2000-2007) was 43 m^3 ha^{-1} year^{-1}, while R2 yielded 53 m^3 ha^{-1} year^{-1}. Fertilizer rates for each rotation are detailed in Table 1, and climatic conditions for each rotation are presented in Table 2. Throughout all rotations, weed control was maintained using glyphosate applications.

2.3. Experimental design and treatments

After clear cutting of R2 (April 2014), the area was managed by coppicing with eight treatments in a randomized block design with four repetitions. Each plot comprised 12 rows of 12 plants; measurements were performed in an inner plot with eight rows of eight plants, thus maintaining a double-row buffer. The treatments assessed the effect of the stumps survival rate (90%, 80%, and 70%), stems per stump (1, 2, and without sprout thinning), and the effect of the failure compensation. As failure compensation, we considered the maintenance of two stems per stump in the stump next to a dead stump, thus returning the number of stems per hectare to 1667, independent of the stump survival rate (Table 3).

Before treatment installation, the stump survival rate of the site was approximately 90%. The stump survival rate was reduced to 80% or 70% by random glyphosate application in the sprouts. During elimination of sprouts to reduce the stump survival rate and during the failure compensation, care was taken to maintain the same level of failure and stems in the inner plot and in the buffer. In this manner, failure in the inner plot was compensated by maintaining two stems in the stump of the inner plot.

2.4. Assessment

At six months after sprout thinning, the canopy cover was assessed using the supervised classification function of ArcGIS software in an RGB image captured by a drone flying at 60 m height.

At 41, 64, and 87 months of R3, the diameter at breast height (DBH) and the height of all trees in the inner plot were measured. At each assessment time, 30 trees were felled in the 90%NC, 90%2st, and 90%NST treatments (10 in each) to evaluate solid wood volume with bark, both per tree (m^3 tree^{-1}) and per hectare (m^3 ha^{-1}).

Table 1. Fertilizer applied at the experimental site during the two first commercial rotations (R1 and R2) and during the experiment R3.

Fertilizer	Period	Nutrient applied						
		N	P	K	Ca	Mg	B	Zn
R1 – 2000 to 2007								
Planting	during planting	18	20	36	480	120		3
1ª Topdressing	4 months after planting	30		32			1,2	
2ª Topdressing	17 months after planting	60						
Total		**108**	**20**	**68**	**480**	**120**	**1,2**	
R2 – 2007 to 2014								
1ª Topdressing	2 months after harvesting	55		49	370	90	2	
2ª Topdressing	1 month after sprout thinning			154			0,35	
3ª Topdressing	5 months after sprout thinning	73					0,16	
Total		**128**		**203**	**370**	**90**	**2,51**	
R3 – 2014 to 2021								
1ª Topdressing	4 months after sprout thinning	106	17	121	480	120	2,5	
Total		**106**	**17**	**121**	**480**	**120**	**2,5**	

Table 2. Weather conditions and soil water balance following the Thornthwaite & Mather (1955) method during three rotations of a *E. grandis* plantation.

Year	Temperature			PP(1)	ETP(2)	ETA(3)	WS(4)	WD(5)	Months with WD(6)
	Maximum	Mean	Minimum						
	ºC			mm					
First rotation (high forest)									
2000	27.8	20.5	15.7	1651	1005	957	556	48	3
2001	28.1	21.1	16.2	1435	1062	1047	387	15	1
2002	29.0	21.9	16.8	1429	1139	1058	371	81	5
2003	28.2	21.0	15.9	1243	1049	992	251	56	4
2004	27.4	21.4	15.5	1509	1094	1052	457	41	2
2005	28.6	22.4	16.2	1631	1181	1149	483	32	2
2006	28.0	21.9	15.9	1479	1143	1065	414	78	4
Mean	**28.1**	**21.5**	**16.0**	**1482**	**1096**	**1046**	**417**	**50**	**3.0**
Second rotation (coppice)									
2007	28.3	22.1	15.9	1439	1165	1089	457	76	3
2008	27.6	21.6	15.7	1305	1114	1080	186	33	3
2009	27.2	21.9	16.5	1966	1137	1137	760	1	0
2010	27.9	21.9	15.8	1553	1140	1089	484	51	4
2011	27.9	21.8	15.8	1703	1131	1068	615	63	3
2012	28.7	22.6	16.5	1592	1222	1174	430	48	4
2013	27.5	21.7	15.9	1509	1118	1090	493	29	2
Mean	**27.9**	**22.0**	**16.0**	**1581**	**1147**	**1104**	**489**	**43**	**2.7**
Third rotation (coppice)									
2014	30.4	23.6	16.9	1073	1324	1062	0	261	8
2015	28.9	23.1	17.3	1504	1261	1227	201	34	4
2016	28.0	22.0	16.1	1575	1163	1128	461	35	2
2017	28.2	22.3	16.3	1402	1185	1118	377	67	4
2018	28.8	22.8	16.8	1075	1225	1079	0	146	6
2019	29.9	23.6	17.2	1133	1324	1158	33	166	5
2020	29.9	23.3	16.6	1216	1282	1051	132	231	6
Mean	**29.2**	**22.9**	**16.7**	**1282**	**1252**	**1118**	**172**	**134**	**5.0**

(1) Mean annual rainfall; (2) Mean potential evapotranspiration; (3) Mean actual evapotranspiration; (4) Water surplus; (5) Water deficit; (6) Months with water deficit higher than 10 mm.

Table 3. Treatment applied to coppice for the third rotation a *E. grandis* plantation.

Treatment[(1)]	Stems per stump	stump survival (%)	Compensation	Stems per ha[(2)]
90%NC	1	90	no	1500
90%C	1	90	yes	1667
80%NC	1	80	no	1334
80%C	1	80	yes	1667
70%NC	1	70	no	1167
70%C	1	70	yes	1667
90%2st	2	90	no	3000
90%NST	NST	90	no	>3000

[(1)] 90%NC - 90% of stump survival without compensation, 90%C - 90% of stump survival with compensation, 80%NC - 80% of stump survival without compensation, 80%C - 80% of stump survival with compensation, 70%NC - 70% of stump survival without compensation, 70%C - 70% of stump survival with compensation, 90%2st – 90% of stump survival with two stems per stump, 90%NST – 90% of stump survival without sprout thinning; [(2)] Number of stems maintained after sprout thinning

The solid volume was calculated using Smalian's equation (Scolforo & Thiersch, 2004), measuring diameters every meter until reaching a minimum top end diameter of 8, 5, and 3 cm. At 87 months of R3, trees were classified by DBH per treatment to determine industrial wood utilization opportunities (e.g., pulp or bioenergy).

Six trees per treatment were collected for the evaluation of basic wood density (g cm^{-3}) at 87 months of the third rotation (R3). In the 90%2st treatment, both stems of the selected stumps were collected, while in the 90%NST treatment, three stems per stump were selected. For the other treatments, only a single stem was collected. Wood discs were extracted from four positions along the stem: base (0%), diameter at breast height (DBH), 50%, and 100% of the commercial height. A 45° wedge was taken from each disc to determine the basic wood density, following the procedures established by the NBR 11941 standard (Associação Brasileira de Normas Técnicas, 2003). The average tree density was calculated using proportional volume of each section.

DBH and height were used as independent variables in the volume estimation model, which was applied across all dates due to the non-significant effect of treatments. The model (Equation 1) had a determination coefficient of 0.99 and a p-value < 0.001:

$$TWV = 0.00642 + 3.297 \times 10^{-5} \times DBH^2 \times H + \varepsilon \quad (1)$$

where: TWV = Total wood volume (m^3); DBH = Diameter at breast height (cm); H = Height (m).

The Schumacher (1939) growth curve (Equation 2) was fitted to estimate the optimal harvest age (OHA) using volume maximization criteria. The OHA, considered as the inflection point of the growth curve, corresponded to the age at which the maximum mean annual increment (MAI) was reached:

$$V = e \wedge \left(\beta_0 + \beta_1 \left(1/I\right)\right) + \varepsilon \quad (2)$$

2.5. Data analysis

Normality (Shapiro-Wilk) and homoscedasticity (Box-Cox) tests confirmed no deviations. The F-test assessed equality probabilities, and when $p < 0.05$, the least significant difference (LSD) test compared treatments. Statistical analyses and volume model parameter estimations were performed using R software (Mendiburu, 2023).

3. RESULTS

3.1. Canopy cover

At two years of R3 (six months after treatment application), the largest canopy cover was found in the no sprout thinning treatment (90%NST), followed by the two stems per stump (90%2st) treatment. All treatments with one stem per stump exhibited a lower canopy cover than the 90%2st and 90%NST treatments. Failure compensation did not significantly affect the canopy cover in the 90% and 70% stump survival treatments but had a significant impact on the 80% stump survival treatment (Figure 1).

3.2. Productivity

The wood volume produced at 41 months of R3 was strongly affected by the treatments ($p < 0.001$). The treatment without sprout

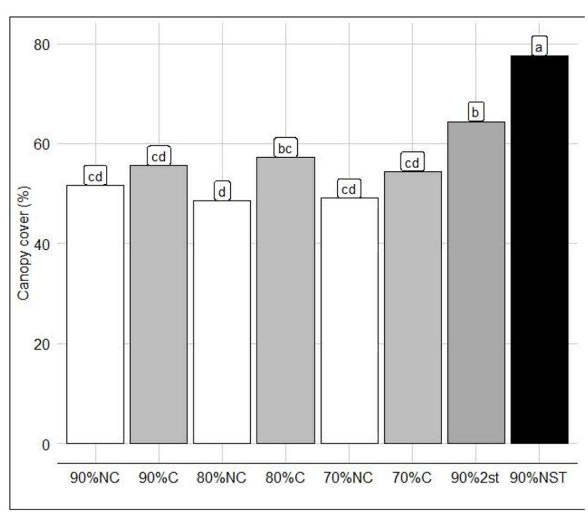

Figure 1. Canopy cover of the coppiced *E. grandis* plantation assessed 6 months after sprout thinning (2 years of R3). Treatments: 90%NC - 90% of stump survival without compensation, 90%C - 90% of stump survival with compensation, 80%NC - 80% of stump survival without compensation, 80%C - 80% of stump survival with compensation, 70%NC - 70% of stump survival without compensation, 70%C - 70% of stump survival with compensation, 90%2st – 90% of stump survival with two stems per stump, 90%NST – 90% of stump survival without sprout thinning. Bars following by same letters do not differ by LSD test (P < 0.05).

thinning had the largest wood volume, followed by the treatment with two stems per stump. At this age, failure compensation increased the wood volume by 7%, 14%, and 11% in the treatments with 90%, 80%, and 70% stump survival, respectively (Figure 2).

The differences among treatments reduced with age. At 64 months, the 90%NST treatment remained the most productive. No difference was found between the 90%2st treatment and the one-stem treatment with failure compensation. The lowest wood volume was found in the 70%NC treatment (Figure 2).

At the end of the third rotation (87 months), no difference (p = 0.151) in wood volume was found among treatments (Figure 2). The average wood volume in R3 was 405 $m^3 ha^{-1}$, surpassing that of R1 (301 $m^3 ha^{-1}$) and R2 (371 $m^3 ha^{-1}$).

3.3. Growth rate

The reduction in productivity differences among treatments over time indicates that the growth rate of the 90%NST treatment was initially higher but declined towards the end of the rotation. In contrast, the growth rate of the 70%NC treatment remained high for a longer period (Figure 3).

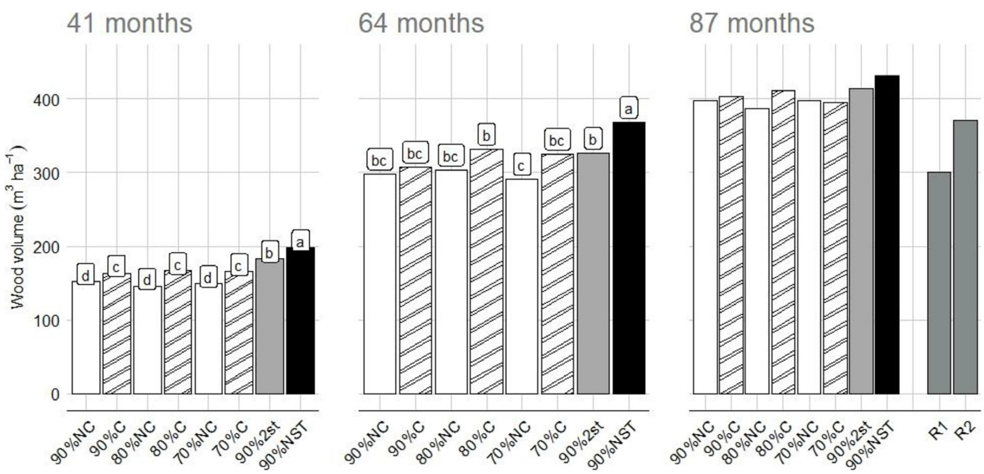

Figure 2. Total wood volume with bark produced by *E. grandis* plantations conducted by coppice in the third rotations. Treatments: 90%NC - 90% of stump survival without compensation, 90%C - 90% of stump survival with compensation, 80%NC - 80% of stump survival without compensation, 80%C - 80% of stump survival with compensation, 70%NC - 70% of stump survival without compensation, 70%C - 70% of stump survival with compensation, 90%2st – 90% of stump survival with two stems per stump, 90%NST – 90% of stump survival without sprout thinning, R1 – first rotation (high forest, 2000-2007), R2 – second rotation (coppice, 2007-2014). Bars following by same letters do not differ by LSD test (P < 0.05).

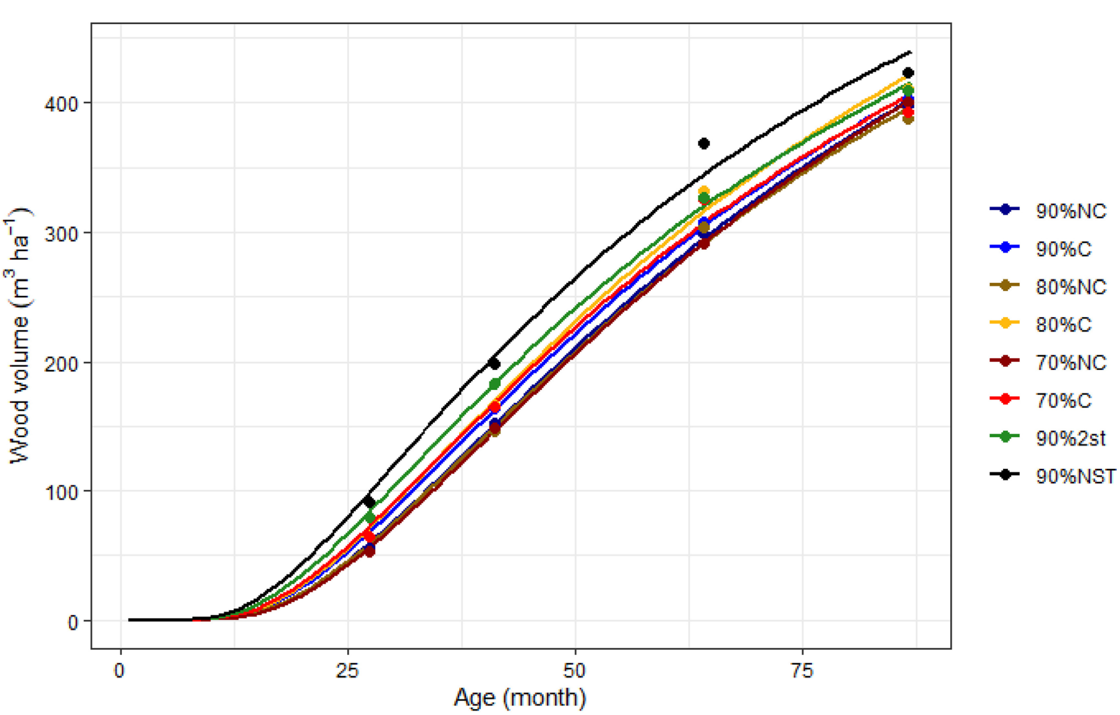

Figure 3. Evolution of total wood volume with age produced by *E. grandis* plantations managed by coppice in the third rotation and modeled using the Schumacher (1939) equation. Treatments: 90%NC - 90% of stump survival without compensation, 90%C - 90% of stump survival with compensation, 80%NC - 80% of stump survival without compensation, 80%C - 80% of stump survival with compensation, 70%NC - 70% of stump survival without compensation, 70%C - 70% of stump survival with compensation, 90%2st – 90% of stump survival with two stems per stump, 90%NST – 90% of stump survival without sprout thinning.

Using the mean annual increment (MAI) maximization criteria, the optimum harvest age (OHA) for the 90%NST treatment was determined to be 60 months, at which point the MAI reached 65 m³ ha⁻¹ year⁻¹. The OHA for the 70%NC treatment was 79 months, with an MAI of 56 m³ ha⁻¹ year⁻¹ (Table 4).

Despite the higher growth rate, the 90%NST treatment had a larger proportion of thin wood. The proportion of wood with a diameter lower than 8 cm increased from 10% in the 1 stem per stump treatment to 18% in the two stems per stump treatment and to 22% in the no sprout thinning treatment (Figure 4).

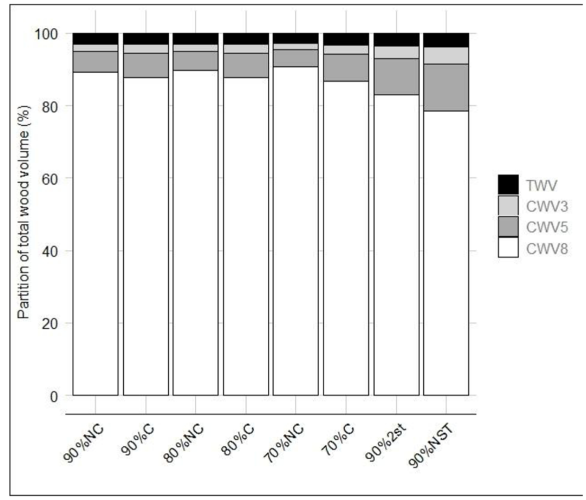

Figure 4. Proportion of the total wood volume (TWV) from the coppiced *Eucalyptus grandis* plantation in the third rotation at 87 months of age, based on the commercial wood volume with minimal diameter greater than 3 cm (CWV3), 5 cm (CWV5), and 8 cm (CWV8). Treatments: 90%NC - 90% of stump survival without compensation, 90%C - 90% of stump survival with compensation, 80%NC - 80% of stump survival without compensation, 80%C - 80% of stump survival with compensation, 70%NC - 70% of stump survival without compensation, 70%C - 70% of stump survival with compensation, 90%2st – 90% of stump survival with two stems per stump, 90%NST – 90% of stump survival without sprout thinning.

3.4. Mean individual volume (MIV)

As no difference was found in the wood volume produced at 87 months of age among treatments, the number of stems per hectare did not affect the total wood volume. However, the number of stems per hectare drastically affected the mean individual wood volume (MIV). The MIV decreased from 0.33 m³ tree⁻¹ in treatments with less than 1500 stems per hectare to 0.15 m³ tree⁻¹ in treatments with more than 2500 stems per hectare (Figure 5).

The treatments also affected the diametric distribution of trees at the end of the rotation (87 months of age). Treatments with two stems per stump and with no sprout thinning had a larger frequency of individuals in the low DBH classes. Failure compensation, especially in the 90% stump survival treatment, resulted in a bimodal distribution pattern. The trees in the non-compensated treatment presented a normal distribution, and the most frequent DBH classes increased with the failure level (Figure 6).

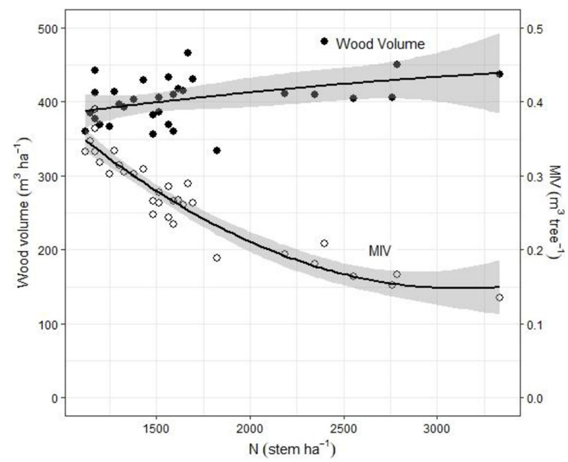

Figure 5. Effect of the stem number (N) on the total wood volume and on the mean individual volume (MIV) of a *Eucalyptus grandis* plantation coppiced for 3 rotations at 87 months of age.

3.5. Wood density

Despite of no difference found in the total wood volume produced at 87 months age, the treatments affected the wood basic density. The average wood density reduced with the increase on the number of stems per hectare. The highest wood density was found to 70%NC treatment and the lowest to 90%NST. Failure compensation decreased the average wood density (Figure 7).

4. DISCUSSION

4.1. Productivity differences among rotations

Physiologically, there are no significant differences between R1 and R2; thus, in principle, the productive potential of a coppice is

Table 4. Optimum harvest age (OHA) by the volumetric criteria using the Schumacher (1939) model and the accumulated wood volume and mean annual increment (MAI) at the OHA.

Treatment[(1)]	Stems[(2)]	OHA	Wood volume	MAI
	ha⁻¹	month	m³ ha⁻¹	m³ ha⁻¹ year⁻¹
90%NC	1335	76.4 ± 3.9	355	55.7
90%C	1543	71.5 ± 4.6	341	57.2
80%NC	1250	76.3 ± 3.2	350	55.0
80%C	1563	71.1 ± 4.9	351	59.3
70%NC	1153	78.9 ± 5.3	367	55.8
70%C	1621	68.8 ± 5.1	331	57.8
90%2st	2188	64.1 ± 6.0	320	60.0
90%NST	2859	59.9 ± 3.9	323	64.8

[(1)] 90%NC - 90% of stump survival without compensation, 90%C - 90% of stump survival with compensation, 80%NC - 80% of stump survival without compensation, 80%C - 80% of stump survival with compensation, 70%NC - 70% of stump survival without compensation, 70%C - 70% of stump survival with compensation, 90%2st – 90% of stump survival with two stems per stump, 90%NST – 90% of stump survival without sprout thinning; [(2)] Stem number with DBH > 5 cm at 7 years of age, per hectare.

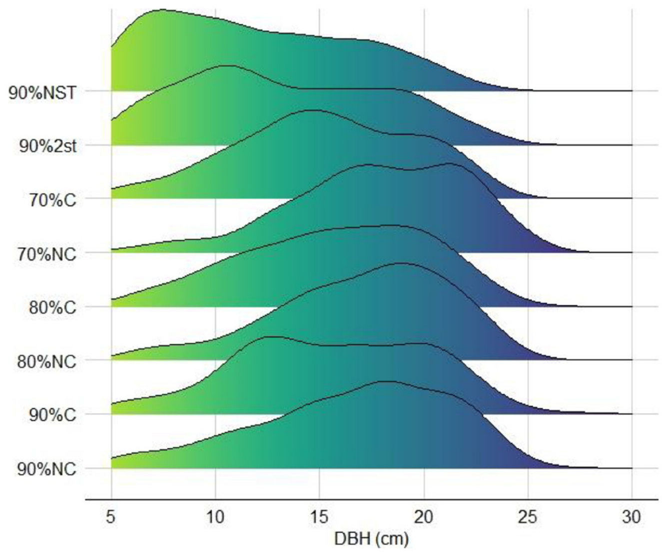

Figure 6. Effect of treatments on the diameter at breast height (DBH) distribution of a *Eucalyptus grandis* plantation coppiced for 3 rotations at 87 months of age. Treatments: 90%NC - 90% of stump survival without compensation, 90%C - 90% of stump survival with compensation, 80%NC - 80% of stump survival without compensation, 80%C - 80% of stump survival with compensation, 70%NC - 70% of stump survival without compensation, 70%C - 70% of stump survival with compensation, 90%2st – 90% of stump survival with two stems per stump, 90%NST – 90% of stump survival without sprout thinning.

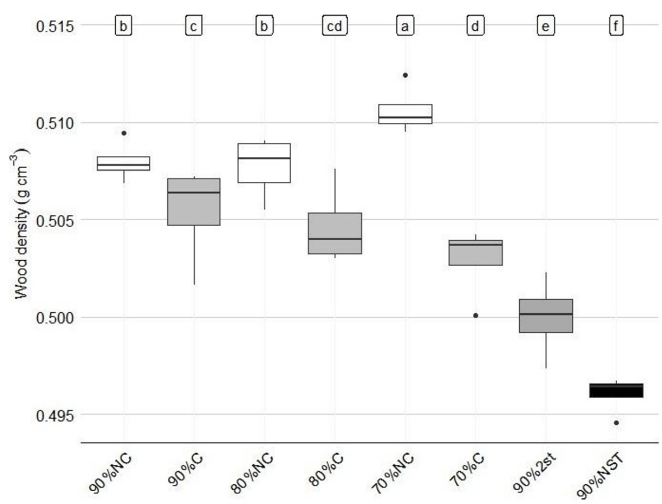

Figure 7. Effect of treatments on the wood basic density of a *Eucalyptus grandis* plantation coppiced for 3 rotations at 87 months of age. Treatments: 90%NC - 90% of stump survival without compensation, 90%C - 90% of stump survival with compensation, 80%NC - 80% of stump survival without compensation, 80%C - 80% of stump survival with compensation, 70%NC - 70% of stump survival without compensation, 70%C - 70% of stump survival with compensation, 90%2st – 90% of stump survival with two stems per stump, 90%NST – 90% of stump survival without sprout thinning.

equivalent to that of a high forest (Reis & Reis, 1997). Gonçalves et al. (2014) analyzed 265 plots in a commercial *Eucalyptus* plantation and found that accumulated precipitation was the main factor influencing productivity differences between R1 and R2. When precipitation levels were similar, productivity remained unchanged. However, factors such as stump survival rate (Reis & Reis, 1997; Little & du Toit, 2002) and nutrient availability (Rocha et al., 2019; Faria et al., 2002) can impact the productivity of R2 compared with R1.

In this study, R2 exhibited a 23% higher productivity than R1 (Figure 2). This difference may be attributed to the lower K application in R1 (Table 1). Given the high K demand and low soil availability, *Eucalyptus* plantations in this region are highly responsive to K fertilization (Gonçalves et al., 2013; Rocha et al., 2019). The recommended K application rate for this soil type is approximately 120 kg ha^{-1} (Gonçalves, 2011). Additionally, R2 experienced 7% higher precipitation than R1 (Table 2), which likely contributed to its increased productivity.

Despite experiencing a 20% reduction in precipitation (Table 2), R3 exhibited a 6% higher productivity than R2 (Figure 2). This can be explained by two main factors. First, the precipitation reduction in R3 was largely due to low rainfall levels in 2014, 2018, 2019, and 2020 (Table 2), affecting the first year and the end of the rotation. *Eucalyptus* plantations typically exhibit the highest water demand between the second and fourth years (Christina et al., 2017), during which precipitation levels in R3 remained sufficient. Second, the larger root system in R3 likely improved water access, enhancing the plantation's resilience to water stress (Reis & Reis, 1997; Teixeira et al., 2002).

4.2. Stump survival and failure compensation

Beyond the necessity of genetic material replacement, stump survival after harvest is the main criterion used by Brazilian forest companies to decide between coppice and high forest management (Arthur Junior et al., 2015). In this study, we found that stump survival can reach 70%, allowing the area to be coppiced without productivity losses if the harvest age is 7 years (Figure 2). Additionally, failure compensation had no significant effect on wood production at 7 years of age (Figure 2). While failure compensation initially influenced canopy cover and wood volume (Figures 1 and 2), this effect was not sustained until the end of the rotation. However, failure compensation reduced the OHA by 5 to 10 months and increased the maximum MAI by 3% to 8% (Table 4).

It is important to highlight that even in the 70%NC treatment, the stocking rate remained at 1153 stems ha^{-1}. Stape & Binkley (2010) found no difference in stand-level volume of high forests with stocking rates ranging from 1100 to 2200 trees ha^{-1} in the same region. This suggests that both stocking density and survival rate should be considered when deciding between sprout conduction and stand replantation. Regardless of survival rate, the number of stems per hectare should align with the optimal range for the site and the intended forest objectives.

According to Reis & Reis (1997), each sprout functions as an independent tree, indicating that coppice stocking criteria can be similar to those applied in high forests. Additionally, the spatial distribution of dead stumps should be considered. When the survival rate was 70%, clusters of dead stumps created open gaps that failure compensation could not effectively close (Figure 1). Large glades may further reduce productivity by diminishing stand-level light capture efficiency.

Although failure compensation did not influence total wood volume at 7 years of age, it did affect the diameter distribution. Maintaining two stems per stump adjacent to a dead stump increased the total wood volume per stump but reduced the diameter of both stems, resulting in a bimodal diameter distribution in compensated treatments (Figure 6). In a similar study in Brazil, Piva et al. (2020) found that treatments with a single stem per stump exhibited a normal diameter distribution, albeit with negative skewness (Figure 6).

4.3. Stems per stump

When the number of stems per hectare is considered independently—regardless of stump survival rate, compensation, or number of stems per stump—the observed effects (Figure 5) align with findings from tree density experiments, as described by Stape & Binkley (2010). This reinforces the concept proposed by Reis & Reis (1997), suggesting that each sprout should be regarded as an individual tree.

As the number of stems per hectare increased, stand volume increased, while individual tree volume decreased (Figure 5). Although within a certain threshold the number of stems per hectare does not alter a site's productive potential, it does affect the age at which this potential is realized. In this study, at 7 years of age, all treatments produced approximately 400 m^3 ha^{-1} of wood, regardless of stem density per hectare, with no significant differences among treatments (Figure 2). However, an increase in stem density reduced the optimum harvest age and consequently, the maximum MAI (Table 4). Similar findings have been reported in other studies on coppice and high forests (Stape & Binkley, 2010; Silva et al., 2020; Simões & Couto, 1985; Souza et al., 2016).

4.4. Wood quality

An increase in stem density per hectare resulted in a higher proportion of thin wood. Depending on the minimum usable diameter, an increase in stem density may lead to a decrease in commercial wood volume. The inverse relationship between stem density per hectare and mean individual volume (MIV) or DBH is well-documented in the literature (Balloni & Silva, 1978; Simões & Couto, 1985; Souza et al., 2016; Silva et al., 2020).

Additionally, an increase in stem density per hectare led to a reduction in wood basic density (Figure 7). Wood density generally increases with tree age (Lima, 1995) and from pith to bark (Oliveira et al., 2005). In treatments with a higher number of stems per hectare, the rapid initial growth followed by an early reduction in growth rate resulted in a higher proportion of earlywood. Conversely, trees in the one-stem treatments had larger DBH values and a higher proportion of latewood, contributing to greater wood density.

4.5. Management considerations

The increase in productivity with successive rotations suggests that there is no decline in vigor, as originally reported by Andrade (1961). This indicates that coppice systems can remain viable for more than two rotations without experiencing productivity losses, provided that survival rates are maintained and sound management practices are implemented.

Areas with low productivity in R1 are typically not considered for coppicing (Arthur Junior et al., 2015). However, our results suggest that forests with low initial productivity in R1 can achieve high productivity in R2 and R3 if management techniques are improved. We propose that low-productivity areas in R1 should only be replanted when poor productivity is due to genetic material limitations. Pereira Filho et al. (2020) found no significant correlation between tree size before harvest and subsequent sprout size, indicating that large trees do not necessarily lead to larger sprouts after harvest.

The ability of *Eucalyptus* plantations to maintain or enhance productivity through multiple rotations provides a strategic advantage for forest growers. Coppicing in Brazil typically costs 30-50% less than establishing high forests (Arthur Junior et al., 2015), which is particularly relevant given the rising costs associated with high forest management (Indústria Brasileira de Árvores, 2024). Beyond cost benefits, coppicing offers additional ecological advantages, including improved soil protection, reduced compaction, and increased soil carbon (C) and nitrogen (N) content (Sandoval López et al., 2020).

In this study, we found no significant effect of stump survival or failure compensation on total wood volume at seven years, indicating that sites with survival rates above 70% can be coppiced without requiring failure compensation. Many Brazilian forestry companies opt to replant sites when stump survival falls below 85-80% (Arthur Junior et al., 2015). However, all treatments in this study maintained stand densities above 1100 stems ha^{-1}. In addition to overall stand density, the number of live stumps per hectare should be a key factor in determining whether to pursue coppice management or replanting.

If the primary objective of a plantation is to maximize wood volume regardless of individual tree size or wood quality, sprout thinning may not be necessary. The no-sprout thinning treatment resulted in higher total wood volume and a reduced optimal harvest age but decreased mean individual volume (MIV) and wood basic density. A reduction in MIV due to increased stem density per hectare may, depending on the harvesting system, impact harvesting efficiency and costs.

5. CONCLUSION

The stump survival rate and the number of stems per stump affected the tree growth in the beginning of the rotation. At 7 years of age the number of stems do not affected the total wood volume per hectare. Despite that, the number of stems per hectare did affected the wood quality. The mean individual volume and the wood basic density reduced with the increase of the number of stems per hectare. We also found no evidence of reduction in the plant vigor in the third rotation, confiming the initial hypotesys: The ability of coppiced stands to maintain productivity comparable to high forests is primarily dependent on effective silvicultural management and the maintenance of an adequate plant population.

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AUTHOR CONTRIBUTIONS

JHTR, AVF, RMM and JLMG: conceptualization, funding acquisition, supervision, writing; GJC, GBV, AV, JHB and EMM: data acquisition, formal analysis.