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Long-term growth response to weed-control strips in *Eucalyptus urograndis* plantations in Brazil

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ABSTRACT

Several studies have reported the effect of weed competition on eucalypt plantations, but most have focused on initial growth. The aim of the study reported here was to evaluate the long-term growth response of *Eucalyptus urograndis* in weed-control strips of different widths and its competitive performance in a rotation area over seven years. An experiment was conducted in a commercial area (12 960 m^2) in Eunápolis, Bahia, Brazil. The treatments consisted of weed-control strips with the following widths on both sides of eucalypt planting lines maintained for the first six months of crop cultivation: 0 cm (weedy check control); 25 cm; 50 cm; 75 cm; 100 cm; 125 cm; 150 cm; 175 cm; and 200 cm (weed-free control). The 125-cm weed-control strip obtained the best eucalypt growth performance after seven years, with a gain of 61.8% compared with the weedy check control. The competitiveness index of *E. urograndis* tended to increase after the first two years of cultivation, the period in which the interference caused by weeds was most accentuated.

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KEYWORDS
competitive performance; forest management; weed control; interference

Introduction

Eucalypt plantations worldwide tend to be highly productive due to their adaptability to various environmental conditions, thus ensuring rapid growth. Currently, more than 20 million ha of eucalypt forest plantations exist worldwide (FAO 2013), of which 5.7 million ha are in Brazil (Ibá 2019).

The Brazilian forest sector generates around BRL 86.6 billion per year, which is 1.3% of national gross domestic product (Ibá 2019). Brazil has the highest *Eucalyptus* productivity in the world, with an average of 36 m^3 ha^{-1} y^{-1} in 2018, due (among other factors) to the development of breeding programs and management strategies aimed at maximising growth (Stape et al. 2004; Pereira et al. 2012; Ibá 2019).

Weed management is important because the uncontrolled presence of weeds can cause losses of up to 67% in eucalypt stem diameter growth (George and Brennan 2002). Weeds in eucalypt plantations compete for water, nutrients and space (Schaller et al. 2003; Garau et al. 2008) and may release allelochemicals into the environment (Graat et al. 2018), slowing eucalypt growth. Thus, several studies of weeds in eucalypt plantations have been conducted worldwide in recent decades (Sands and Nambiar 1984; Caldwell et al. 1995; Nilsson and Orlander 1999; Schaller et al. 2003; Toledo, Victoria Filho, Alves et al. 2003; Rose and Rosner 2005; Wagner et al. 2006; Little et al. 2007; Garau et al. 2009; Vargas et al. 2018).

Adequate weed control increases the availability of water and nutrients for the eucalypts, especially in the period of initial growth (i.e. the first two years after planting – YAP), which has been identified as the most important for tree growth (Nambiar and Sands 1993; Florentine and Fox 2003; Garau et al. 2009; Eyles et al. 2012; Vargas et al. 2018). However, the complete removal of vegetation cover from forest areas can lead to soil degradation, including soil erosion and impoverishment (Gonçalves et al. 2008). Weed management strategies using control strips is a viable alternative for reducing the interference of weeds in crop growth while contributing to soil cover between planting lines. Weeds provide several benefits, including by helping maintain humidity; increasing the amount of organic matter and nutrient cycling; and preserving the physical properties of the soil and improving its permeability (Menezes et al. 2002; Oliveira et al. 2002; Gonçalves et al. 2008; Machado et al. 2013).

Despite substantial investment in research into the response of eucalypt plantations to weed communities, most studies have focused on assessing initial eucalypt growth. There is a lack of knowledge, especially in Brazil, about the long-term effects of weed communities on eucalypt plantations (Wagner et al. 2006). Thus, studies aimed at assessing the magnitude of weed interference in different management strategies up to eucalypt harvest can provide important information for producers and the scientific community.

Minimising weed interference in the initial growth of eucalypts is important. Thus, we hypothesised that (1) the use of weed-control strips in the first six months offers greater benefits in terms of eucalypt growth at seven years of age compared with the control; and (2) eucalypts tend to have a higher tolerance of weed competition over time. The aim of this work was to evaluate the effect of weed-control strips of various widths on the growth of *Eucalyptus urograndis* (a hybrid of *Eucalyptus urophylla* S.T. Blake × *Eucalyptus grandis* W. Hill ex Maiden) and its competitive performance over a rotation of seven years.

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Materials and methods

Experimental area, plant material and planting system

The experiment was carried out in field conditions from August 2005 to August 2012 in a commercial area belonging to Veracel® Celulose, in Eunápolis, Bahia, Brazil (16° 22′40″S; 39°34′48″W and 189 m altitude – Figure 1), with sandy loam soils (chemical and physical analysis in Table 1).

According to the Köppen (1948) classification, the region's climate is the Aw tropical type, with the highest precipitation index during summer. The monthly meteorological data recorded during the experimental period are shown in Figure 2.

The experimental area was selected for uniformity in initial weed infestation, according to a survey carried out previously using a random-sampling technique (Matteucci and Colma 1982).

For planting procedures, glyphosate (792.5 g a.i. ha^{-1} – Scout®) was sprayed initially over the entire area, post weed emergence. Then, the soil was prepared using a subsoiler at 60 cm depth. A fertiliser of reactive natural phosphate (phosphate rock) was applied at a rate of 350 kg ha^{-1} in the subsoiling furrow in a continuous fillet. The seedlings were planted in a semi-mechanised manner, with manual planters and the use of gel to retain moisture at the seedling root. Another fertiliser was applied 5 days after planting (DAP), comprising formulated nitrogen, phosphorus and potassium (NPK) in the proportion of 6:30:6, with the addition of 1.0% copper (Cu) + 1.0% manganese (Mn) + 0.8% zinc (Zn), in two pits, one on each side of the seedling, at a rate of 83.3 kg ha^{-1}. *Eucalyptus urograndis* seedlings were used, which were an average of 100 days old at the time of planting.

Experimental treatments and herbicide application technology

The treatments consisted of weed-control strips with the following widths on both sides of the eucalypt planting lines: 0 cm (weedy check control – T1); 25 cm (T2); 50 cm

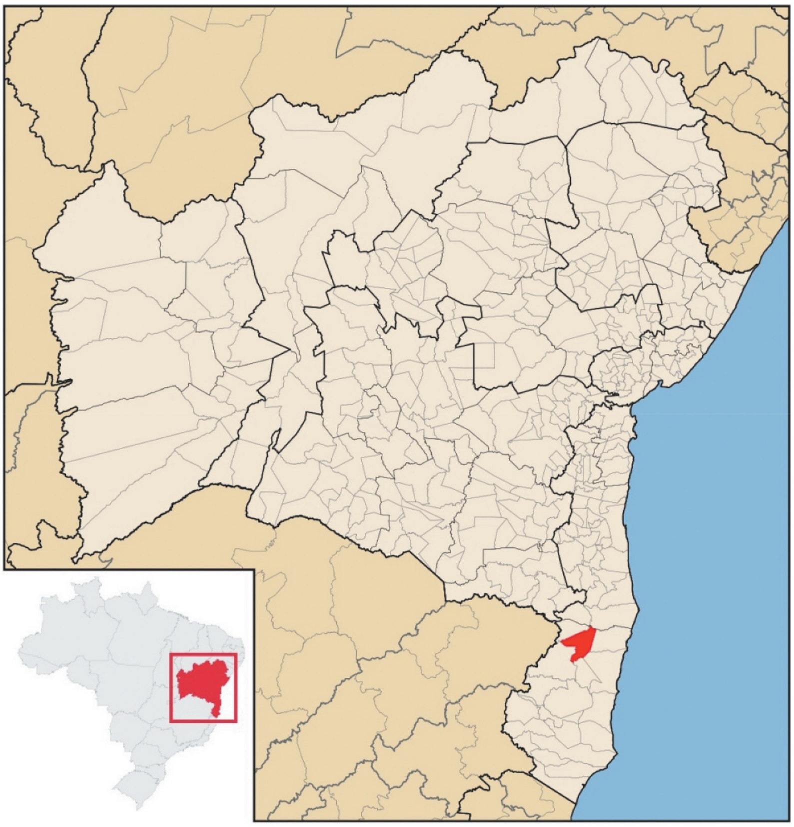

Figure 1. Map showing the location of the municipality of Eunápolis, Bahia, Brazil. Image: Raphael Lorenzeto de Abreu

Table 1. Chemical and physical analysis of soil taken from experimental plots

Depth (cm)	pH $CaCl_2$	OM (g dm^{-3})	P resin (mg dm^{-3})	K	Ca	Mg	H + Al	SB	CEC	%BS
				(mmol$_c$ dm^{-3})						
0–20	5.61	2.30	0.6	40	1.38	0.35	0.5	1.83	2.33	78.5
20–40	5.23	1.65	0.6	28	1.17	0.27	4.3	1.51	5.81	26.0

Depth (cm)	Clay	Silt	Sand: Fine	Sand: Coarse	Texture class
	(g kg^{-1})				
0–20	17	4	12	67	Sandy loam
20–40	30	8	16	46	Sandy clay loam

BS = base saturation; CEC = cation exchange capacity; OM = organic matter; SB = sum of bases.

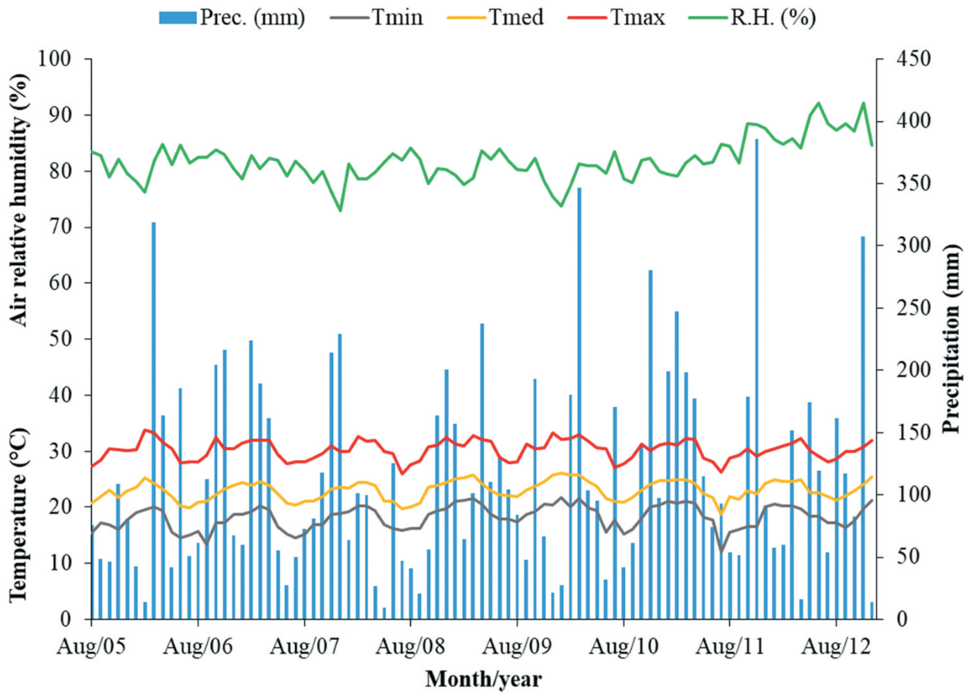

Figure 2. Monthly meteorological data for the region of the municipality of Eunápolis, Bahia, Brazil during the experimental period (2005–2012) Prec. = precipitation; R.H. (%) = air relative humidity; Tave = average temperature; Tmax = maximum temperature; Tmin = minimum temperature.

(T3); 75 cm (T4); 100 cm (T5); 125 cm (T6); 150 cm (T7); 175 cm (T8); and 200 cm (weed-free control – T9). The experimental plot consisted of seven planting rows with six *E. urograndis* seedlings each, at a spacing of 4 × 3 m (360 m^2). The three central rows (18 plants) were considered as a useful plot, totalling 240 m^2. A randomised block design was used, with four replications, with a total experimental area of 12 960m^2.

To keep the seedlings free of weed interference, the control strips were manually weeded in the first six months after planting. After the first six months, the total area was kept free of weeds by spraying with the herbicides isoxaflutol (150 g a.i. ha^{-1} – Fordor® 750 WR) and glyphosate (792.5 g a.i. ha^{-1} – Scout®). For this, a backpack sprayer was used at constant pressure (CO_2), equipped with a TTI 11002 bar with four tips and regulated for a tank volume of 200 1 ha^{-1}.

Weed community identification in the experimental area was carried out at 0, 90 and 180 DAP of the seedlings. In each experimental plot, 1.0 m^2 was sampled, corresponding to four subsamples of 0.25 m^2, all in the crop inter-rows. The weed species were identified, counted and taken to the laboratory, where they were washed and dried in an air-forced circulation oven at 70°C for 96 hours to determine the dry matter of the aerial part, after weighing on an electronic scale.

Two weed species were predominant: *Brachiaria humidicola* (Rendle) Schweick (koronivia grass), with densities of 50 plants m^{-2}, 53 plants m^{-2} and 55 plants m^{-2} for the evaluations carried out at 0, 90 and 180 DAP, respectively, and a dry mass of 417 g m^{-2}, 523.8 g m^{-2} and 553.5 g m^{-2}, respectively; and *Sida glaziovii* K. Schum. (guanxuma), with densities of 3 plants m^{-2}, 3 plants m^{-2} and 4 plants m^{-2} for the evaluations carried out at 0, 90 and 180 DAP, respectively, and a dry mass of 35 g m^{-2}, 33.5 g m^{-2} and 42.9 g m^{-2}, respectively.

Assessed variables and statistical analysis

The height of the *E. urograndis* trees and the diameter at breast height (1.3 m from the ground – DBH) were measured annually until the end of the experimental period (7 YAP). From those measurements, the wood volume per hectare (VHA) was estimated based on the following formula (adapted from Schumacher and Hall (1933) logarithmised):

$$VHA = \left[e^{(-10.0954 + 1.7907 * \mathrm{Ln(DBH)} + 1.1306 * \mathrm{Ln(Height)})} \right] * 825$$

Based on the acquired data, the absolute growth rates (AGRs) and relative growth rates (RGRs) were calculated according to the following formulas:

$A.G.R._X = (X_2 - X_1)/(t_2 - t_1)$, where X_2 and X_1, correspond to the variables of the trees from two successive assessments in times t_2 and t_1, respectively.

$R.G.R._X = [Ln(X_2) - Ln(X_1)]/(t_2 - t_1)$, where X_2 and X_1, correspond to the variables of the trees from two successive assessments in times t_2 and t_1, respectively.

Data on height, stem diameter and wood volume collected at the end of the experimental period were submitted to regression analysis using the sigmoidal model of Boltzmann (Equation 1).

$$Y = (A1 \ - A2)/1 + e^{(x - x0)/dx} + A2 \qquad (1)$$

where *Y* is the evaluated variable; *x* is the upper limit of the weed-control strip; *A*2 is the maximum value of the variable; *A*1 is the minimum value of the variable; (*A*1 – *A*2) is the gain or loss of the variable; *x*0 is 50% of the upper limit of the weed-control strips; and *dx* is the parameter that indicates the speed of loss or gain of the variable.

The eucalypt competitive performance was measured for the variables of VHA, height and stem diameter over the seven years of the experiment. For this we used the proportion of cumulative tree growth under complete vegetation cover (weed-control strip of 0 cm)/cumulative growth in the best cultivation condition (weed-control strip of 125 cm) (index WCS 0/WCS 125) (Mohammed et al. 1998).

Data were subjected to analysis of variance by the *F*-test, and the means were compared using Duncan's test at the level of 5% of probability. For the graphics, the software Origin® v.8.0 (MicroCal) was used.

Results

Height

Over the experimental period, T1 (weedy check treatment) provided the least height gain in the eucalypts (Figure 3a). At 7 YAP, the treatments could be grouped into four, from tallest to shortest: (1) T4, T6, T7 and T9; (2) T3, T5 and T8; (3) T2; and (4) T1. The 125-cm weed-control strip (T6) had the greatest height, differing from the two thinner strips (0 cm and 25 cm). The treatments in the second group showed intermediate growth, differing only from the weedy check control (Figure 3a and Table 2).

There was a marked difference between treatments for RGR, mainly in the first 12 months after planting, and for AGR, which remained until 2 YAP (Figure 3c, d). After this initial growth period, there was a tendency for equality between treatments for these parameters (Figure 3c, d).

At the end of the experimental period, the trees obtained a height gain of 0.8 m for every centimetre increase in the width of the weed-control strip, from 18.7 m to the upper limit of 33.2 m, above which it stabilised (Figure 3b).

Stem diameter

The difference between the weedy growth control (T1) and the best-performing weed-control strip (T6) was even more pronounced for stem diameter growth than for height (Figure 4a). The trees in the best weed-control strip

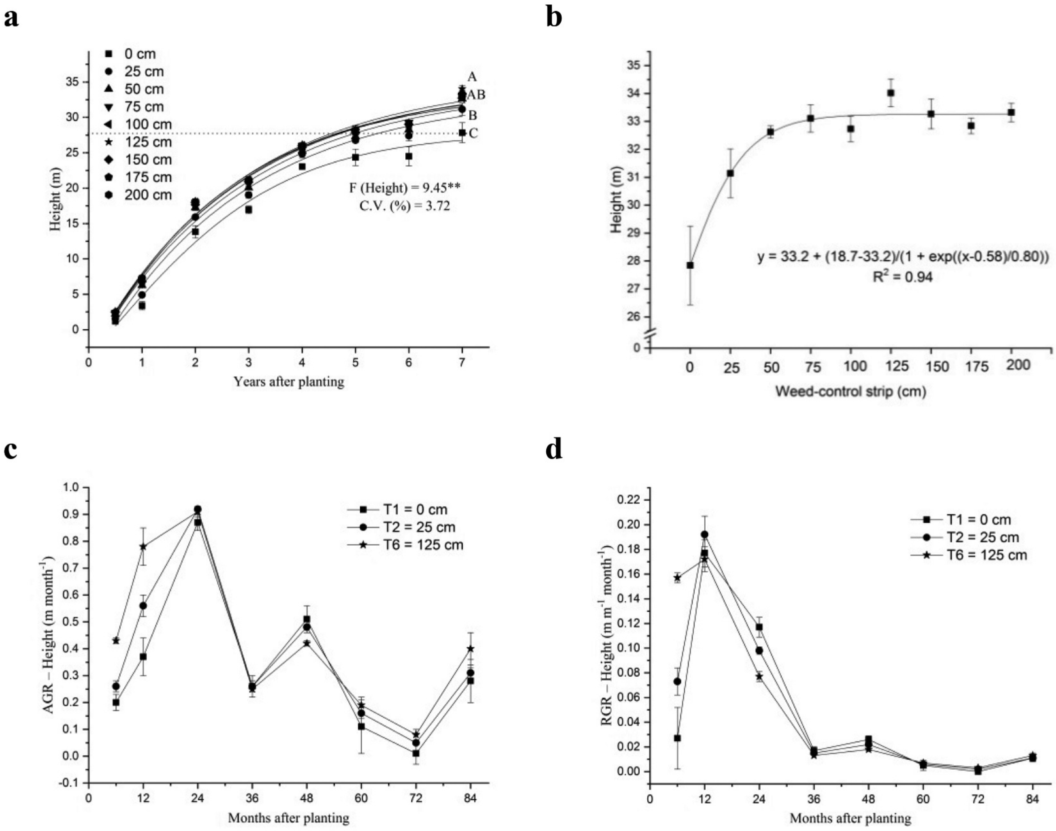

Figure 3. Height during the experimental period (a), height regression analysis at seven years, by weed-control strip width (b), absolute growth rate (AGR) in height (c) and relative growth rate (RGR) in height (d). Averages ± SEM; averages followed by the same letter do not differ by Duncan's test at the 5% probability level

Table 2. Effect of increasing weed-control strips in height (m), stem diameter at breast height (DBH – cm) and wood volume (volume – $m^3\ ha^{-1}$) of *Eucalyptus urograndis* after seven years of cultivation

Treatment (width of weed-control strip) (cm)	Height (m)	DBH (cm)	Volume ($m^3\ ha^{-1}$)
T1 = 0	27.8 c	15.9 c	249.4 c
T2 = 25	31.1 b	18.3 b	335.9 b
T3 = 50	32.6 ab	19.0 ab	360.1 ab
T4 = 75	33.1 a	19.3 ab	365.7 ab
T5 = 100	32.7 ab	19.3 ab	368.4 ab
T6 = 125	34.0 a	20.1 a	403.6 a
T7 = 150	33.3 a	19.5 ab	373.9 ab
T8 = 175	32.8 ab	19.6 ab	379.4 ab
T9 = 200	33.3 a	19.7 ab	382.7 ab
F (Treat)	9.45**	6.84**	7.52**
F (Block)	2.91^{ns}	0.76^{ns}	0.43^{ns}
CV (%)	3.72	4.99	9.07

Means followed by the same letter in the column do not differ at the 5% probability level by Duncan's test; ** = significant values at the level of 1% probability (*F*-test); CV = coefficient of variation; *F* = *F*-test values; ns = not significant at the 5% probability level (*F*-test)

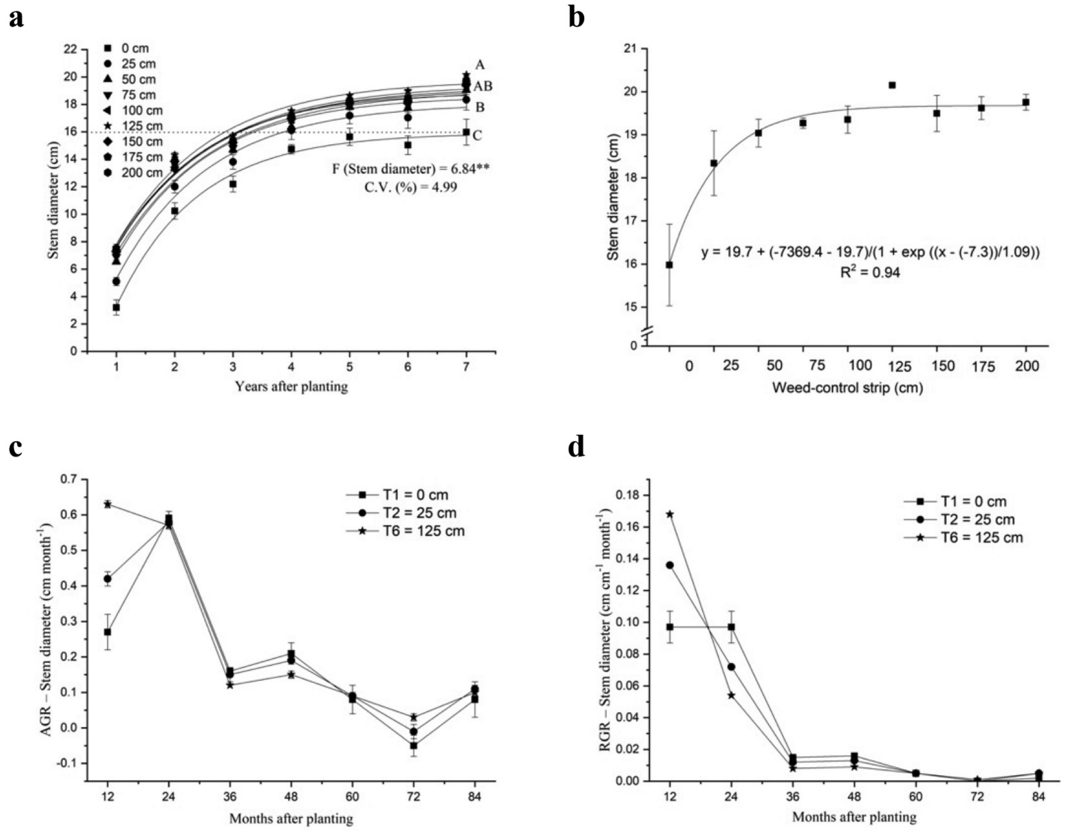

Figure 4. Stem diameter during the experimental period (a), regression analysis of stem diameter at seven years by weed-control strip width (b), absolute growth rate (AGR) in diameter (c) and relative growth rate (RGR) in diameter (d). Averages ± SEM; averages followed by the same letter do not differ by Duncan's test at the 5% probability level

(T6 = 125 cm) at 3 YAP reached values equal to the weedy check control at 7 YAP. At the end of the experiment, the difference between T1 and T6 was 26.4% in favour of T6, which also differed significantly from T2 but not from the others (Figure 4a and Table 2).

For AGR and RGR, there was a large discrepancy in values between T1, T2 and T6 (i.e. 0 cm, 25 cm and 125 cm, respectively) at 1 YAP (Figure 4c, d). In general, both growth rates showed higher values in the first 2 YAP, followed by a decrease in the following years (Figure 4c, d). These data underscore the importance of the first year of growth for the crop because even though the T6 treatment had lower AGR values at 3 YAP and 4 YAP and a lower RGR value at 2 YAP, there was considerable discrepancy between this treatment and T1 after seven years of tree growth (Figure 4a, c and d).

The regression analysis based on the last evaluation verified that, compared with height, diameter increased more for each centimetre of increase in the width of the weed-control strip (Figure 4b). An increase of 5.53% was observed in the upper limit value for each additional centimetre of area without weeds (Figure 4b), compared with 2.41% for height (Figure 3b). Thus, this parameter is more sensitive than height to coexistence with weeds.

Volume per hectare

For wood volume over the experimental period, the treatments can be grouped into four, based on the results of the Duncan's test ($P < 0.05$ – data not shown) followed by a first-order regression analysis (Figure 5a). The four groups, in ascending order by wood volume, are (1) T1; (2) T2; (3) all other treatments; and (4) T6. T1 obtained the smallest angular coefficient (40.5), followed by T2 (51.3), with values close to those of the other treatments (53.0); T6 obtained the highest value (57.2) (Figure 5a).

For AGR, T6 obtained the highest accumulation of wood volume in each year of the experimental period, except in 4 YAP (Figure 5c). T6 also had the highest RGR at 2 YAP, but declined in the two subsequent evaluations and, by the end of the assessment period, there was minimal difference in RGR between treatments (Figure 5d).

According to the regression analysis, wood volume was the most sensitive variable to increase in the width of weed-control strips (Figure 5b). Thus, for each centimetre increase in width, there was a 6.9% increase in the volume of the upper limit value (Figure 5b).

For both stem diameter and wood volume, evaluated at 7 YAP, the highest values were obtained for T6, which were 26.4% and 61.8% higher, respectively, than the values obtained for T1 (no weed control) (Table 2). The values for T2 were higher than those for T1 but lower than T6. The other treatments, including weed-free (T9), obtained intermediate values, differing significantly only from T1 (Table 2). For height, values for T4, T7 and T9 were not significantly different from T6 but were significantly different from T1 and T2 (Table 2).

Figure 6 presents wood volume at 7 YAP for T2–T9 as a percentage of the wood volume obtained for T1 (i.e. the weedy check control). It shows that an increase of 35% was obtained for the thinnest weed-control strip (i.e. 25 cm, T2). T6 obtained the higher gains in wood volume (61.8%), being the

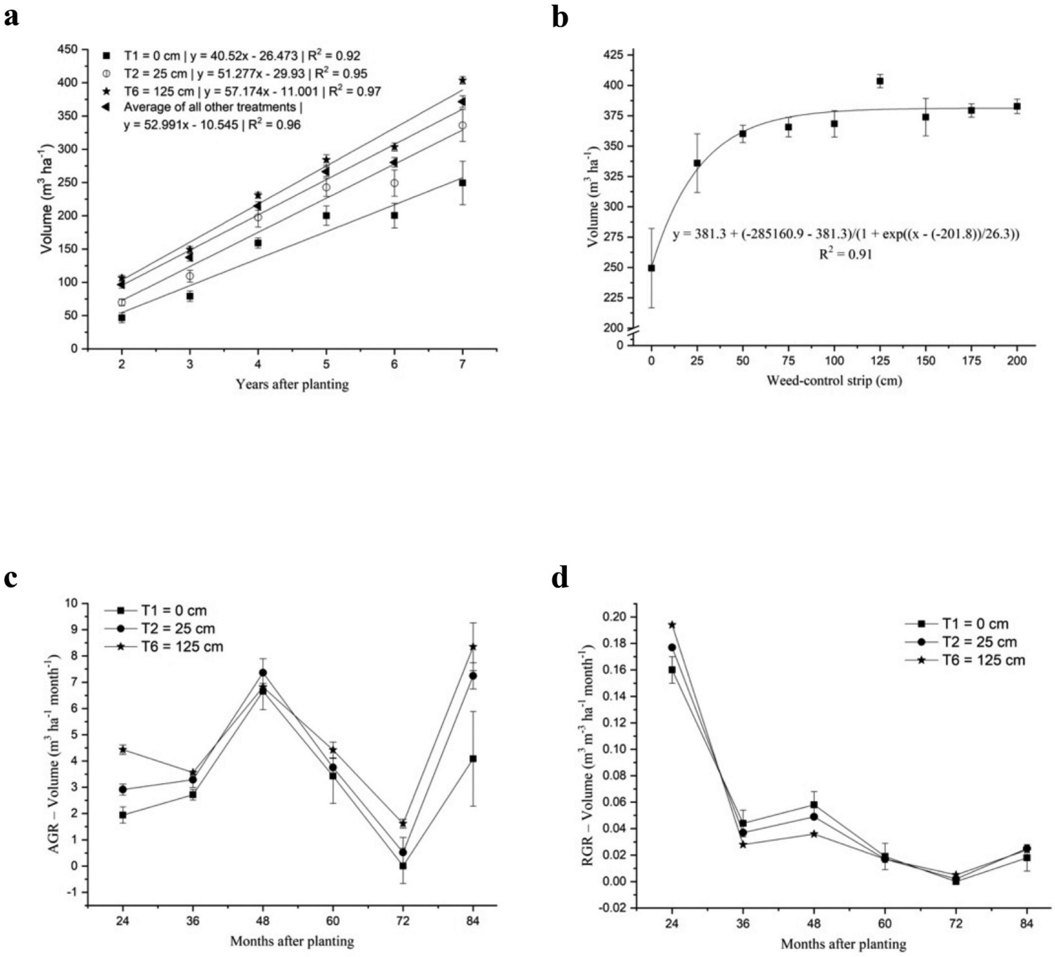

Figure 5. Wood volume during the experimental period (a), regression analysis of the wood volume at seven years, by weed-control strip width (b), absolute growth rate (AGR) in wood volume (c) and relative growth rate (RGR) in wood volume (d). Averages ± SEM

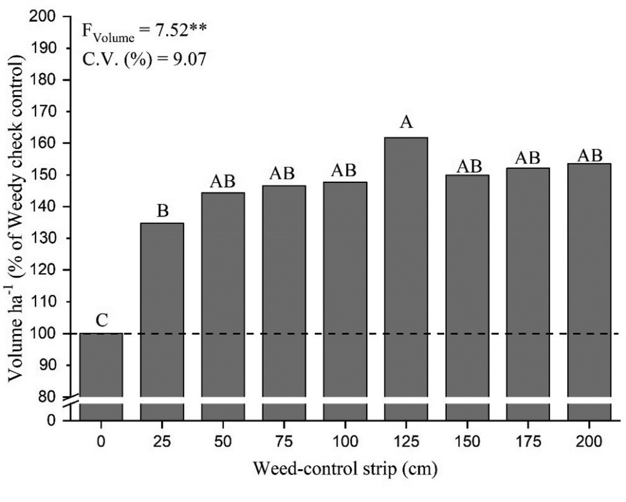

Figure 6. Effect of weed-control-strip width on wood volume per hectare of *Eucalyptus urograndis* trees at seven years after planting (end of the experimental period). The values were transformed into the percentage of the weedy check control. Equal letters do not differ by Duncan's test at the 5% probability level

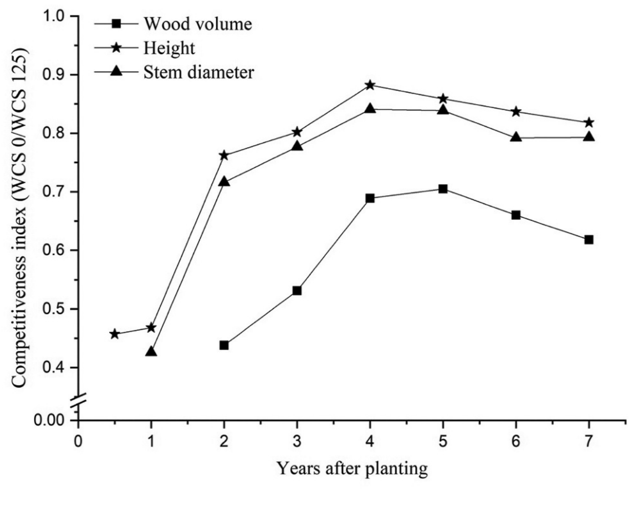

Figure 7. Proportion of cumulative growth of *Eucalyptus urograndis* stem under complete vegetation cover (weed control strip of 0 cm)/cumulative stem growth in the best cultivation condition (weed control strip of 125 cm) (index WCS 0/WCS 125) for volume per hectare, height and *Eucalyptus* stem diameter during seven years of experiment in the field in Eunápolis, Bahia, Brazil

only treatment statistically different from T2 (Figure 6). This suggests that 125 cm is the optimal strip width, and wider widths achieve no benefit in tree growth compared with this treatment and T2 (Figure 6).

Regarding temporal variation in eucalypt competitive ability, the WCS 0/WCS 125 index showed a close relationship between height and stem diameter, with both increasing rapidly between 1 YAP and 2 YAP (Figure 7). The response pattern for wood VHA was slightly different, with WCS 0/WCS 125 index values greater than 0.55 only from 4 YAP. Nevertheless, all three variables increased in value during the experimental period (Figure 7).

Discussion

The reductions in eucalypt growth parameters (height, stem diameter and wood volume) observed in this experiment (Figures 3–6) with differing widths of weed-control strip is due to interference with crop growth caused by weeds.

Interference is a set of actions that directly or indirectly affects the growth of crops (Pitelli 1985). In eucalypt plantations, in addition to direct effects, weeds cause indirect interference by serving as intermediate hosts of pests and pathogens, hindering cultivation practices and increasing the risk of fire (Pitelli 1987; Pitelli and Marchi 1991). Direct interference is caused by the sum of the effects of competition for water and nutrients (Ellis et al. 1985; Nambiar and Sands 1993; Adams et al. 2003; Little et al. 2003; Borders et al. 2004; Hunt et al. 2006; Garau et al. 2009; White et al. 2009) and the release of allelopathic compounds into the environment (Graat et al. 2018).

The direct interference of weeds on eucalypts has been studied widely recently (Nilsson and Orlander 1999; Toledo et al. 2000; George and Brennan 2002; Adams et al. 2003; Florentine and Fox 2003; Coll et al. 2004; Harper et al. 2005; Garau et al. 2009; Cruz et al. 2010; Bacha et al. 2016) because it can considerably affect eucalypt productivity. In the present work, trees in competition with a weed community in the absence of a control strip (T1, 0-cm weed-control strip) showed a reduction of 18.2% in height and 38.2% in wood volume compared with the best treatment (T6, 125-cm strip). In an experiment also conducted in Brazil, Toledo, Victoria Filho, Bezutte et al. (2003) found even greater reductions in wood volume (61.1%) at 6.5 YAP. Adams et al. (2003) pointed out that the control of weeds in the first year after planting guaranteed 80% of the growth in stem diameter of *Eucalyptus globulus* Labill., evaluated at 2 YAP.

The limitation for eucalypt growth is that competition for resources in the environment affects the photosynthetic characteristics of plants. Huang et al. (2008) observed that keeping eucalypts free of competition with a control strip of 1 m on each side of a planting line increased the photosynthetic rate of light-saturated and maximum stomal conductance by 37.9% and 22.4%, respectively, compared with plots maintained without weed-control strips. In semi-controlled (greenhouse) conditions, Santos et al. (2015) observed that forage species (*Brachiaria* spp.), which are often reported as weeds in areas of Brazil (Toledo et al. 2000; Toledo, Victoria Filho, Bezutte et al. 2003; Bacha et al. 2016), negatively affected *E. urograndis* gas exchange. Other studies have also reported the impacts of the limitation of resources caused by competition on the photosynthetic characteristics of trees (Sands and Nambiar 1984; Ellis et al. 1985; Woods et al. 1992).

Note that differences in eucalypt growth found in the abovementioned studies are directly linked to the degree of interference that the weed community exerts on the crop, which also depends on other factors, including edaphoclimatic conditions of the study region (Toledo, Victoria Filho, Alves et al. 2003; Garau et al. 2009; Vargas et al. 2018); weed density (Dinardo et al. 2003; Bacha et al. 2016); the eucalypt and weed species present in the field (Cruz et al. 2010; Pereira et al. 2013; Graat et al. 2015; Colmanetti et al. 2017); and the distance between crop plants and the weed community (Bleasdale 1960; Pitelli 1985).

Several studies have identified the ideal width of weed-control strips for eucalypt species and clones, including Toledo, Victoria Filho, Alves et al. (2003), Huang et al. (2008), Silva et al. (2012), Machado et al. (2013) and Vargas et al. (2018), although only the latter measured impact up to harvest. Despite the scarcity of studies of long-term responses in Brazil, the results obtained by Toledo, Victoria Filho, Alves et al. (2003) corroborate those obtained in the present study. Toledo et al. found that a 125-cm weed-control strip obtained a 105% gain in wood volume compared with the weedy check control. Evaluating root interactions between *Eucalyptus deglupta* Blume and grasses, Schaller et al. (2003) found that competition reduced the total number of lateral eucalypt roots by up to 40% compared with a control. This highlights the importance of studies on the optimal distance between a crop and the weed community to avoid harmful effects on trees due to competition for resources while also maintaining adequate soil protection.

It is generally considered that fewer weeds in a planted forest area will lead to greater productivity. In this work, however, the weed community had a positive influence on the *E. urograndis* plantation. In terms of productivity at the end of the experimental period, it was noted that the optimal weed-control-strip width in the first six months of cultivation was 125 cm for this productive area (Figure 6). With this treatment, it was possible to minimise weed interference in tree growth and also take advantage of the beneficial effects of weeds on soil conservation, such as maintenance of humidity; reduction of direct sunlight; increase in the amount of organic matter and nutrient cycling; and the preservation of the physical properties of the soil, which causes an increase in permeability and consequently leads to better root growth (Menezes et al. 2002; Oliveira et al. 2002; Gonçalves et al. 2008; Machado et al. 2013).

Based on the RGR data obtained in the present study (Figures 3d, 4 d and 5d), the most important growth stage for eucalypts is the first 2 YAP. Beyond this period, RGR values of even the weedy check control (0 cm) were higher than those of the best-performing control strip (125 cm). The competitiveness index (Figure 7) showed that, over time, the eucalypts were less sensitive to competition from weeds, corroborating results obtained in other studies (Sands and Nambiar 1984; Caldwell et al. 1995; Nilsson and Orlander 1999; Adams et al. 2003; Florentine and Fox 2003; Schaller et al. 2003; Toledo, Victoria Filho, Alves et al. 2003; Rose and Rosner 2005; Wagner et al. 2006; Little et al. 2007; Garau et al. 2008, 2009; Vargas et al. 2018).

It is concluded that the 125-cm weed-control strip on both sides of planting lines in the first six months after planting provided better growth performance for the eucalypts after seven years. The competitiveness index of eucalypts tended to increase after the first two years of cultivation – the period in which interference caused by the weeds was most accentuated.

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Disclosure statement

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