RODRIGO NOGUEIRA DE SOUSA

EUCALYPT PRODUCTIVITY IN RESPONSE TO SOIL PROFILE CONDITIONING IN THE BRAZILIAN CERRADO

Dissertação apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Solos e Nutrição de Plantas, para obtenção do título de *Magister Scientiae.*

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APROVADA: 28 de junho de 2018

Haroldo Nogueira de Paiva

Ivan Francisco de Souza

Ivo Ribeiro da Silva
(Coorientador)

Leonardus Vergütz
(Orientador)

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Dedico

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BIOGRAFIA

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Em 2004 concluiu o ensino fundamental na escola municipal Domingos Azzolini em Santo Antônio do Leste – MT, cidade em que cresceu. Em 2007 concluiu o ensino médio na escola Prevest em Goiânia – GO.

Em 2010 ingressou no curso de Agronomia na Universidade Federal de Viçosa, concluindo em julho de 2016. Durante todo o tempo de graduação foi estagiário e bolsista no departamento de solos, sendo vinculado ao laboratório de isótopos estáveis (LIE), sob orientação do professor Ivo Ribeiro da Silva.

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Em agosto de 2016 ingressou no programa de pós-graduação em solos e nutrição de plantas, em nível mestrado, na área de concentração fertilidade do solo, na Universidade Federal de Viçosa, submetendo à defesa da dissertação em junho de 2018.

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ABSTRACT

SOUSA, Rodrigo Nogueira, M.Sc., Universidade Federal de Viçosa, junho de 2018. **Eucalypt productivity in response to soil profile conditioning in the Brazilian Cerrado.** Adviser: Leonardus Vergütz. Co-advisers: Ivo Ribeiro da Silva, Samuel Vasconcelos Valadares and Fernando Antonio Vieira Rodrigues.

The eucalyptus production has a big importance in the Brazilian market due its high commercial influence. Thus, continuous research investments in genetic materials, soil quality and plant nutrition in order to improve forest management are demanded. In this study we tested the influence of limestone and gypsum combined with limestone on soil chemical properties improvement of two oxisols with contrasting clay contents, and its impact on eucalyptus growth and performance. We performed two field experiments over 84 months, varying the limestone and gypsum in broadcast or band incorporated or not. At the end of the experiment were evaluated the impact of treatments in soil chemical properties, root growth, density and biomass, nutrient content, dry matter of the tree components and litter, also plant nutrient recovery and eucalypt productivity. Both treatments with limestone and gympsum combined had more K in the soil profile in both sites. The treatments that only received limestone (band or broadcast) showed no difference in terms of K concentration in both soils. The treatments receiving gypsum also had the highest input of $S\text{-}SO_4^{2-}$ showing more sulfur in the soil profile in both sites, specially when gypsum was applied concentrated. Limestone applied on band promoted the highest Ca^{2+} levels and distribution in the soil profile in both, sandy loam and clay soils however did not show the highest productivity. The control treatment, had good roots growth in upper soil layers. Nonetheless, treatment receiving gypsum and lime combined showed a greater root density (RD) and dry biomass in deeper soil layers. Gypsum applied banded also promoted the highest increase on dry matter of all tree components and, consequently, the total plant dry weight in both soils, also increased all nutrients content on the shoots in both sites, and finally this treatment promoted the best eucalypt productivity. We assumed that the S has an essential importance to plants development. First, due the S to be crucial element for the whole plant physiology and metabolism, once it has large relevance in cysteine and methionine biosynthesis. Second, its consequent downward movement in soil profile, which allow higher roots exploration for nutrients and water.

RESUMO

SOUSA, Rodrigo Nogueira, M.Sc., Universidade Federal de Viçosa, junho de 2018. **Produtividade do eucalipto em resposta ao condicionamento do perfil do solo no Cerrado Brasileiro.** Orientador: Leonardus Vergütz. Coorientadores: Ivo Ribeiro da Silva, Samuel Vasconcelos Valadares e Fernando Antonio Vieira Rodrigues.

A cultura do eucalipto tem uma grande importância no mercado brasileiro devido a sua grande influência comercial. Com isso é demandado grande investimento em pesquisas em relação a materiais genéticos, qualidade do solo e nutrição de plantas, entre outros. Neste estudo testamos a influência do calcário e do gesso combinado com calcário na melhoria das propriedades químicas de dois latossolos com teores contrastantes de argila e seu impacto no crescimento e desempenho do eucalipto. Foram montados dois experimentos de campo ao longo de 84 meses, variando o calcário e o gesso em área total ou faixa incorporado ou não. Ao final do experimento foram avaliados o impacto dos tratamentos nas propriedades químicas do solo, crescimento, densidade e biomassa radicular, teor de nutrientes, matéria seca dos componentes arbóreos e serapilheira, taxa de recuperação de Ca, Mg e S e produtividade do eucalipto. Os dois tratamentos com calcário e gesso (faixa e área total) combinados, apresentaram mais K no perfil do solo (0-10, 10-20 50-40 e 40-60 cm) em ambos os locais do que os tratamentos só com aplicação de calcário. Esses mesmos dois tratamentos também apresentaram as maiores concentrações de S-SO_4^{2-}, mostrando mais enxofre no perfil do solo em ambos os locais, especialmente quando o gesso foi aplicado concentrado. O calcário aplicado em faixa promoveu os maiores níveis de Ca^{2+} e sua distribuição ao longo do perfil do solo em ambos os solos, arenoso e argiloso, no entanto, não apresentou a maior produtividade. Já o tratamento com gesso e calcário combinados mostrou maior densidade radicular (RD) e massa seca na camada mais profunda estudada. O gesso aplicado em faixa não incorporado também promoveu o maior aumento na matéria seca de todos os componentes arbóreos e consequentemente, a massa total das plantas em ambos os solos, também elevou o conteúdo total de nutrientes na planta e, finalmente, promoveu a melhor produção de eucalipto. Assumimos que o S tem uma importância crucial para o desenvolvimento das plantas. Primeiro, o S é um elemento essencial para a fisiologia e metabolismo das plantas, uma vez que tem grande relevância na biossíntese de cisteína e metionina. Segundo, seu consequente movimento descendente no perfil do solo, permite maior exploração de raízes de nutrientes e água.

INTRODUCTION

Brazilian forest-based industry is known worldwide for the high productivity of its planted areas, 7.84 millions of hectares, in which approximately 72% refers to the eucalyptus cultivation (IBÁ, 2017). Brazil is home to the highest productivity (measured as the volume of wood produced per unit area per year), 36 m^3 $ha^{-1}year^{-1}$ and the shortest rotation (period between planting and harvesting of trees) in the world (IBÁ, 2017). Around 21% of eucalypt plantations are established in the Cerrado biome (Leonardo et al., 2013). Despite the capacity of eucalypt to growth on acid soils, the Brazilian Cerrado soils are highly weathered, acidic and nutritionally poor, both in surface as in subsurface horizons, limiting plant production (Carvalho and Van Raij, 1997; Ritchey et al., 1980). These soils show high Al^{3+} saturation and P fixation due the predominance of oxides and hydroxides of Fe and Al (Lopes & Guimarães Guilherme, 2016; Pavan et al., 1982). Due to this fact, for a long time it was believed that such areas were unproductive. However, with technological and scientific advances such soils were better managed through the time, specially in terms of acidity correction (Lopes & Guimarães Guilherme, 2016).This soil pH correction allowed the establishment of crops in the Cerrado (Van Raij, 1977). On the other hand, since eucalyptus is tolerant to acid soils (Neves et al., 1982), the common practice is not to correct the soil pH to eucalyptus plantation (Barros and Novais, 1999). However, since this cultivation requires base saturation around 50%, liming is generally required (Furtini-Neto et al., 2004), and eucalyptus fertilization results in expressive productivity gains (Barros, 1982; Barros et al., 1992; McLaughlin, 1996). Hence, management strategies of soil fertility are essential in order to achieve deeper roots and high productivities.

Limestone application is the cheapest and most accessible way to provide Ca and Mg to plants, in addition to reducing the soil acidity, Al toxicity, and also increase the cation exchange capacity (CEC) of soils (Zambrosi et al., 2007). Moreover, the higher the Ca applied in the soil the more Ca is found in the plant (Bognola et al., 2011), indicating the importance of understanding soil-plant dynamics for that nutrient. However, due to the low solubility of Limestone, and mobility of Ca and Mg these cations added remains limited to superficial soil layers, requiring a long time to achieve deeper layers (Alleoni et al., 2010). And the low availability of Ca in deeper layers restrain the roots growth to upper layers, increasing plants vulnerability to drought (Sá et al., 2010).

To increase Ca, Mg and K availability in subsurface horizons and reduce phytotoxic forms of soluble Al, studies have showing that the gypsum ($CaSO_4.2H_2O$), has great effectiveness (Mclay and Ritchie, 1993; Santos et al., 2010; Van Raij et al., 1998). In addition, the combination of gypsum and limestone also can have good response on the soil conditioning (Pavan et al., 1983). According to Caires et al. (2004), these combination increased corn production by 17 %, while for gypsum applied separately the increase was only 5 % . The gypsum is moderately soluble, consequently there is an easier movement of sulfate (SO_4^{2-}) with water through soil layers. The binding of SO_4^{2-} with Al^{3+} can lead to neutral water-soluble aluminum complexes or formation of less toxic ionic par, such as $AlSO_4^+$ (Pavan et al., 1982; Santos et al., 2010). Thus, with the improvement of deeper soil quality, there is higher root growth stimulation toward these layers (Pauletti et al., 2014) and plants can explore a greater soil volume with better nutrient and water uptake (Caires et al., 2003; Morelli et al., 1992).

Since soils are progressively depleted on nutrients and climate has been changing (more unstable), lime management and soil fertilization under eucalyptus plantations that enables integrated understanding of soil-plant system have been increasingly demanded. Thus, as the gypsum display a big potential on soil conditioning here we compared the effect of only limestone and gypsum with limestone combined on soil chemical properties of two oxisols with contrasting clay contents and its impact on eucalyptus growth.

MATERIAL AND METHODS

Location and site descriptions

Two field experiments were carried out over 84 months, in the Brazilian Cerrado biome. The experiments were located in two municipalities of Minas Gerais (Três Marias -18°12'07" S; 45°00'01" W and Curvelo - 18°43'05.7" S; 44°49'09.6" W). The both region´s climate is tropical (Köppen's Aw) with average annual temperature 23.5 °C (about 1214 mm/year of precipitation) to Três Marias and 22.1 °C (about 1221 mm/year of precipitation) to Curvelo.

Eucalypt plantations were evaluated at harvesting age, under sandy loam texture (Tres Marias – 20 % clay), soil classified as Latossolo Vermelho Amarelo distrofico (EMBRAPA, 2013) or Rhodic Haplustox (Soil Survey Staff, 2014) and clay texture (Curvelo – 62,1 % clay), soil classified as Latossolo Vermelho distrófico (EMBRAPA, 2013) or Typic Haplustox (Soil Survey Staff, 2014). Chemical characterization of the soils from the two sites were conducted before the study (Table 1), at four depths (0-10, 10-20, 20-40 and 40-60 cm).

The dose of Ca was determined and calculated using the NUTRICALC® software (BARROS et al., 1995) which is widely used in Brazil for guide the recommendations of chemical corrective and fertilizers in eucalypt plantations.

Experimental design

The experiment was arranged in randomized blocks design with four replications totalizing 36 experimental units with the following distributions, Limestone: with (+L) and without (-L); application location: Band (Ba) and broadcast (Br); Soil incorporation: incorporated (I) and non-incorporated (NI) (Figure. 1). A scheme of the experiment can be found in the figure 1.

The spacing used for planting was 3,40 x 2,65 m. Each experimental unit was composed by 8 rows with 19 trees each, in which two external rows of each side are inserted in the surrounding (buffer) area, so the effective plot is constituted by 4 rows. The limestone was applied (spread) in broadcast or band of 60 cm width under the planting row. The gypsum when applied also was in broadcast or band of 60 cm width under area that received previous limestone in broadcast (Figure. 1).

Table 1. Main soil characteristics at beginning of the experiment (2010) under Sandy loam soil and Clay soil sites

Experimental site	Depth	pH	Ca^{2+}	Mg^{2+}	Al^{3+}	(H+Al)	P	K	Cu	Zn	Fe	Mn	S	B	SOM	Clay
	.. cm ..		.... $cmol_c\ dm^{-3}$				.... mg dm^{-3}								dag kg^{-1}	%
Sandy loam soil	0-10	4.06	0.00	0.01	0.80	4.60	0.91	17.46	0.20	0.34	125.45	10.17	15.91	0.14	2.35	19.72
	10-20	4.88	0.00	0.00	0.52	3.72	0.58	12.28	0.20	0.20	139.05	8.96	14.19	0.10	1.71	19.95
	20-40	5.25	0.00	0.00	0.31	2.90	0.32	8.84	0.17	0.10	124.66	7.77	13.96	0.07	1.33	20.55
	40-60	4.33	0.00	0.00	0.19	2.35	0.41	5.64	0.13	0.06	87.45	7.88	13.82	0.09	1.03	21.67
Clay soil	0-10	4.05	0.14	0.26	1.56	6.22	1.06	85.97	0.83	0.38	91.60	52.77	13.85	0.14	3.77	63.37
	10-20	4.36	0.00	0.12	1.56	5.76	0.62	61.64	0.97	0.27	98.96	29.96	15.35	0.19	2.64	61.54
	20-40	4.59	0.00	0.05	1.41	4.89	0.44	39.43	0.74	0.18	83.96	23.91	15.67	0.12	2.29	61.86
	40-60	4.85	0.00	0.01	1.09	3.99	0.17	19.68	0.52	0.12	79.18	19.74	17.76	0.06	1.77	61.63

Soil samples collected in December 2010 pH in water (1:2.5 v v^{-1}); Ca^{2+} and Mg^{2+} extracted by KCl (1 mol L^{-1}); Al^{3+} extracted with KCl (1 mol L^{-1}); H+Al extracted with calcium acetate (0.5 mol L^{-1}) at pH 7.0; P, K, Cu, Zn, Fe and Mn extracted by Mehlich-1 solution; S extracted by [$Ca(H_2Po_4)_2$ 500 mg L^{-1} of P in HOAc 2 mol L^{-1}]; B extracted by $CaCl_2$ 5 mmol L^{-1}; OM: organic matter, determined by the Walkley-Black method; clay determined following Ruiz (2005).

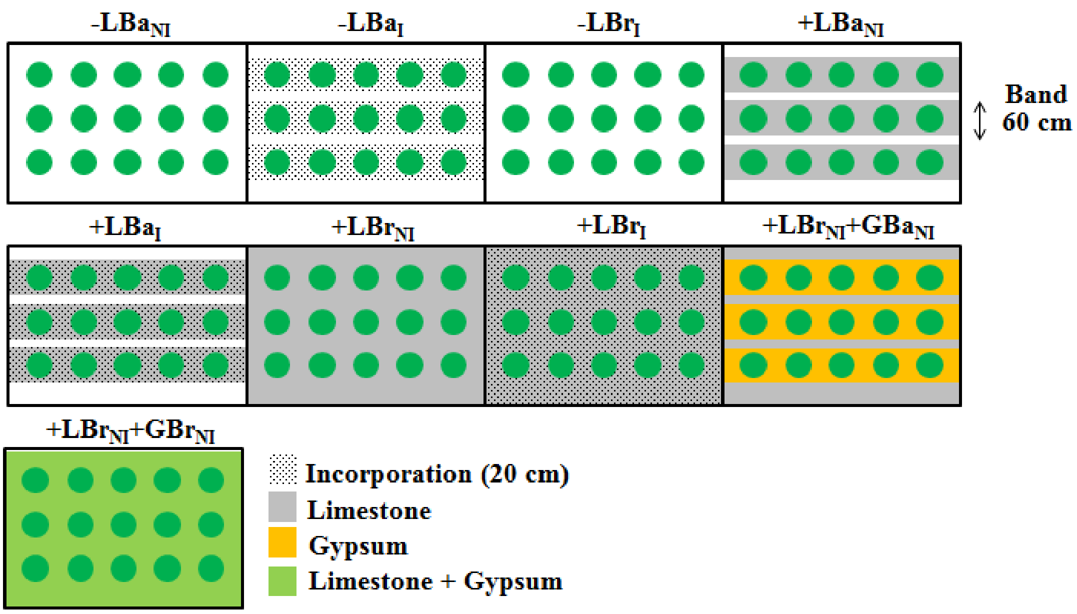

Figure 1. Scheme of treatments arrangement. -L=without limestone; +L=with limestone; +G=with gypsum; Ba=band; Br=broadcast; I=incorporated; NI=non-incorporated.

The incorporation (or just revolving for that treatments without limestone, controls) when required, was in the depth of 20 cm. It was applied 200 kg ha^{-1} of monoammonium phosphate (MAP) in subsoiling furrow (45 cm depth) as phosphorus source. The Ca, Mg and S doses are described in Table 2. The sandy loam and clay soil experiment have the same treatments, what sets them apart beyond the fact in the texture differences is that the last one received an extra limestone dose of 3 Mg ha^{-1} in all nine treatments one month before the experiment set up (Table 2). The limestone used was characterized with 20.9 % of Ca and 10.4 % of Mg (Neutralizing power= 98.6 and relative power of total neutralization=98,5). The gypsum used was characterized with 23% of Ca and 14.3% of sulfur (S).

The eucalypt seedlings were transplanted to field 7 days after the treatment set up. In equals amount for all treatments, 100 g of NPK (6-30-6 + 1.5 % B + 0.5 % Cu + 0.5 % Zn) was applied next 15 cm per plant in side dress, five days after the transplanting. Fertilizers top-dressing were applied in the fourth month after transplanting 52.8 kg ha^{-1} of K_2O; 1.8 kg ha^{-1} of B and 0.6 kg ha^{-1} of Cu. In addition, in the Thirteenth month was applied 70.4 kg ha^{-1} of K_2O; 2.4 kg ha^{-1} of B and 0.8 kg ha^{-1} of Cu, as KCl (44 % K_2O + 1.5 % B + 0.5 % Cu).

Table 2. Plot fertilization management (source and total amount of nutrients applied) under Sandy loam soil and clay soil sites

Exp. sites	Treatment	+L	+G	MAP	L*	Ca ^{total}	Mg ^{total}	S ^{total}
		.... Mg ha $^{-1}$....................................						
SLS	-LBa$_{NI}$	-	-	0.200	-	-	-	-
	-LBa$_{I}$	-	-	0.200	-	-	-	-
	-LBr$_{I}$	-	-	0.200	-	-	-	-
	+LBa$_{NI}$	3.000	-	0.200	-	0.627	0.312	-
	+LBa$_{I}$	3.000	-	0.200	-	0.627	0.312	-
	+LBr$_{NI}$	3.000	-	0.200	-	0.627	0.312	-
	+LBr$_{I}$	3.000	-	0.200	-	0.627	0.312	-
	+LBr$_{NI}$+GBa$_{NI}$	2.400	1.000	0.200	-	0.732	0.250	0.143
	+LBr$_{NI}$+GBr$_{NI}$	2.400	1.000	0.200	-	0.732	0.250	0.143
CS	-LBa$_{NI}$	-	-	0.200	3.000	0.627	0.312	-
	-LBa$_{I}$	-	-	0.200	3.000	0.627	0.312	-
	-LBr$_{I}$	-	-	0.200	3.000	0.627	0.312	-
	+LBa$_{NI}$	3.000	-	0.200	3.000	1.254	0.624	-
	+LBaI	3.000	-	0.200	3.000	1.254	0.624	-
	+LBr$_{NI}$	3.000	-	0.200	3.000	1.254	0.624	-
	+LBr$_{I}$	3.000	-	0.200	3.000	1.254	0.624	-
	+LBr$_{NI}$+GBa$_{NI}$	2.400	1.000	0.200	3.000	1.359	0.562	0.143
	+LBr$_{NI}$+GBr$_{NI}$	2.400	1.000	0.200	3.000	1.359	0.562	0.143

SLS= sandy loam soil; CS= clay soil; Ca^{total}, Mg^{total} and S^{total} (Mg ha^{-1}) applied by Limestone and Gypsum. -L=without limestone; +L=with limestone; +G=with gypsum; Ba=band; Br=broadcast; I=incorporated; NI=non-incorporated; MAP=monoammonium phosphate; Limestone*=extra limestone dose applied one month before the experiment set up.

Soil sampling and plant measurement

The DBH (diameter at 1.30 m high) was measured in all trees, 84 months after planting. The average tree was harvested and height measure, also fresh matter from their components weighted (leaf, bark, branch and wood). For wood volume calculation, each tree harvested was divided in four segments: 25%; 50%; 75% and

100% from commercial height (measurement from tree base until the tip, where trunk diameter corresponds to 3 cm). Then, 5 cm thick disks were sawed off at the base of each segment, measured and weighed with and without bark. Afterwards, these disks were dried until they reached constant weight, then the dry biomass of the components in each tree was calculated proportionally. So, using Smalian's formula, it was possible to calculate the volumes of wood with and without bark. The volume of wood produced per hectare was calculated by multiplying the tree measurements by the number of trees per ha^{-1} (i.e. 1,111 trees). Furthermore, samples of the litter were collected using a rectangular frame (0.5 m^2) in triplicate in each plot, and were grouped in a composite sample. The litter samples were divided in fine branches (Ø<10 mm), coarse branches (Ø>10 mm) and leaves.

Plant components (leaf, bark, branch and wood) were weighted, sampled and oven-dried at 65° C to a constant weight. The dried plant material was ground (Wiley mill with 0.5 mm sieve) and subjected to acid digestion (nitric-perchloric). Nutrient concentrations (P, K, Ca, Mg, and S) were determined by Spectrophotometer Optical Induced Plasma emission (ICP-OES). The Nitrogen was determined through sulfuric acid digestion by Kjeldahl method (Bradstreet, 1954).

Soil samples were randomly collected in 16 points per plot, at 0-10, 10-20, 20-40 and 40-60 cm soil layer, 35 cm from planting row, to avoid the subsoiling furrow. The samples from each soil layer were grouped in composite sample. Subsequently, samples were air-dried, crushed, 2-mm sieved.

The plant recovery efficiency (Pre) or nutrient recovery rate was calculated by the following equation:

$$PreNUij = (NUCij - NUCi0)/(NUAij) \qquad \text{Eq 1.}$$

PreNUij = Plant recovery efficiency of nutrient *i* by plant, (kg ha^{-1}/ kg ha^{-1}) in the *j* treatment (kg ha^{-1});
NUCij = Nutrient content *i* in the plant of treatment *j* (kg ha^{-1});

NUCi0 = Average of nutrient content *i* in the plants of the treatments without application of nutrient *i* (zero dose) (kg ha^{-1});
NUAij = Nutrient applied *i* in the treatment *j* (kg ha^{-1}).

In this current study was not possible to calculate Pre rate for Ca and Mg in the clay soil since we have not treatments (controls) without application of both nutrients. The sum of nutrients content in the leaves, branches, barks and wood results in total accumulated aboveground, indicating the nutrient demand by the plant.

Root sampling and measurement

Due to the difficulty of to measure the root system, the sampling concerned only two contrasting treatments, $–LBa_{NI}$ and $+LBr_{NI}+GBa_{NI}$. It was used an auger for sampling the roots (Ø de 5.7 cm). We sampled 7 pre-defined points per tree (Figure 2), in two different directions: three points in planting-row (PR) and four in planting inter-row (PI). At each point samples were collected in the following depths 0-10, 10-20, 20-40 e 40-60 cm (Figure 2). The roots were separated manually from the soil, gently washed and weighted. The processed roots were immersed in a HCl solution (3% - v/v) for 30 seconds, washed with distilled water (Bataglia et al., 1978), and scanned. The scanned roots were stored in alcohol (30 %, v/v) for subsequent analysis.

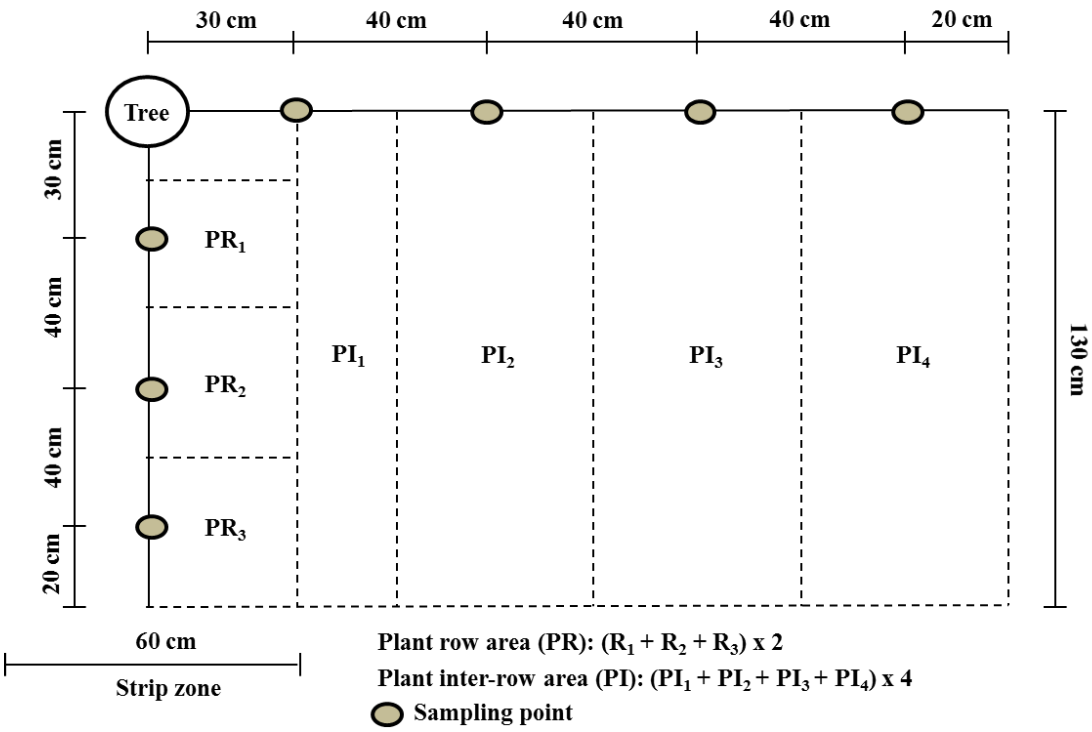

Figure 2. Scheme representing each root sampling point per tree. The plant row area (PR) plus plant inter-row area (PI) are representing a quarter of the tree total area.

Statistical analysis

ANOVA analysis was used to assess the differences in analyzed variables. Tukey's test was performed to compare means for different land-uses (α=0.05). Statistical analyzes were performed using the software package SISVAR (Ferreira, 2008).

RESULTS

Effect of treatment application on soil nutrients contents

The broadcast and band aplication of limestone and gypsum influenced the soil chemical properties in different ways and proportions at the end of the experiment. Nutrients concentration in all four studied depths were different in all nine treatments to both areas ($p < 0.01$).

In general, higher P levels was observed in all nine treatments in 20-40 cm to both areas (Figures 3a and 4a). This response is probably due to the residual effect of the previous rotation, where it was common practice using natural rock phosphate in the subsoiling furrow. In both treatments with limestone and gympsum combined ($+LBr_{NI}+GBa_{NI}$) and ($+LBr_{NI}+GBr_{NI}$), was identified highest K in the soil profile in the both sites, specially in the 40-60 cm layer (Figures 3b and 4b). These results highlight the gypsum effect over the K concentration in the soil, especially favoring its downward movement. The soils that only received limestone (band or broadcast) showed no difference in terms of K concentration in both sites ($p < 0.05$).

The treatments that receveid gypsum, also promoted the highest input of S-SO_4^{2-} as expected, showing more sulfur in the soil profile in both sites (Figures 3c and 4c), particularly when gypsum was applied concentrated $+LBr_{NI} + GBa_{NI}$. It led to largest S-SO_4^{2-} level in the sandy loam soil, which was in the 40-60 cm layer (33.7 mg dm^{-3}), eight-fold higher than the control, $-LBa_{NI}$ (Figure 3). However, when gypsum was applied broadcast $+LBr_{NI}+GBr_{NI}$ to this same soil, just were observed increasing in the 10-20 and 20-40 cm layers ($p < 0.05$). To clay soil, even though the concentration of S in the 40-60 cm layer was lower (19.11 mg dm^{-3}) in $+LBr_{NI} + GBa_{NI}$ compared to sandy loam soil, it increased nineteen-fold comparing to the control, $-LBa_{NI}$ (Figure

4). When gypsum was applied broadcast $+LBr_{NI}+GBr_{NI}$ was not observe increase in $S\text{-}SO_4^{2-}$ concentration in the clay soil.

Limestone applied banded promoted the highest Ca^{2+} levels and distribution in the soil profile in both, sandy loam and clay soils (Figures 3d and 4d). It was higher when lime was incorporated $+LBa_{I}$, compared to the non-incorporated $+LBa_{NI}$, along to all soil layers ($p<0.05$) in both soils. The limestone applied broadcasted did not cause any difference in the Ca content comparing to treatments without limestone (controls). In the Clay soil, both $+LBr_{NI}+GBa_{NI}$ and $+LBr_{NI}+GBr_{NI}$ had the same Ca^{2+} content.

As for Ca^{2+}, Mg^{2+} content in the clay soil was higher in the whole soil profile when lime was applied on band, incorporated $+LBa_{I}$ or not $+LBa_{NI}$ (Figures 3e and 4e). For the sandy loam soil, incorporated lime $+LBa_{I}$ showed higher Mg^{2+} content. However, treatments that included gypsum did not show higher contents of Mg^{2+} for both sites, even though it was combined with limestone ($p < 0.05$).

The $+LBa_{I}$ and $+LBa_{NI}$ treatments applications were the most efficient in decreasing Al^{3+} levels in the clay soil profile (10-20, 20-40 and 40-60 cm) (Figures 3f and 4f). The use of gypsum $+LBr_{NI}+GBr_{NI}$, had the same effect only at the 40-60 cm layer. At 0-10 cm in the clay soil, all treatments that received limestone in strip and gypsum combined with limestone, independently of the location, decreased the Al^{3+} concentration ($p < 0.05$). In the sandy loam soil, Al^{3+} concentration decreased at 0-10 cm layer only when lime was concentrated, $+LBa_{I}$ and $+LBa_{NI}$ and in the 10-20 cm layer when it was incorporated $+LBa_{I}$.

Effect of gypsum application on root density, dry biomass and root: shoot ratio

The root density (RD) showed a non-uniform distribution in the soil profile of both treatments evaluated, lime and gypsum combined $+LBr_{NI}+GBa_{NI}$, and the control

$-LBa_{NI}$, in the plant row (PR) as well as in plant inter row (PI), in the both soils (Figures 5a and 5d). In the clay soil, the control treatment had a higher RD in the upper layer (0-10 cm), in plant row and inter-row than the soils receiving gypsum and lime combined, three-fold higher. However, in this treatment receiving gypsum and lime combined showed a greater RD in deeper soil layers varying from 0.39 to 1.61 g dm^{-3} four-fold increase, from 0-10 to 40-60 cm layers in PI respectively.

In the sandy loam soil, RD was also higher in the upper layer (0-10 cm) in the planting row and inter rows of the control treatment ($p<0.05$). The same pattern remains in the 10-20 cm of $-LBa_{NI}$ in plant row. The root dry biomass had similar performance in both soils (Figures 5b and 5e), in which there was greater root mass at 0-10 and 10-20 cm layer in the $-LBa_{NI.}$ Root biomass in the 0-10 cm layer was 70 and 40 % larger in the control treatment, for the clay and sandy loam soils, respectively ($p<0.05$). However, there was an opposite performance at the deepest layer (40-60 cm) of both soils. Root dry mass were 36 % higher in the presence of lime and gypsum combined in the clay soil and 40 % higher in the sandy loam soil ($p<0.1$). Regarding the root:shoot biomass ratio, the treatment receiving lime and gypsum combined showed a lower root:shoot in both soils (Figure 5c and 5f). In the clay soil this difference was 26 % ($p<0.05$), while at the sandy loam soil it was 56 % ($p<0.1$).

Nutrient content and dry matter of tree components and litter

Gypsum and limestone combined applied in band and incorporated, $+LBr_{NI}+GBa_{NI}$ significantly promoted the highest increase on dry matter of all tree components (Leaves, Branches, Barks and Wood) and, consequently, the total plant dry weight in both soils (Table 3). It also happened for the litter components (F. branches, C branches and leaves) in the clay soil ($p<0.05$). Despite the most treatments that only received limestone the shoots and litters did not differ that from gypsum treatments, they had a tendency of equal with the others including the controls (without limestone). This fact did not repeat in gypsum treatments.

In general, the application of gypsum combined with limestone increased all nutrients content on the shoots in both sites, except for N and Mg in the clay soil (Figure 6 and 7). Specifically, the $+LBr_{NI}+GBa_{NI}$ reflected in highest total nutrient contents in shoot, in which in the clay soil its total Ca shoot content was 1.32-fold higher than $+LBa_{NI}$, and S was 1.54-fold higher (Figures 7d and 7f, respectively). Only Mg was higher in the $+LBa_{NI}$ in clay soil (Figure 7e). An interesting factor detected in this study was that, in clay soil more than 60% of the Sulphur(S) found in the total shoot was exported by wood in all treatments. In the sandy soil this removal was around 50% by wood. This fact emphasizes the need for this nutrient to be replenished in soil.

Nutrients content in the whole litter (leaves litter + coarse branches litter + fine branches litter) was fairly uniform among the groups: without limestone, only limestone and gypsum and limestone combined (Figure 6 and 7). However, gypsum application increased Ca and S contents in total litter, which were this way, the highest among all treatments. To litter in the three treatments without limestone ($-LBa_{NI}$, $-LBa_{I}$ and $–LBr_{I}$), the lowest nutrients contents were observed, the same pattern found in the shoot content. In the sandy loam soil, the lowest tendency of nutrients content in these treatments without limestone was detected mainly to Ca, Mg and S. In addition, in clay soil the same pattern was observed just to Ca and S contents.

Plant nutrients recovery and eucalypt wood volume

The experiment in the sandy loam soil allows us to quantify the recovery rates of Ca, Mg, and S in the plants from limestone and limestone with gypsum combined treatments (Figure 8). The highest Ca recovery rates were found when gypsum was applied, 34.1% for the $+LBr_{NI}+GBa_{NI}$ followed by 29.3% for the $+LBr_{NI}+GBr_{NI}$. When just limestone was applied the Ca recovery was significantly lower, varying from 24.7 to 19.0%.

As occurred to Ca, Mg recovery rates were also higher when gypsum was supplied, with the banded gypsum providing the highest Mg recovery rate (26.4%) followed by the broadcasted gypsum (21.4 %). When just limestone was applied Mg recovery rates were significantly lower, varying from 18.2 $+LBr_{NI}$ to 15.5 %, an average for the other limestone treatments that were not significantly different.

Even though the amount of S provided by the gypsum being significantly lower than the amount of Ca and Mg provided by the limestone, S recovery was still lower than the recovery of Ca and Mg. But as it happened for Ca and Mg, S recovery rate was higher when gypsum was banded $+LBr_{NI}+GBa_{NI}$, reaching 13.6 % compared to the broadcasted gypsum (10.9 %).

In the clay soil S recovery rate was higher than in the sandy loam soil, reaching 16.6 % for the banded gypsum and 11.75% for the broadcasted gypsum (Figure 8, in description).

Regarding eucalypt wood volume, we can group treatments into three groups, without limestone, only limestone, and limestone with gypsum combined. Treatments that showed highest volume were the ones including gypsum (Figures 9a and 9b). The banded gypsum $+LBr_{NI}+GBa_{NI}$, led to highest production, 334.2 m^3 ha^{-1} in the sandy loam soil and 363.2 m^3 ha^{-1} to clay soil, 58 and 29.1 % higher than the control ($-LBa_{NI}$), respectively. Broadcasted gypsum led to second higher production in both soils, 311.74 m^3 ha^{-1} for the sandy loam soil and 341.70 m^3 ha^{-1} for the clay soil, but not significantly higher than the treatments with only limestone. In the sandy loam soil, the groups that received only limestone had higher volume than without limestone (controls). In this soil, the four treatments that received only limestone showed an average volume of 286 m^3 ha^{-1} (35,4 % higher than -LSa_{NI}). However, in the clay soil these differences were not evidenced, in which the control treatments showed similar production as those that received limestone. In the clay soil the four treatments receiving limestone showed an average volume of 317 m^3 ha^{-1} (12.9 % higher than –LSa_{NI}).

DISCUSSION

Limestone application effect

As limestone has relatively low solubility with consequent slow mobility (Pavinato et al., 2009) (1.4 mg L^{-1} a 25 ºC; Vitti et al.,2008), this led to high residual potential. Thus, even 7 years after the limestone application in strip +LBa_I and +LBa_{NI} to both soils, the highest Ca^{2+} and Mg^{2+} concentration and distribution were found along soil profile than soils without limestone application –LBa_{NI}, -LBa_I and –LBr_I (Figure 3d-e and Figure 4d-e). The great residual effect of limestone has been shown recently in a southern Brazilian sandy Ultisol, where there was only 20% of re-acidification of the original potential acidity after 24 years from limestone application (Rheinheimer et al., 2018). Since the amount of limestone applied banded or broadcasted was the same, banded limestone added more Ca^{2+} and Mg^{2+} to the planting row, where soil sampling was done. Even though limestone has a slow mobility in the soil, the incorporation leads to a higher distribution of these cations in the soil profile (Figure 3d-e and Figure 4d-e) (Gonzalez-Erico et al., 1977).

Besides the increasing of Ca^{2+} and Mg^{2+} availability in the soil region in which it was applied, the +LBa_I also improved all the other soil chemical characteristics evaluated in both soils (SB, CEC, $CEC_{pH=7.0}$, V, pH and m; Supplementary material 1 and 2). The fact that the incorporation was done up to 20 cm and changes on soil chemical characteristics also occurred up to 40 cm reinforces the hypothesis that may have been a downward movement of fine particles of limestone as a result of the high amount of limestone applied banded. The downward movement of fine particles of limestone resulting in a neutralization gradient will depends on the association with the water-soluble organic binder with hydroxyl (R-OH) and carboxyl (COOH-R) functional groups present on the soil surface (Rheinheimer et al., 2018; Veronese et al., 2012).

Despite the improvement in Ca^{2+} and Mg^{2+} availability and other soil chemical characteristics provided by +LBa_{I}, it did not translate into a higher wood volume in comparison with the broadcasted limestone (Table 3). In the sandy loam soil, just limestone application promoted higher total dry matter of tree components compared to no limestone application. Similar effect could be observed in the plant nutrient contents (N, P, K, Ca, Mg and S) in the sandy loam soil with limestone. In general, higher plant response to limestone application was verified in the sandy loam soil than in the clay soil (Table 3, Figure 6a-f and Figure 7a-f). A major cause of it, is the fact that the experiment in the clay soil received a base limestone application performed before eucalyptus planting in the whole area (3.0 t ha^{-1}; Table 2), which increased the nutrients availability and consequent uptake by plant, even in treatments which did not received limestone afterwards (Figure 6a-f and Figure 7a-f). Low effects were observed with only limestone application in Sandy loam soil (Figure 8). It is interesting to notice that plant recovery of Ca and Mg from limestone, two nutrients that are non-specifically bounded to the soils, is relatively low, even after 80 months of growth. The Ca recovery rate varied from 24.7 % (+LBa_{I}) to 19 % (+LBa_{NI}). The Mg recovery rate was even lower, varying from 18.2 % for +LBr_{NI} to 15.1 % for +LBa_{NI}. It is even more interesting because we are working with eucalyptus, a well-known plant for having a well-developed root system and a greater ability to extract nutrients from the soil compared to other plants (Barros and Novais, 1990).

The increase in Ca^{2+} and Mg^{2+} availability, as well as the improving of other soil chemical characteristics caused by limestone, increased eucalypt productivity in the sandy loam soil varying from 29-39 % for $+LBr_I$ and $+LBa_I$ respectively, comparing to $-LBa_{NI}$ (Figure 9a). On the other hand, in the clay soil these effects of limestone were not very pronounced (Figure 9a), mainly due to the base limestone application performed before eucalypt planting. According to Amor and Marcelis (2003), Ca is an important ion mediating many processes in plant physiology and development. But even though limestone improved soil chemical characteristics, it was not enough to achieve the highest eucalypt productivity, which was only achieved when limestone and gypsum combined were applied (Figure 9a-b).

Eucalypt soil conditioning and eucalypt productivity responses to gypsum application are still scarce. Gypsum is used to ameliorate soil profile chemical characteristics, specially distributing Ca^{2+} (and other basic cations) and SO_4^{2-} in the soil profile. In tropical soils, the most limiting factors for root development is the low concentration of Ca^{2+} and high concentration of Al, especially in deeper soil layers. However, in this study gypsum application was able to bring only SO_4^{2-} down to 60 cm in both soils. This is fairly common since SO_4^{2-} is readily leached from surface soils (Lehmann and Schroth, 2003). In fact, it is needed to bring cations down the soil profile. But in order for the SO_4^{2-} to bring cations like Ca^{2+}, K^+ and Mg^{2+} down the soil profile are needed: water movement in the soil profile and high cations concentration in the soil solution. Thus, is clear the importance of adequate $S\text{-}SO_4^{2}$

concentrations in soil profile to achieve high eucalypt productivity, which was not possible for soils with only limestone application. In our results, to Clay soil more than 60 % of total S uptaken by plant was found into the wood, while to Sandy loam soil this value was around 50 % (Figure 6f and Figure 7f). Considering that the wood is removed from the field, eucalypt plantations exports high concentrations of $S\text{-}SO_4^{2}$ from the soil in each rotation, which should be replaced to reach higher productivities (Figure 9a-b).

Gypsum application effect

Gypsum and limestone combined application, banded or broadcasted, showed lower Ca^{2+} and Mg^{2+} concentrations in subsoil layers compared with treatments receiving only limestone banded, after 7 years in both soils (Figure 3 and 4). Due the high solubility of gypsum in water (2.04 g L^{-1}, 25ºC; Vitti et al., 2008), most of it has already been solubilized and Ca^{2+} and Mg^{2+} were uptaken by plants (Figure 6d-e and Figure 7d-e).

On other hand, the highest $S\text{-}SO_4^{2-}$ concentrations was favored by the pH increase, provided by gypsum combined with limestone, as the retention of $S\text{-}SO_4^{2-}$ is reduced after correction of soil acidity (Caires et al., 2006). This fact sign a downward movement of $S\text{-}SO_4^{2}$ (possibly as ionic pair $CaSO_4^0$ and $MgSO_4^0$), which when in the deeper soil layers allowed the availability of Ca^{2+} + Mg^{2+} and the reduction of Al^{3+} activity by the formation of $AlSO_4^+$ (Mclay and Ritchie, 1993; Pavan et al., 1983), (later effect, 7 years after gypsum application was observed with increments in S and V% parameters and reduction in m% parameter; Supplementary material 1 and 2).

The improvement in the chemical environment in deeper soil layers allowed the root to develop better in depth. There was more roots biomass in the $+LBr_{NI}+GBa_{NI}$ at 40-60 cm soil layer in both soils (Figure 5b and e) and higher root density in the clay soil (Figure 5d). The volume of soil explored by $+LBr_{NI}+GBa_{NI}$ and root system distribution was higher than in the $-LBa_{NI}$, which was limited to the upper soil layer with coarser roots (Supplementary material 5). Nonetheless, the total root biomass was higher when there was no application of limestone (Figure 5b and e). Due the lack of nutrients, the plant without limestone invested more C in roots (mainly in superficial soil layers) as a strategy for nutrient acquisition from litter decomposition (Supplementary material 6). More than 90 % of plants species have specialized strategies to enhance nutrient uptake like localized root proliferation in enriched zones (litter zone in this case) and mycorrhiza associations (Lambers et al., 2008). Consequently, the root/shoot ratio was higher in the $-LBa_{NI}$ than $+LBr_{NI}+GBa_{NI}$ (Figure 5c and 5f). In addition, enhancing sulfur availability in the soil decreases root/shoot ratio of eucalyptus (Furtini Neto, 1988).

Besides the alteration of the chemical environment in the subsurface soil layers, the root activity through its rhizodepositions stimulates the soil microbial activity close to the root zone (Kuzyakov, 2002; Tian et al., 2013). Both, roots and soil microbes release organic acids that can solubilize insoluble K in micas and feldspars releasing K^+ to the soil solution (Qureshi et al., 2017; Song and Huang, 1988; Wang et al., 2000). In our study, soil K^+ concentration was relatively high even before the experiment, mainly in the clay soil (Figures 3 and 4). However, gypsum application kept a higher K^+ concentration in the soil, reflecting in a higher K uptake and content in the plants (Figure 6c and Figure 7c). This fact corroborates with the hypothesis of K released from potassium-bearing minerals fractions to soil solution by root activity.

The greater root exploration in deeper soil layers contribute to higher water and nutrients uptake by trees (Figure 5b and 5e) (Caires et al., 2003; Carvalho and Van Raij, 1997). This factor undoubtedly contributes to higher drought tolerance (Lynch and Wojciechowski, 2015), keeping the stomata opened longer and influencing directly in the plant growth. Lopes and Reynolds (2010), found a good association between roots depth with yield under drought stress in wheat. Our data showed increases in dry matter of tree components in both soils when gypsum was applied (Table 3). Also, it promoted the highest nutrient contents in the shoot.

Besides a better root system development, another key aspect favoring better plant growth and development in response to gypsum was $S\text{-}SO_4^{2-}$ availability in the soil, promoting higher S content in the plant tissue (Figure 6f and Figure 7f). Many studies have demonstrated high yield response to gypsum in annual crops, like sugar cane (Araújo et al., 2016; Lima et al., 2013), soybean (Ascari and Mendes, 2017) and corn (Caires et al., 2004). However, eucalypt has higher S demand than annual crops (Alvarez et al., 2007), explaining the significant plant response to the availability of $S\text{-}SO_4^{2}$ in the soil.

The Sulfur is a crucial element for the whole plant physiology and metabolism due to its large relevance in cysteine and methionine biosynthesis (Duke and Reisenauer, 1986; Lucheta and Lambais, 2012). According to Lunde et al. (2008), low availability of S during plant growth lead to an impact on plant fitness and decreases crop yield and quality. Sulfur integrates the structure of many enzymes and proteins, (e.g. cofactor coenzyme A) which are vital for photosynthesis. Also, S availability may influence protein arrangement (Duke and Reisenauer, 1986; Kertesz and Fellows, 2007; Takahashi et al., 2011). Hence, S has a substantial importance on alleviating abiotic and biotic stresses (e.g. oxidative stress due to drought) (Bloem et al., 2005).

In addition, the interaction between S and N is essential to plants. According to Yamada et al. (2007), there is a great synergism between S and N in which the lack of S leads to a decrease in the use efficiency of N, due to less S amino acids and proteins. In our work, plants in treatments receiving gypsum had the greatest N use efficiency (Supplementary material 3 and 4).

The beneficial S effect in plant physiology and metabolism together with the greater water uptake by root exploration in subsurface soil layers probably made it possible to higher plant uptake recovery of Ca and Mg when gypsum was applied (Figure 8). As a result, eucalypt production of wood volume increased 58 and 47 % when gypsum was applied banded ($+LBr_{NI}+GBa_{NI}$) and broadcast ($+LBr_{NI}+GBr_{NI}$) in the sandy loam soil, and 29 and 21 % when gypsum was applied banded and broadcast in the clay soil (Figure 9).

CONCLUSION

In summary, the limestone applied by band incorporated $+LBa_{I}$ provided a residual effect with increasing in soil Ca^{2+} and Mg^{2+} availability with improving on all chemical characteristics studied in soil profile even 7 years after application, which allowed increases in the eucalypt production 39.4 and 16.7% of wood volume compared with $-LBa_{NI}$ to sandy loam and clay soil, respectively.

However, when there was gypsum and limestone combined application banded it promoted a high concentration of $S\text{-}SO_4^{2}$ in soil and consequently its downward movement in soil profile, which allowed a highest exploration root at 40-60 cm soil layer, nutrients content and nutrients recovery rates (Ca and Mg). This fact led to best eucalyptus production 58% and 29 % of wood volume than $-LBa_{NI}$ to sandy loam and clay soil, respectively.

TABLES AND FIGURES.

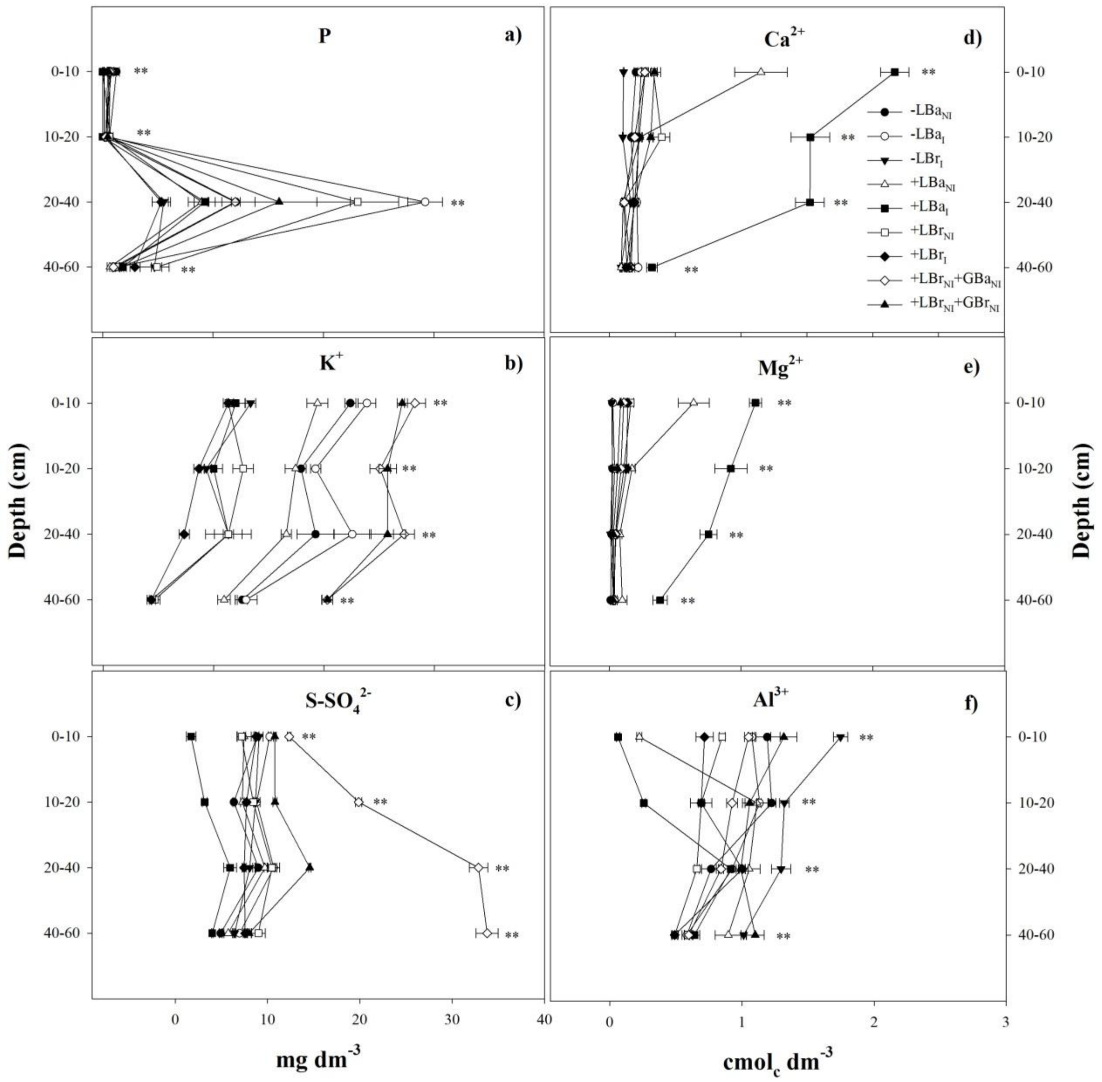

Figure 3. Soil P, K$^+$, S-SO$_4^{2-}$ (mg dm^{-3}; a-c) and Ca^{2+}, Mg^{2+},Al^{3+} (cmol$_c$ dm^{-3}; d-f) to different soil layers (0-10, 10-20, 20-40 and 40-60 cm) in the Sandy loam soil under eucalypt plantation without (-L) or with (+L) Limestone application, banded (Ba) or broadcasted (Br), incorporated (I) or non-incorporated (NI). Furthermore, gypsum application banded (Ba) or broadcasted (Br) with limestone application in broadcast (+L). ^{ns}: no significant; **: significant at 1 %; *: significant at 5 % by the F-test. Different capital letters denote significant differences among the treatments to 40-60 cm soil layer by the Tukey's test (*α=0.05*). Error bars denote the standard error of the mean (n=4).

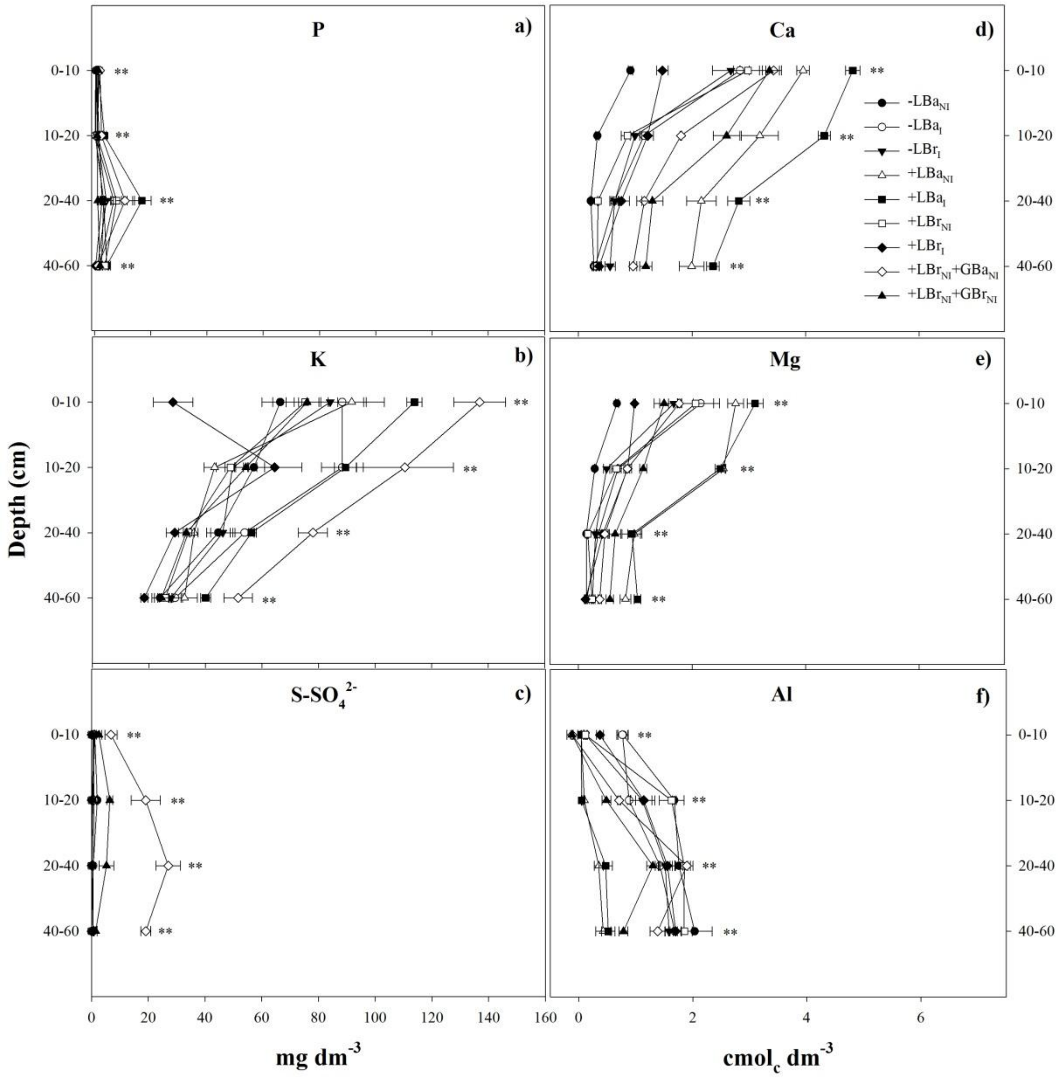

Figure 4. Soil P, K^+, $S\text{-}SO_4^{2-}$ (mg dm^{-3}; a-c) and Ca^{2+}, Mg^{2+},Al^{3+} ($cmol_c$ dm^{-3}; d-f) to different soil layers (0-10, 10-20, 20-40 and 40-60 cm) in the Clay soil under eucalypt plantation without (-L) or with (+L) Limestone application, banded (Ba) or broadcasted (Br), incorporated (I) or non-incorporated (NI). Furthermore, gypsum application (+G) in band (Ba) or broadcast (Br) with limestone application in broadcast (+L). ^{ns}: no significant; **: significant at 1 %; *: significant at 5 % by the F-test. Different capital letters denote significant differences among the treatments to 40-60 cm soil layer by the Tukey's test (*α=0.05*). Error bars denote the standard error of the mean (n=4).

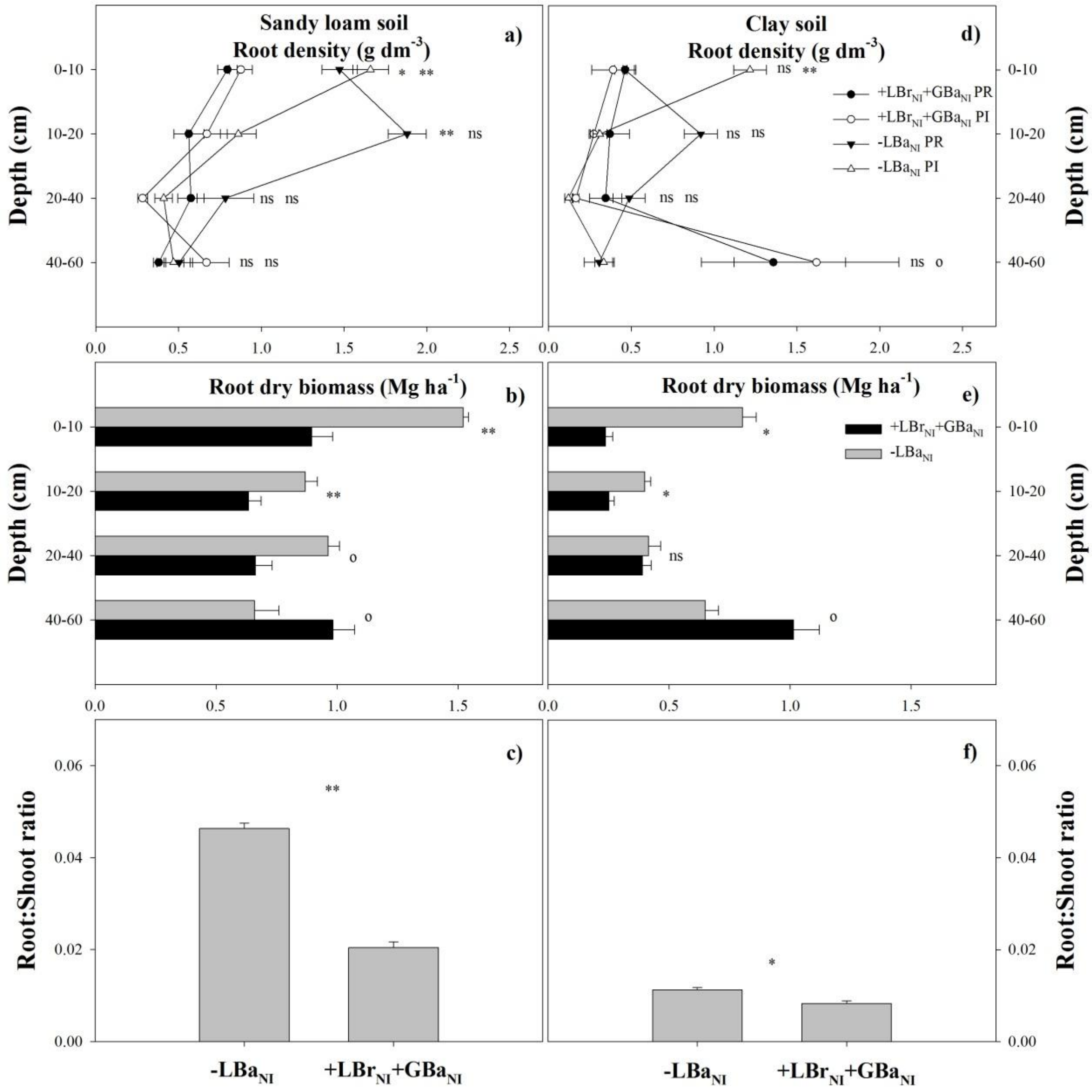

Figure 5. Root density in plant row (PR) and plant inter row (PI) (g dm^{-3}; a and d) and Root dry biomass (Mg ha^{-1}; b and e) to different soil layers (0-10, 10-20, 20-40 and 40-60 cm) and Root:Shoot ratio (c and f) of eucalypt plantation in the Sandy loam soil and Clay soil under plantation without (-L) or with (+L) Limestone application in broadcast (Br) non-incorporated (NI). Furthermore, gypsum application (+G) in band (Ba). ^{ns}: no significant; *: significant at 5 % by the F-test. In graph a and d the first symbol represent differences between -LBa$_{NI}$ and +LBr$_{NI}$+GBa$_{NI}$ to PR, while the second symbol represent differences between -LBa$_{NI}$ and +LBr$_{NI}$+GBa$_{NI}$ to PI. Error bars denote the standard error of the mean (n=4).

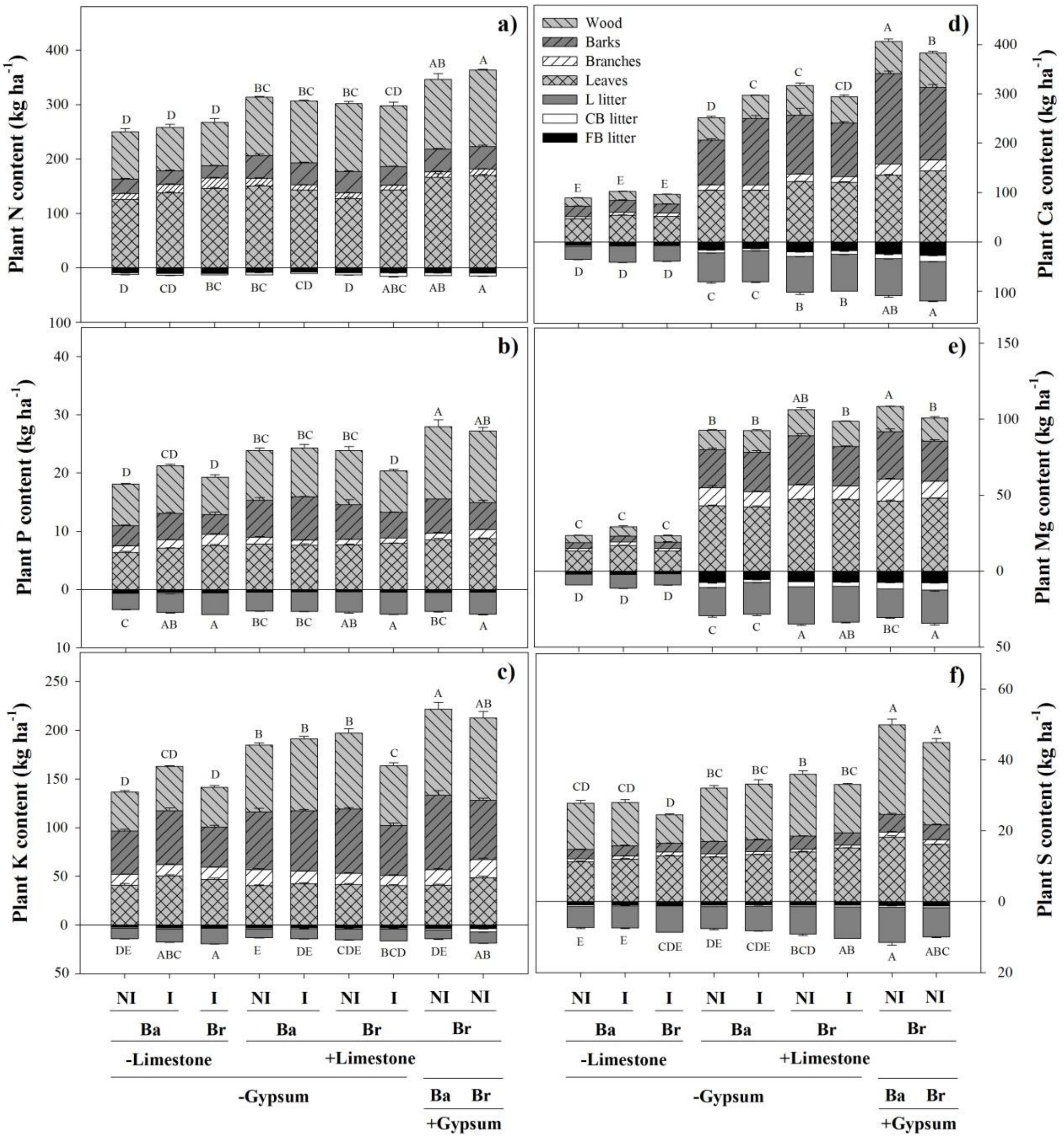

Figure 6. N, P, K, Ca, Mg and S content (kg ha^{-1}) in wood, bark, branches, and leaves (above 0) and leaves litter (L litter), coarse branches litter (CB litter), and fine branches litter (FB litter) (below 0) of a eucalyptus experiment in a sandy loam soil. The treatments include the use of limestone (with or without it, +Limestone or –Limestone, respectively), applied banded (Ba) or broadcasted (Br), incorporated (I) or non-incorporated (NI); and the use of gypsum (with or without it, +Gypsum or –Gypsum, respectively), banded (Ba) or broadcasted (Br) on the soil. Different capital letters denote significant differences among the treatments to Total shoot (wood + barks + branches + leaves) and Total litter (leaves litter + coarse branches litter + fine branches litter) by the Tukey's test (*α=0.05*). Error bars denote the standard error of the mean (n=4).

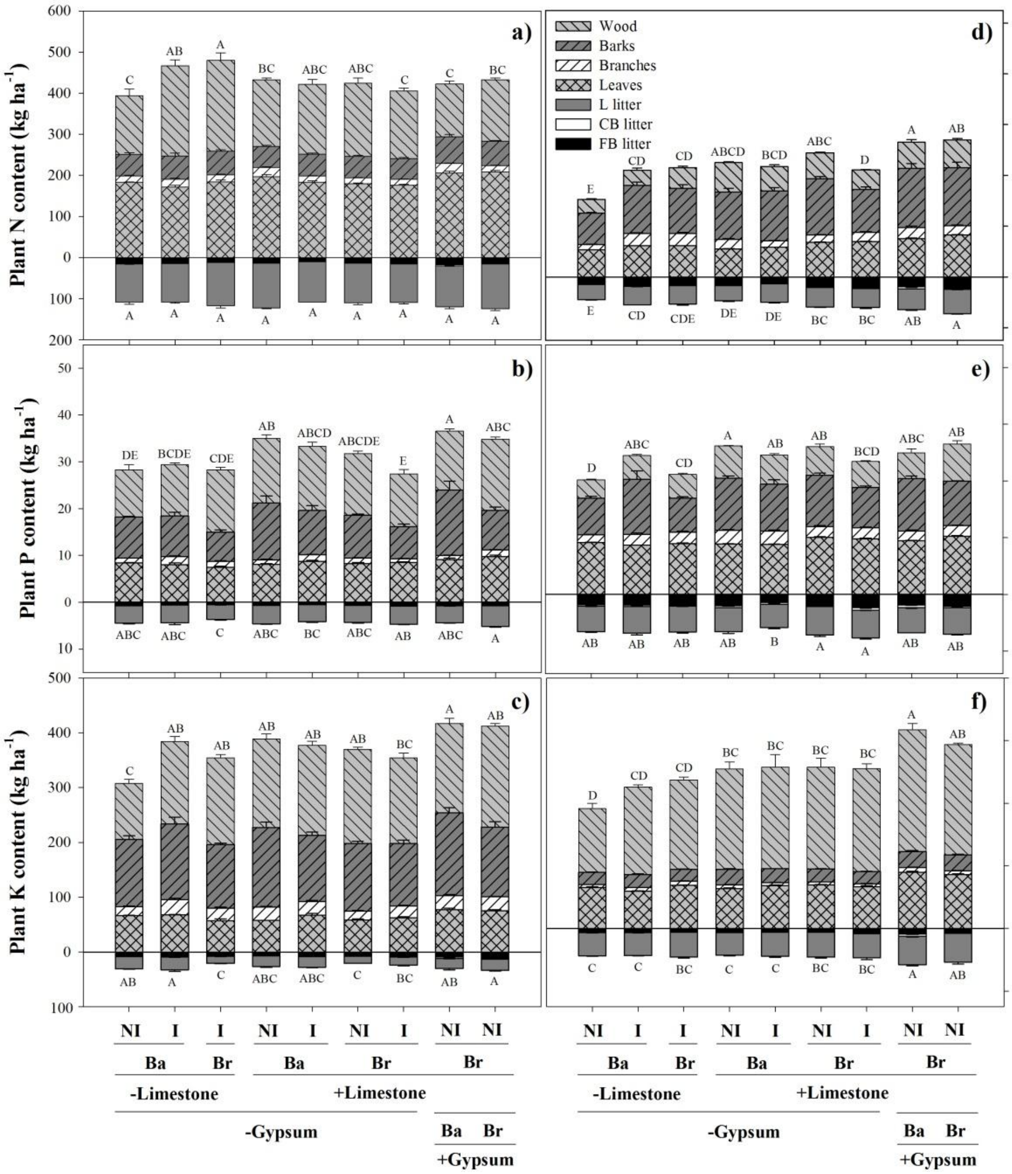

Figure 7. N, P, K, Ca, Mg and S content (kg ha^{-1}) in wood, bark, branches, and leaves (above 0) and leaves litter (L litter), coarse branches litter (CB litter), and fine branches litter (FB litter) (below 0) of a eucalyptus experiment in a clay soil. The treatments include the use of limestone (with or without it, +Limestone or –Limestone, respectively), applied banded (Ba) or broadcasted (Br), incorporated (I) or non-incorporated (NI); and the use of gypsum (with or without it, +Gypsum or –Gypsum, respectively), banded (Ba) or broadcasted (Br) on the soil. Different capital letters denote significant differences among the treatments to Total shoot (wood + barks + branches + leaves) and Total litter (leaves litter + coarse branches litter + fine branches litter) by the Tukey's test (*α=0.05*). Error bars denote the standard error of the mean (n=4).

Table 3. Dry matter of tree components (Leaves, Branches, Barks and Wood) and litter components (Fine branches - F branches, Coarse branches – C branches and Leaves) (Mg ha^{-1}) of the eucalypt plantation in the Sandy loam soil and Clay soil under plantation without (-Limestone) or with (+Limestone) Limestone application, in band (Ba) or broadcast (Br), incorporated (I) or non-incorporated (NI). Furthermore, gypsum application (+Gypsum) in band (Ba) or broadcast (Br) with limestone application in broadcast (+L). Different capital letters denote significant differences among the treatments by the Tukey's test (*α=0.05*)

Plant components	-Gypsum							+Gypsum	
								Ba	Br
	-Limestone			+Limestone					
	Ba		Br	Ba		Br		Br	
	NI	I	I	NI	I	NI	I	NI	NI
	Sandy loam soil								
Shoot	Mg ha^{-1}								
Leaves	3.37 C	3.94 BC	3.78 BC	5.01 A	4.65 AB	4.16 ABC	4.45 AB	5.02 A	4.69 AB
Branches	4.00 D	4.39 BCD	5.74 ABC	5.40 ABCD	4.55 ABCD	4.20 CD	3.84 D	6.26 A	6.05 AB
Barks	10.92 BC	10.21 C	10.36 C	14.13 AB	14.58 A	14.76 A	13.78 ABC	16.20 A	15.67 A
Wood	82.41 CD	82.67 CD	74.70 D	116.26 AB	120.73 AB	118.91 AB	112.31 BC	147.31 A	140.86 AB
Total	100.69 CD	101.21 CD	94.58 D	140.80 AB	144.51 AB	142.03 AB	134.38 BC	174.79 A	167.26 AB
Litter									
F branches	3.32 D	3.67 CD	3.88 BCD	4.72 A	3.86 BCD	3.75 BCD	4.44 AB	4.16 ABC	4.07 ABC
C branches	2.49 BC	1.63 C	1.37 C	3.26 AB	2.42 BC	3.25 AB	3.27 AB	4.22 A	3.57 AB
Leaves	11.32 B	11.62 B	12.03 B	12.89 AB	12.61 AB	12.20 B	14.77 A	12.77 AB	13.35 AB
Total	17.13 C	16.92 C	17.28 C	20.87 AB	18.90 BC	19.20 BC	22.48 A	21.15 AB	20.99 AB

Continued…

	Clay soil								
Shoot	.... Mg ha^{-1}								
Leaves	4.20 AB	3.64 B	3.67 AB	3.90 AB	3.93 AB	4.07 AB	3.57 B	4.80 A	4.13 AB
Branches	7.08 C	8.65 ABC	10.45 AB	10.11 ABC	9.66 ABC	7.76 BC	7.34 C	11.58 A	8.39 BC
Barks	17.75 AB	17.46 B	18.67 AB	20.97 AB	19.11 AB	20.29 AB	17.35 B	22.41 A	20.45 AB
Wood	138.43 B	155.68 AB	174.42 AB	184.06 A	183.87 A	174.02 AB	168.56 AB	179.46 A	183.43 A
Total	167.46 B	185.43 AB	207.21 AB	219.04 A	216.57 A	206.14 AB	196.82 AB	218.25 A	216.40 A
Litter									
F branches	5.89 A	5.42 A	6.40 A	5.58 A	4.40 B	6.07 A	6.40 A	6.76 A	6.62 A
C branches	1.64 AB	1.51 B	0.87 B	1.79 AB	1.28 B	0.86 B	1.33 B	2.65 A	1.21 B
Leaves	11.15 A	11.52 A	11.62 A	11.56 A	10.73 A	11.59 A	12.13 A	11.99 A	12.40 A
Total	18.67 AB	18.45 AB	18.90 AB	18.94 AB	16.40 B	18.52 AB	19.86 AB	21.40 A	20.22 AB

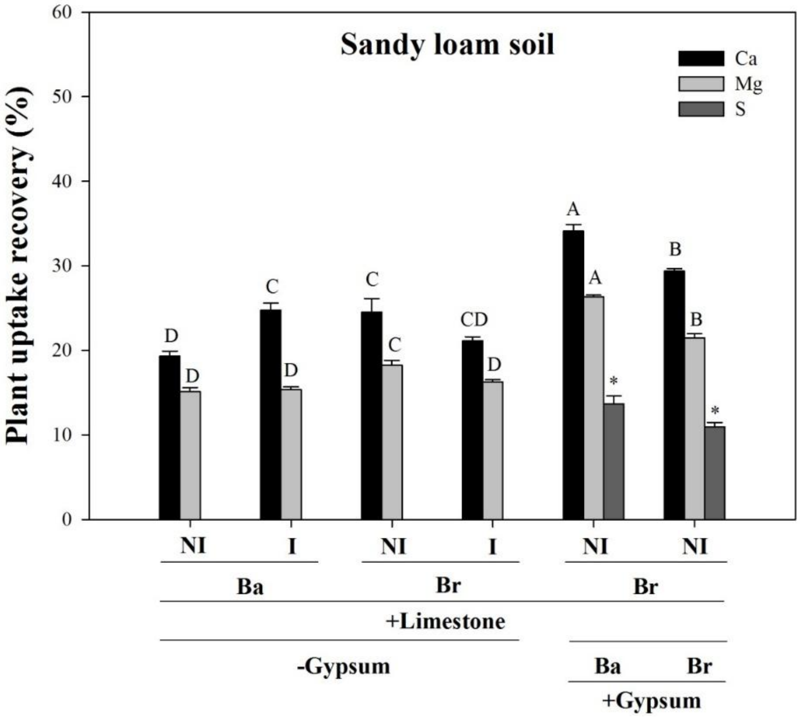

Figure 8. Plant uptake recovery (%) to Ca, Mg and S in the Sandy loam soil under eucalypt plantation with (+Limestone) Limestone application, in band (Ba) or broadcast (Br), incorporated (I) or non-incorporated (NI). Furthermore, gypsum application (+Gypsum) banded (Ba) or broadcasted (Br) with limestone application in broadcast (+L). Different capital letters denote significant differences among the treatments by the Tukey's test (*α=0.05*). *: significant at 5 % by the F-test. Error bars denote the standard error of the mean (n=4). To clay soil, just was possible to calculate the plant uptake recovery for S, in which to $+LBr_{NI}+GBa_{NI}$ it was 16.65%* and $+LBr_{NI}+GBr_{NI}$ it was 11.75%*.

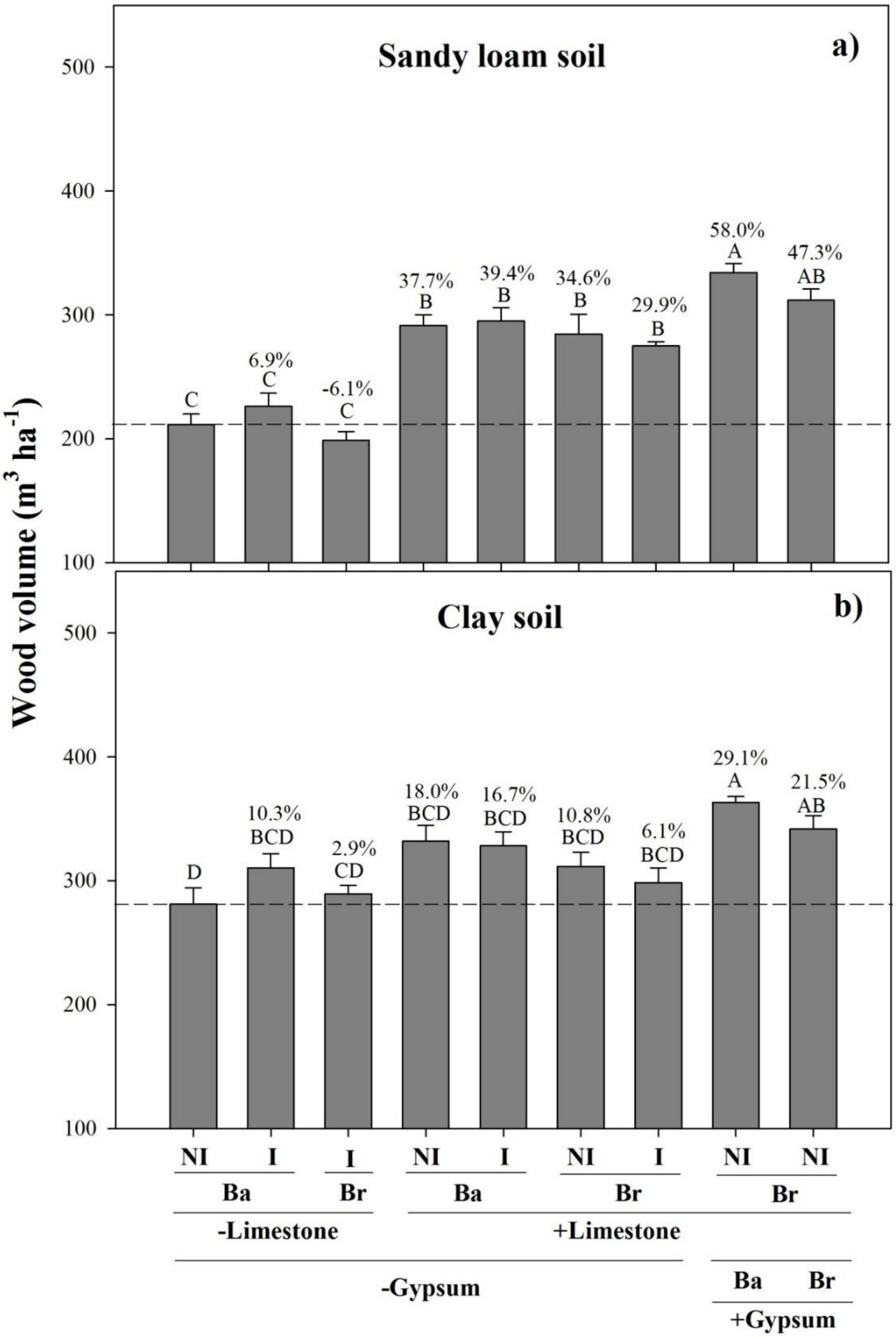

Figure 9. Wood volume at seven years of age (m^3 ha^{-1}) as a result of lime application (+Limestone or –Limestone), banded (Ba) or broadcasted (Br) on the soil, incorporated (I) or non-incorporated (NI); and the use of gypsum (with or without it, +Gypsum or –Gypsum, respectively), banded (Ba) or broadcasted (Br), in a sandy loam (a) and a clay soil (b). Different capital letters denote significant differences among the treatments by the Tukey's test (*α=0.05*). Percentage values on the top of each bar represent the variation of the eucalyptus productivity in comparison with the control ($–LBa_{NI}$). Error bars denote the standard error of the mean (n=4).

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SUPPLEMENTARY MATERIAL

Supplementary material 1. Soil H+Al, S, CEC, CEC $_{pH=7.0}$ (cmol$_c$ dm^{-3}) and V, m (%) and pH to different soil layers (0-10, 10-20, 20-40 and 40-60 cm) in the Sandy loam soil under eucalypt plantation without (-L) or with (+L) Limestone application, banded (Ba) or broadcasted (Br), incorporated (I) or non-incorporated (NI). Furthermore, gypsum application (+G) banded (Ba) or broadcasted (Br) with limestone application in broadcast (+L). Different capital letters denote significant differences among the treatments to 0-10, 10-20, 20-40 and 40-60 cm soil layer by the Tukey's test (*α=0.05*)

Treatment	Depth	H+Al	SB	CEC	CEC $_{pH=7.0}$	V	m	pH
	... cm ...	.... cmol$_c$ dm^{-3}			....	...... %		
-LBa$_{NI}$	0-10	4.53 A	0.28 C	1.47 BC	4.81 A	5.83 D	80.78 B	4.53 CD
	10-20	6.56 A	0.24 BC	1.46 BC	6.80 A	3.49 DE	83.89 AB	4.58 B
	20-40	5.65 A	0.25 B	1.02 CD	5.90 A	4.22 B	75.10 B	4.61 B
	40-60	4.65 A	0.21 B	0.79 C	4.86 AB	4.26 B	73.87 BC	4.71 CD
-LBa$_{I}$	0-10	3.32 B	0.33 C	1.40 BC	3.64 ABC	9.03 D	76.73 BC	4.56 CD
	10-20	4.68 BC	0.31 BC	1.44 BC	4.99 BC	6.16 CDE	78.87 BC	4.52 B
	20-40	4.80 B	0.29 B	1.21 BC	5.09 B	5.64 B	75.68 B	4.62 B
	40-60	4.52 AB	0.29 B	0.87 BC	4.81 AB	6.00 B	66.76 C	4.75 C
-LBr$_{I}$	0-10	3.77 AB	0.16 C	1.91 B	3.94 ABC	4.08 D	91.57 A	4.42 D
	10-20	5.16 B	0.15 C	1.47 BC	5.31 BC	2.78 E	89.98 A	4.45 B
	20-40	5.24 AB	0.20 B	1.49 B	5.43 AB	3.66 B	86.59 A	4.54 B
	40-60	4.90 A	0.13 B	1.14 A	5.04 AB	2.61 B	88.54 A	4.73 C
+LBa$_{NI}$	0-10	1.12 C	1.84 B	2.06 B	2.96 CD	61.00 B	11.51 F	5.16 B
	10-20	2.08 D	0.45 BC	1.56 B	2.53 E	17.69 B	71.23 CD	4.87 B
	20-40	3.61 C	0.22 B	1.28 BC	3.83 C	5.82 B	82.12 AB	4.88 AB
	40-60	3.55 BC	0.21 B	1.11 AB	3.76 C	5.77 B	80.33 AB	5.00 AB
+LBa$_{I}$	0-10	0.88 C	3.31 A	3.37 A	4.18 AB	79.01 A	1.88 G	5.98 A
	10-20	1.56 D	2.47 A	2.73 A	4.03 D	61.12 A	9.64 F	5.82 A
	20-40	3.01 C	2.30 A	3.22 A	5.31 AB	43.22 A	28.63 C	5.43 A
	40-60	3.46 C	0.72 A	1.36 A	4.18 BC	17.14 A	47.55 D	5.09 A
+LBr$_{NI}$	0-10	3.83 AB	0.53 C	1.38 BC	4.36 AB	12.64CD	62.39 DE	4.79 C
	10-20	5.28 B	0.54 B	1.23 BC	5.82 B	9.36 C	56.03 E	4.73 B
	20-40	5.13 AB	0.18 B	0.84 D	5.31 AB	3.46 B	78.46 AB	4.62 B
	40-60	4.48 AB	0.18 B	0.67 C	4.66 ABC	3.97 B	73.11 BC	4.74 C
+LBr$_{I}$	0-10	3.40 B	0.44 C	1.15 C	3.84 ABC	11.42 D	61.83 E	4.71 CD
	10-20	4.72 BC	0.38 BC	1.07 C	5.10 BC	7.44 CD	64.67 DE	4.76 B
	20-40	5.65 A	0.26 B	1.26 BC	5.91 A	4.39 B	79.32 AB	4.68 B
	40-60	5.24 A	0.17 B	0.66 C	5.41 A	3.20 B	74.22 BC	4.84 BC
+LBr$_{NI}$+GBa$_{NI}$	0-10	3.05 B	0.45 C	1.50 BC	3.50 BCD	12.87CD	70.04 CD	4.55 CD
	10-20	4.61 BC	0.34 BC	1.27 BC	4.95 BC	6.92 CDE	72.87 CD	4.50 B
	20-40	4.92 B	0.23 B	1.07 CD	5.14 AB	4.42 B	78.72 AB	4.41 B
	40-60	4.61 A	0.25 B	0.84 C	4.86 AB	5.07 B	70.87 BC	4.48 D

Continued…

+LBr$_{NI}$+GBr$_{NI}$	0-10	1.84 C	0.49 C	1.81 BC	2.33 D	21.34 C	72.62 C	4.68 CD
	10-20	3.97 C	0.44 BC	1.50 BC	4.41 CD	10.02 C	70.46 CD	4.56 B
	20-40	4.61 B	0.28 B	1.28 BC	4.90 B	5.81 B	77.72 AB	4.65 B
	40-60	4.74 A	0.23 B	1.33 A	4.97 AB	4.66 B	82.47 AB	4.77 BC

H+Al extracted with calcium acetate (0.5 mol L^{-1}) at pH=7.0; SB: sum of bases (SB = Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}); CEC: cation-exchange capacity [CEC = SB +Al^{3+}]; CEC $_{pH=7.0}$ = cation-exchange capacity at pH = 7.0 [CEC $_{pH=7.0}$ = CSB + (H+Al); V: base saturation [V = (SB/ CEC $_{pH=7.0}$) × 100]; m: aluminum saturation [m = (Al^{3+}/CEC) x 100]; pH in water (1:2.5 v v^{-1}).

Supplementary material 2. Soil H+Al, S, CEC, CEC $_{pH=7.0}$ (cmol$_c$ dm^{-3}) and V, m (%) and pH to different soil layers (0-10, 10-20, 20-40 and 40-60 cm) in the clay soil under eucalypt plantation without (-L) or with (+L) Limestone application, in band (Ba) or broadcast (Br), incorporated (I) or non-incorporated (NI). Furthermore, gypsum application (+G) in band (Ba) or broadcast (Br) with limestone application in broadcast (+L). Different capital letters denote significant differences among the treatments to 0-10, 10-20, 20-40 and 40-60 cm soil layer by the Tukey's test (*α=0.05*)

Treatment	Depth	H+Al	S	CEC	CEC $_{pH=7.0}$	V	m	pH
	... cm ...	.... cmol$_c$ dm^{-3}				...... %		
$-LBa_{NI}$	0-10	4.53 A	1.76 D	2.54 D	6.30 BC	27.15 F	30.29 A	4.48 D
	10-20	6.56 A	0.77 F	2.44 G	7.33 BC	11.22 G	68.62 A	4.70 D
	20-40	5.65 AB	0.47 C	2.23 E	6.12 A	7.36 F	78.61 A	4.73 C
	40-60	4.65 AB	0.48 D	2.51 BC	5.13 CD	8.54 C	80.48 A	4.62 D
$-LBa_{I}$	0-10	3.32 BC	5.22 C	5.99 BC	8.54 A	61.12 CD	12.81 B	4.89 BCD
	10-20	4.68 B	2.07 E	2.96 DEF	6.76 C	30.68 E	29.95 CD	4.71 D
	20-40	4.80 CD	1.12 BC	2.55 CDE	5.92 A	20.17 CD	56.07 B	5.07 BC
	40-60	4.52 AB	0.52 D	2.20 C	5.04 D	10.27 C	76.26 AB	4.86 D
$-LBr_{I}$	0-10	3.77 ABC	4.58 C	4.70 C	8.35 AB	57.25 D	2.57 C	4.79 CD
	10-20	5.16 B	1.62 E	2.73 FG	6.78 C	22.05 F	40.29 BC	4.85 CD
	20-40	5.24 ABC	1.06 BC	2.57 CDE	6.29 A	16.75 DE	58.97 B	5.18 BC
	40-60	4.90 A	0.88 CD	2.46 BC	5.78 BCD	13.96 C	64.83 B	4.94 CD
$+LBa_{NI}$	0-10	1.12 E	6.96 AB	7.00 AB	8.07 ABC	86.16 A	0.60 C	5.41 ABC
	10-20	2.08 D	5.86 B	5.95 B	7.94 AB	73.65 B	1.62 F	5.87 AB
	20-40	3.39 E	3.24 A	3.59 ABC	6.63 A	50.53 A	10.21 D	6.55 A
	40-60	3.55 C	2.90 A	3.33 AB	6.45 AB	48.73 A	13.40 E	5.88 AB
$+LBa_{I}$	0-10	0.88 E	8.23 A	8.27 A	9.11 A	90.33 A	0.50 C	6.10 A
	10-20	1.56 D	7.05 A	7.10 A	8.61 A	81.92 A	0.70 F	6.46 A
	20-40	3.01 E	3.91 A	4.39 A	6.92 A	54.02 A	10.76 D	6.43 A
	40-60	3.77 BC	3.51 A	4.03 A	7.28 A	48.19 A	12.66 E	6.33 A
$+LBr_{NI}$	0-10	3.83 AB	5.24 C	5.36 BC	9.08 A	57.82 D	2.39 C	4.67 CD
	10-20	5.28 B	1.66 E	3.28 DE	6.94 C	23.94 F	49.07 B	4.74 D
	20-40	5.89 A	0.60 C	2.45 DE	6.49 A	9.19 EF	75.45 A	5.42 BC
	40-60	4.48 AB	0.64 D	2.49 BC	5.12 CD	14.04 C	74.17 AB	5.17 BCD
$+LBr_{I}$	0-10	3.40 BC	2.54 D	2.91 D	5.94 C	42.78 E	12.61 B	5.23 BCD
	10-20	4.72 B	2.25 DE	3.39 DE	6.97 BC	33.97 E	33.68 C	4.85 CD
	20-40	5.65 AB	1.26 BC	2.81 BCDE	6.91 A	20.66 CD	56.18 B	5.08 BC
	40-60	5.24 A	0.54 D	2.24 C	5.77 BCD	10.62 C	75.84 AB	5.05 CD
$+LBr_{NI}+GBa_{NI}$	0-10	2.72 CD	5.56 BC	5.44 BC	8.27 AB	67.19 BC	0.00 C	5.27 BCD
	10-20	4.49 BC	2.95 D	3.66 CD	7.44 BC	39.60 D	19.38 DE	5.27 BCD
	20-40	4.92 BCD	1.82 B	3.72 AB	6.74 A	26.88 BC	51.27 BC	5.37 BC
	40-60	4.61 AB	1.47 BC	2.85 BC	6.08 BC	24.11 B	48.32 C	5.30 BCD

Continued…

+LBr_{NI}+GBr_{NI}	0-10	1.84 DE	5.06 C	4.95 C	6.90 ABC	73.24 B	0.00 C	5.71 AB
	10-20	3.80 C	3.89 C	4.37 C	7.68 ABC	50.59 C	11.05 EF	5.41 BC
	20-40	4.43 D	2.03 B	3.33 ABCD	6.47 A	31.28 B	39.51 C	5.86 AB
	40-60	4.74 A	1.81 B	2.59 BC	6.54 AB	27.46 B	30.49 D	5.66 ABC

H+Al extracted with calcium acetate (0.5 mol L^{-1}) at pH=7.0; SB: sum of bases (SB = Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}); CEC: cation-exchange capacity [CEC = SB +Al^{3+}]; $CEC_{pH=7.0}$ = cation-exchange capacity at pH = 7.0 [$CEC_{pH=7.0}$ = CSB + (H+Al); V: base saturation [V = (SB/ $CEC_{pH=7.0}$) × 100]; m: aluminum saturation [m = (Al^{3+}/CEC) x 100]; pH in water (1:2.5 v v^{-1}).

Supplementary material 3. Nutrient use efficiency (NUE) (kg of dry biomass kg of nutrient accumulated in the shoot biomass^{-1}) to Leaves, Branches, Barks, Wood and Total shoot biomass of the eucalypt plantation in the Sandy loam soil under plantation without (-Limestone) or with (+Limestone) Limestone application banded (Ba) or broadcasted (Br), incorporated (I) or non-incorporated (NI). Furthermore, gypsum application (+Gypsum) in band (Ba) or broadcast (Br) with limestone application in broadcast (+L). Different capital letters denote significant differences among the treatments by the Tukey's test (*α=0.05*)

Plant components	Nutrients	-Gypsum							+Gypsum	
									Ba	Br
		-Limestone			+Limestone					
		Ba		Br	Ba		Br		Br	
		NI	I	I	NI	I	NI	I	NI	NI
Leaves	N	66.19 C	71.31 BC	69.15 BC	83.59 A	78.36 AB	82.40 A	83.53 A	76.44ABC	71.44 BC
	P	1139.85 AB	1246.99 A	1162.68 AB	1208.67 AB	1198.46 AB	1101.32 AB	1209.73 AB	1095.93 AB	1058.66 B
	K	125.43 EF	118.44 F	136.88 DE	182.78 A	167.04 ABC	164.12 BC	182.95 A	172.06 AB	149.77 CD
	Ca	331.61 A	313.90 A	316.94 A	212.04 B	202.23 B	210.91 B	213.48 B	201.14 B	193.40 B
	Mg	849.25 B	666.65 C	973.71 A	365.55 D	347.40 D	336.24 D	329.93 D	340.39 D	342.91 D
	S	891.29 AB	858.04 BC	893.74 AB	972.17 A	938.33 AB	885.43 B	918.95 AB	790.66 CD	758.73 D
Branches	N	341.68 EF	294.47 F	312.18 F	391.33 DE	436.60 CD	387.94 DE	479.09 BC	558.08 A	501.87 AB
	P	3924.21 B	2917.12 C	3170.43 C	4877.35 A	4892.18 A	4765.59 A	4192.83 AB	4785.90 A	3518.84 BC
	K	381.64 B	378.96 B	476.77 A	362.57 B	331.52 BC	342.39 BC	352.21 B	362.19 B	293.67 C
	Ca	745.99 B	753.86 B	956.11 A	561.61 C	436.98 D	271.28 E	351.05 DE	307.92 E	256.47 E
	Mg	2056.30 B	2037.35 B	3426.53 A	386.91 C	414.56 C	466.52 C	432.19 C	469.06 C	580.08 C
	S	5123.78 B	5004.10 B	5016.22 B	6672.03 A	5255.75 B	5374.51 B	4791.68 BC	4762.57 BC	3995.21 C

Continued…

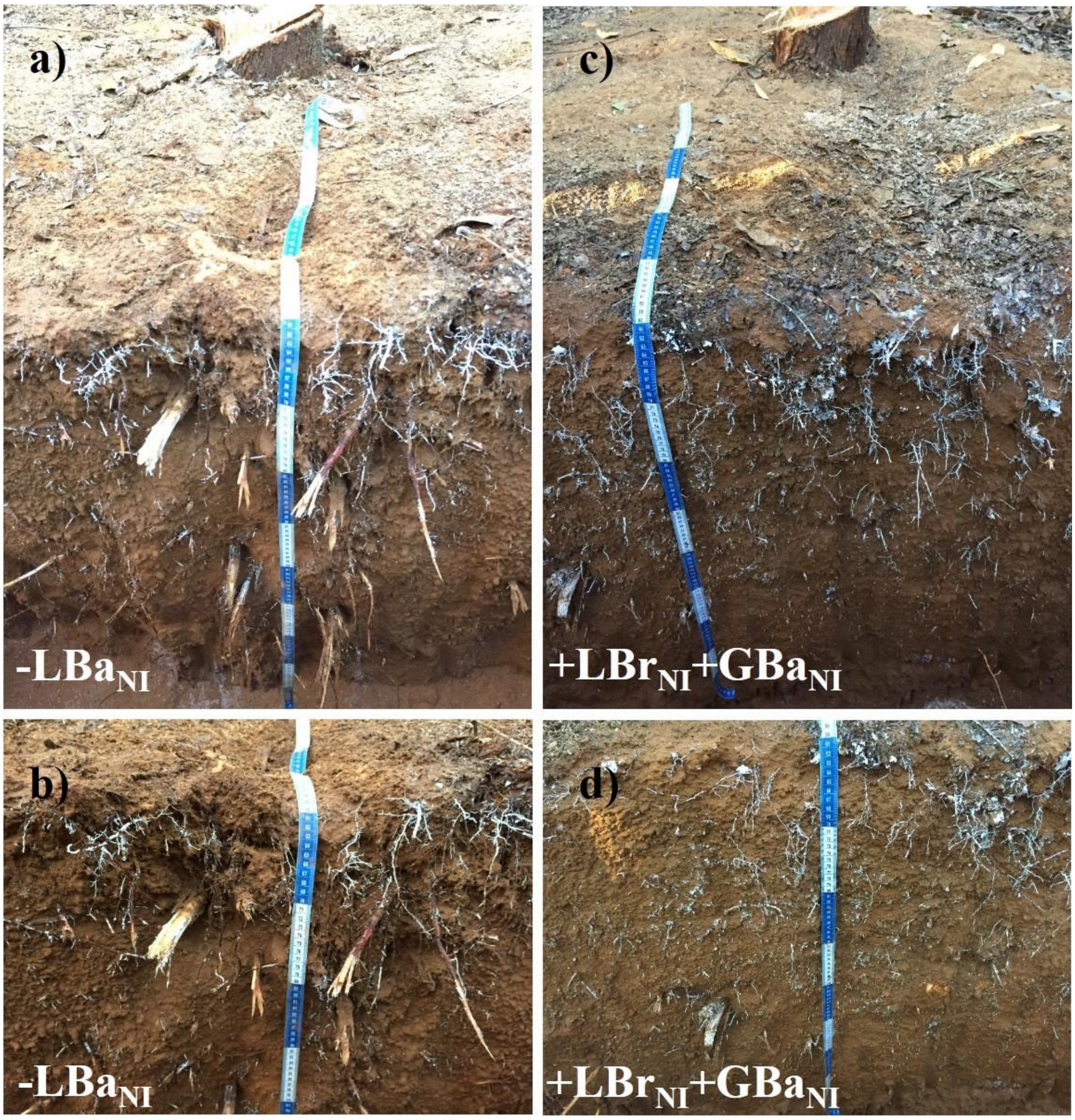
Barks	N	419.69 A	432.32 A	434.41 A	343.57 C	362.68 BC	397.62 ABC	396.29 ABC	356.01 BC	408.41 AB
	P	3140.99 AB	2138.45 D	2870.28 BC	2475.26 CD	1958.62 D	2070.19 D	3121.65 AB	2544.7 BCD	3559.19 A
	K	246.1 ABCD	196.94 E	270.96 AB	238.38 BCD	235.87 CD	213.16 DE	262.68 ABC	217.70 DE	275.65 A
	Ca	548.71 A	458.80 B	541.11 A	148.13 C	104.46 CD	135.81 C	126.92 CD	81.89 D	106.76 CD
	Mg	2993.17 A	3014.35 A	2424.54 B	604.29 C	541.75 C	410.46 C	551.45 C	569.10 C	559.73 C
	S	4023.57 A	3884.23 AB	4292.91 A	4227.66 A	4240.11 A	3850.36 AB	3960.15 AB	3396.56 C	3575.87 BC
Wood	N	954.38 C	1047.92 AB	915.93 C	1039.21 AB	1059.52 AB	924.39 C	1010.57 B	1059.45 AB	1070.41 A
	P	11632.74 E	10852.79 F	12250.40 DE	13626.12 B	13724.11 B	11669.30 DE	15757.77A	12915.38 C	12266.13 D
	K	2059.51 A	1907.34 B	1902.89 C	1632.32 F	1570.90 G	1418.53 H	1760.16 D	1725.41 E	1570.58 G
	Ca	4900.69 A	4727.24 B	3799.72 C	2492.09 E	2595.83 D	1831.88 H	2244.87 F	2528.29 E	2162.09 G
	Mg	17221.49 A	11854.33 C	16074.58 B	9085.25 D	8767.81 DE	6415.33 G	6677.93 G	7968.30 F	8642.27 E
	S	6807.67 CD	6326.04 E	8817.62 A	8063.17 B	7223.04 C	6498.69 DE	8218.90 B	6330.75 E	6502.23 DE
Total Shoot biomass	N	574.20 BC	577.86 BC	535.44 C	615.79 ABC	647.84 AB	646.22 AB	642.89 AB	708.94 A	642.99 AB
	P	6672.29 G	6153.26 I	6299.47 H	6957.06 F	7035.51 E	7498.47 D	8323.25 A	7676.45 B	7592.75 C
	K	794.71 BCD	692.35 E	772.75 CDE	789.7 BCDE	817.9 ABCD	747.39 DE	885.04 AB	868.08 ABC	913.01 A
	Ca	1893.80 A	1662.52 B	1669.55 B	826.09 C	670.70 CD	666.39 CD	693.24 CD	541.21 D	673.80 CD
	Mg	6823.03 A	5310.78 C	6378.20 B	2296.10 DE	2183.94 DE	2049.66 E	2128.34 DE	2065.48 E	2378.36 D
	S	5198.54 E	4722.40 I	5761.92 B	5574.91 C	5537.99 D	5083.27 F	5905.24 A	4831.24 H	5069.49 G

Supplementary material 4. Nutrient use efficiency (NUE) (kg of dry biomass kg of nutrient accumulated in the shoot biomass^{-1}) to Leaves, Branches, Barks, Wood and Total shoot biomass of the eucalypt plantation in the Clay soil under plantation without (-Limestone) or with (+Limestone) Limestone application, in band (Ba) or broadcast (Br), incorporated (I) or non-incorporated (NI). Furthermore, gypsum application (+Gypsum) in band (Ba) or broadcast (Br) with limestone application in broadcast (+L). Different capital letters denote significant differences among the treatments by the Tukey's test (*α=0.05*)

Plant components	Nutrients	-Gypsum							+Gypsum	
									Ba	Br
		-Limestone			+Limestone					
		Ba		Br	Ba		Br		Br	
		NI	I	I	NI	I	NI	I	NI	NI
Leaves	N	54.23 AB	60.35 A	53.22 AB	53.58 AB	49.22 B	56.20 AB	53.70 AB	55.46 AB	52.72 AB
	P	1060.81 AB	926.79 BC	940.08 BC	1128.39 A	867.35 C	959.07 BC	974.42 BC	1063.73 AB	933.76 BC
	K	113.18 AB	109.81 BC	102.13 BC	130.73 A	100.25 BC	109.44 BC	93.19 C	104.49 BC	103.10 BC
	Ca	243.41 AB	245.75 A	221.81 AB	237.76 AB	227.98 AB	223.66 AB	204.10 B	228.45 AB	214.45 AB
	Mg	322.6 ABCD	363.85 A	326.0 ABCD	330.85 ABC	279.14 CD	298.53 BCD	356.76 A	345.42 AB	274.37 D
	S	945.16 AB	1023.76 A	793.86 CDE	921.10 ABC	812.96 CDE	851.70 BCD	852.71 BCD	767.15 DE	688.66 E
Branches	N	440.69 DE	457.14 CDE	616.67 AB	409.38 E	687.79 A	515.03 CD	542.00 BC	553.02 BC	508.01 CD
	P	7560.19 E	5641.80 H	7650.17 D	9388.09 B	7106.66 G	7183.25 F	8098.26 C	11749.14 A	5179.49 I
	K	407.55 ABCD	318.53 D	448.91 ABC	477.08 AB	390.06 ABCD	497.30 A	369.95 BCD	419.36 ABCD	338.27 CD
	Ca	322.94 B	188.68 E	194.63 DE	262.22 C	380.00 A	287.71 BC	179.74 E	239.24 CD	240.77 CD
	Mg	1017.51 BC	800.55 CD	1097.59 B	928.81 BCD	743.09 D	860.00 CD	835.79 CD	1434.30 A	971.37 BCD
	S	8459.09 AB	7564.91 B	8806.46 AB	8093.63 AB	10161.05 A	8537.73 AB	8657.73 AB	7834.50 AB	6712.52 B

Continued…

Barks	N	351.68 BC	362.85 ABC	307.86 C	420.13 A	346.38 BC	400.90 AB	355.99 BC	378.43 AB	358.07 BC
	P	2016.77 CD	1917.97 DE	2916.54 A	1574.70 EF	1855.29 DE	2315.80 BC	2366.36 BC	1391.51 F	2423.87 B
	K	144.76 AB	120.96 B	160.22 A	145.55 AB	167.90 A	164.60 A	153.28 A	163.82 A	166.09 A
	Ca	149.42 A	86.49 D	95.24 CD	119.33 B	97.39 CD	96.72 CD	109.75 BC	106.93 BC	82.02 D
	Mg	528.64 ABC	441.67 CD	598.06 A	454.99 CD	429.74 D	447.73 CD	487.77 BCD	550.25 AB	501.42 BCD
	S	4536.68 AB	4264.30 AB	4928.07 A	4261.53 AB	4299.30 AB	4797.59 AB	4453.72 AB	4361.80 AB	4032.35 B
Wood	N	916.78 E	643.03 F	840.83 E	1138.07 BC	1086.00 CD	1078.02 CD	959.61 DE	1500.86 A	1260.18 B
	P	12859.22 F	14181.57 E	12052.63 H	14198.34 D	14182.26 E	14231.40 C	15523.81 A	14552.31 B	12114.79 G
	K	1451.63 A	1120.55 BC	1056.32 BC	1185.04 BC	1195.43 B	1088.49 BC	1123.72 BC	1144.20 BC	1020.16 C
	Ca	2718.58 A	2469.68 AB	2138.33 BC	1533.97 D	2112.44 BC	1820.30 CD	2102.62 BC	1628.99 D	1787.16 CD
	Mg	8475.00 B	6945.25 F	8755.51 A	6470.04 G	7555.46 C	6374.13 H	7059.85 E	7219.55 D	5227.65 I
	S	6842.44 A	5933.42 ABC	6091.16 AB	5466.00 BC	5301.04 BC	5873.85ABC	5124.04 BC	4637.95 C	5214.15 BC
Total Shoot biomass	N	573.29 C	562.69 C	589.67 C	691.97 AB	691.29 AB	618.14 BC	629.95 BC	750.94 A	710.74 AB
	P	6795.66 C	7181.18 BC	7868.75 B	7690.48 BC	7412.43 BC	7941.89 B	8937.02 A	7155.19 BC	7460.02 BC
	K	573.55 AB	527.04 B	594.26 AB	584.04 AB	643.81 A	623.15 A	595.60 AB	566.26 AB	589.15 AB
	Ca	736.19 A	614.61 BC	641.68 BC	650.81 ABC	596.97 C	604.77 C	696.77 AB	564.99 C	568.00 C
	Mg	2374.11 BC	2003.54 D	2774.93 A	2242.51 CD	2389.53 BC	2283.23 BCD	2581.27 AB	2517.66 ABC	2228.04 CD
	S	5674.42 A	5349.82 AB	5402.54 AB	4970.69 B	3977.75 E	5223.13 AB	4850.27BCD	4224.46 DE	4513.44 CDE



Supplementary material 5. Trench for visualization of root exploration in sandy loam soil profile without limestone application (-LBa$_{NI}$; a-b) and with limestone and gypsum combined application (+LBr$_{NI}$+GBa$_{NI}$; c-d).

Supplementary material 6. Visual root exploration in sandy loam soil surface without limestone application (-LBa_{NI}; a-b) and limestone and gypsum combined application (+LBr_{NI}+GBa_{NI}; c-d).