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Residual Influence of Nitrogen, Phosphorus and Potassium Doses on Soil and Eucalyptus Nutrition in Coppice

Natasha Mirella Inhã Godoi [1], Rodolfo de Niro Gazola [2], Salatiér Buzetti [2], Arshad Jalal [2],
Thiago de Souza Celestrino [2], Carlos Eduardo da Silva Oliveira [1], Thiago Assis Rodrigues Nogueira [2],
Alan Rodrigo Panosso [3] and Marcelo Carvalho Minhoto Teixeira Filho [2,*]

[1] Postgraduate Program in Agronomy, Faculty of Engineering (FEIS), São Paulo State University (UNESP), Ilha Solteira, SP 15385-000, Brazil; natashagodoi@bol.com.br (N.M.I.G.); ces.oliveira@unesp.br (C.E.d.S.O.)

[2] Department of Plant Protection, Rural Engineering and Soils, Ilha Solteira Faculty of Engineering (FEIS), São Paulo State University (UNESP), Ilha Solteira, SP 15385-000, Brazil; rodolfo.gazola@unesp.br (R.d.N.G.); salatier.buzetti@unesp.br (S.B.); arshad.jalal@unesp.br (A.J.); thiagocelestrino@yahoo.com.br (T.d.S.C.); tar.nogueira@unesp.br (T.A.R.N.)

[3] Department of Engineering and Exact Sciences, Faculty of Agricultural and Veterinary Sciences, São Paulo State University (UNESP), Jaboticabal, SP 14884-900, Brazil; alan.panosso@unesp.br

* Correspondence: mcm.teixeira-filho@unesp.br; Tel.: +55-18-3743-1940

Abstract: The management of fertilizer is an important strategy for better nutrition and productivity of eucalyptus. Therefore, the objective of this research was to evaluate the isolated residual effect (carryover) of N, P and K fertilization on macro- and micronutrients in soil, leaf litter, leaf nutritional diagnosis and initial growth attributes of eucalyptus in a coppice system. Three experiments were carried out in a randomized block design with five replications. Experiment 1: four residual doses of N (0, 70, 105 and 140 kg ha^{-1}) were applied as ammonium nitrate. Experiment 2: four residual doses of P2O5 (0, 40, 70 and 100 kg ha^{-1}) were applied to plantations in furrows using triple superphosphate. Experiment 3: four residual K$_2$O doses (0, 90, 135 and 180 kg ha^{-1}) were applied as potassium chloride. The residual N doses did not influence leaf nutrient contents and initial growth of eucalyptus; however, increasing P residual doses increased soil P and Zn content, litter K content, decreased leaf Mg content, and increased initial growth (height and wood volume of eucalyptus). The residual K doses increased leaf litter K content and leaf Mn and Zn content but decreased leaf litter Ca, B and Fe and leaf Mg content. Residual potassium fertilization did not significantly influence the initial growth of eucalyptus in the Brazilian Cerrado.

Keywords: *Eucalyptus urophylla* × *E. grandis*; residual fertilization; eucalyptus regrowth; low fertility soil; nutritional status of plants

1. Introduction

The total planted forest area of Brazil in 2019 corresponded to 9.0 million hectares. Of this, eucalyptus was planted over 77% of the forested area (6.97 million hectares) [1]. The forest industry generated a total revenue of 18.2 billion USD, corresponding to 1.2% of national GDP in 2019. Further investments of approximately 6.73 billion USD in expansion and new plants is expected [1]. The planted forest industry has a high impact on the social and economic sector of Brazil, as it works along the production chain to generate employment and income, in addition providing rural producers with attractive investment potential. However, the activity of eucalyptus plantation is still little explored in terms of its productive capacity and land availability [2].

The coppice system is characterized by forest regeneration through sprouting of shoot stumps. This system can be an attractive alternative for small producers to meet their daily wood needs, or even for large companies to reduce their costs of renovation and re-plantation of forest [3]. Another benefit of eucalyptus sprouting in a coppice managed

system is the low cost of planting due to savings on the acquisition of seedlings and their planting. These advantages stimulated the interest of forest industries to use this management system for the planation of eucalyptus forests. The management of forests via clear cutting and regeneration shoot sprouting has the advantage of a high initial growth rate as compared to fresh plantations (first productive cycle) due to having an established root system that contains organic and inorganic reserves for immediate uptake [4].

Despite the apparent advantages, it has been recorded that many eucalyptus forests have shown a decrease in productivity in subsequent cycles; however, this decrease is not always associated with a reduction in the number of trunks of the original stand [5]. Faria et al. [6] found an average decrease in productivity of 52% from the first to the second productive cycle of eucalyptus due to nutrient export, especially potassium (K) export, in the first growth cycle, causing a reduction in soil fertility. However, fertilizers applied to eucalyptus plantations are ensuring an economic return on financial investments, for example phosphate fertilization could have a great effect on wood productivity, even at a low concentration in eucalyptus plants. Fertilization of eucalyptus is one of the most important strategies that contributes 30–50% of the gains in wood productivity in forest sites [6]. It is also worth noting that approximately 86% of the eucalyptus wood volume in the second cycle can be obtained from the supply of soil and root nutrient reserves while 14% of productivity was obtained due to mineral fertilization [7]. Therefore, proper fertilization in the first cycle of eucalyptus can fulfill almost all the nutritional demands of the second production cycle in the Cerrado region.

However, there is lack of relevant studies and recommendations on the residual influence of isolated applied N, P and K fertilizers in the first productive cycle of eucalyptus on the growth and productivity of subsequent cycles via coppice. The productivity and cycling of nutrients are favored by the availability of nutrients in the soil or even in the root system of the first cycle, which may help to better understand nutrient dynamics in eucalyptus growth cycles (planting and sprouting). Despite this, changes in the conditions of the forest site during the first cycle, such as the availability of nutrients, was altered by the export of harvesting wood, residual fertilizer, deposition, and the mineralization of forest residues arising throughout the first planting cycle, as well as root and plant litter decomposition. In this sense, increasing fertilizer doses can result in greater productivity of the first cycle of eucalyptus by increasing nutrient availability, mainly in the soil conditions under study. However, an increase in productivity implies a greater accumulation of nutrients and nutrient exportation in the form of wood harvesting, which reinforces the importance of fertilization for the subsequent cycles. The fertilization of eucalyptus production cycles must be different for replanting or sprouting. Thus, the hypothesis of this research is that there may be a positive residual effect of nitrogen, phosphate and potassium fertilization in the second productive cycle of eucalyptus.

In this context, the residual effect of fertilization with nitrogen, phosphorus and potassium from the first production cycle was studied in three different experiments in order to evaluate the macro- and micronutrient contents of the soil, leaf nutritional diagnosis and leaf litter, along with the initial growth parameters of eucalyptus in a coppice system in the Brazilian Cerrado.

2. Materials and Methods

2.1. Location and Climate

The experiments were conducted from May 2018 to April 2019 at Renascença Farm, an agricultural (eucalyptus) area managed by Cargill Agrícola S/A, geographically located at 20°34' S, 51°50' W with an average altitude of 305 m in the municipality of Três Lagoas, State of Mato Grosso do Sul, Brazil (Figure 1). The experimental area was originally occupied by natural vegetation, mainly by plants from the Cerrado biome, after which this area was cultivated with Brachiaria (*Urochloa decumbens*) as a pasture for around twenty years before the plantation of eucalyptus in 2011. Animals graze in this area to consume forage grasses.
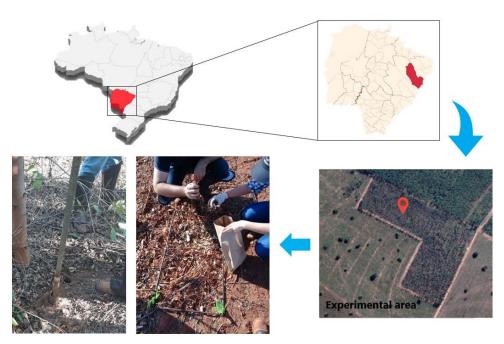
Figure 1. Study area at Três Lagoas, State of Mato Grosso do Sul, Brazil (20°34′ S, 51°50′ O, and altitude of 305 m). The map was created by using geographic information system (QGIS) software and the Google Earth program. Accessed on 2 August 2021. This image was taken from Google Earth, Google Company (2021). Map data: Google, Maxar Technologies.

The soil is classified as an Arenosol according to the World Reference Base for Soils (WRB) or an orthosic Quartzarenic Neosol (Entisols) according to Brazilian soil classification [8]. The climate in the region is Aw according to the Köppen–Geiger classification system [9], and is characterized as humid and tropical with a rainy season in the summer and a dry season in the winter. The mean temperature and rainfall are 24.2 °C and 1240 mm per year, respectively.

Prior to the establishment of the first eucalyptus cycle, soil samples were collected at depths of 0–20 and 20–40 cm to determine the soil's chemical attributes according to the methodology of Raij et al. [10]. The chemical attributes at a depth of 0–20 cm were: pH $CaCl_2$ 4.2; organic matter (OM) 7.4 g dm^{-3}; P resin 1 mg dm^{-3}; and the K, Ca, Mg, H + Al and Al contents were 0.2, 4.2, 1.9, 17.0 and 4.3 $mmol_c$ dm^{-3}, respectively, with a base saturation (V%) of 27%. At a depth of 0.20–0.40 m, the chemical attributes were: pH $CaCl_2$ of 4.2; OM 6.8 g dm^{-3}; P resin 1 mg dm^{-3}; the K, Ca, Mg, H + Al and Al contents were 0.3, 1.6, 1.1, 18.0 and 4.5 $mmol_c$ dm^{-3}, respectively, with a V% of 14%. The granulometric analysis showed that the soil of the experimental site was composed of clay (43.9%), sand (47.1%), and slit (9.0%).

2.2. Management History

The experimental area prior to the plantation of the first cycle was covered with 1500 kg ha^{-1} of limestone (PRNT 80%—dolomitic limestone) and 500 kg ha^{-1} of gypsum in September 2011. Then, the soil was prepared in January 2012 using a subsoiler to make planting furrows for eucalyptus at a depth of 45 cm. The planting of eucalyptus hybrid seedlings [*Eucalyptus urophylla* × *E. grandis* (clone I144)] was carried out in January 2012 (first cycle) with a spacing of 3.0 × 2.5 m. Each plot consisted of 56 plants, distributed in seven rows of eight plants each with a 420 m^2 plot size.

The treatments of the experiment with phosphate fertilization were fully applied at the time of planting eucalyptus. The treatments applied in the experiments with nitrogen and potassium fertilization were split at two, nine and 14 months after planting, respectively. More details will be described in subtopic 2.3. The first cycle harvest of the experimental area was carried out in May 2018, when the plants were 6 years and four months old.

Following this operation, the stumps were covered with clean plant residue within a radius of 0.15 m from the edge of the stump in order to prevent shoot emissions from harm.

The thinning was carried out when shoots reached an average height of 2.5–3.0 m (October 2018). Studies showed that shoots defined in this medium range height favor resistance to wind action (shoots at this stage are strong enough to withstand the mechanical action of the wind) regardless of the number of shoots to be chosen per stump. The two most vigorous shoots were selected, which are located at the upper part of the stump (upper side of the stump) in all three experiments. The shoots that grow and develop closer to the cutting area of the stump have low falling and tipping rates and provide better "fixation", while the shoots located on the lower side of the stump, close to the soil surface, break, drop or are pulled out easily in the case of contact with machinery and/or agricultural equipment.

2.3. Treatments and Experimental Design

2.3.1. Experiment 1—Nitrogen Fertilization

The experimental design was a randomized block with four treatments (residual of N doses: 0, 70, 105 and 140 kg ha^{-1}, using ammonium nitrate as N source) and five replications. At the time of planting, fertilization of 70 kg ha^{-1} of P_2O_5 (triple superphosphate) and 15 kg ha^{-1} of K_2O (potassium chloride) were applied while 49.5, 49.5 and 66 kg ha^{-1} of K_2O in coverage was applied two, nine and fourteen months, respectively, after plantation. The treatments were applied at four time points, one at planting and three in covers (at two, nine and 14 months after planting, respectively) in the form of ammonium nitrate. The application of N fertilizer followed the schedule: 0.0, 15.0, 15.0 and 15.0 kg N ha^{-1} at planting; 0.0, 16.5, 27.0 and 37.5 kg N ha^{-1} at two and nine months; and 0.0, 22.0, 36.0 and 50.0 kg N ha^{-1} at 14 months. The residual of N doses were evaluated after the first harvest in the second eucalyptus cycle.

2.3.2. Experiment 2—Phosphate Fertilization

The experimental design was a randomized block with four treatments (residual P_2O_5 doses: 0, 40, 70 and 100 kg ha^{-1} of P_2O_5) applied totally to planting furrows (using triple superphosphate as the source) and five replications. At the time of plantation, fertilization of 15 kg ha^{-1} of N (urea) and K_2O (potassium chloride) were applied, respectively. In topdressing fertilization, 37.5, 37.5 and 50 kg N ha^{-1} (ammonium nitrate) and 49.5, 49.5 and 66 kg K_2O ha^{-1} (potassium chloride) were applied at two, nine and fourteen months, respectively. Residual of P_2O_5 doses were evaluated after the first harvest in the second eucalyptus cycle.

2.3.3. Experiment 3—Potassium Fertilization

The experimental design was a randomized block with four treatments (residual doses of K_2O: 0, 90, 135 and 180 kg ha^{-1} of K_2O) and five replications. At the time of planting, fertilization of 70 kg ha^{-1} of P_2O_5 (triple superphosphate) and 15 kg ha^{-1} of N (urea) were applied while 37.5, 37.5 and 50 kg ha^{-1} of N were applied to the topdressing at two, nine and fourteen months, respectively, in the form of ammonium nitrate. The treatments were applied at four times: at plantation and two, nine and fourteen months after planting. The four planting times had the following schedule: 0.0, 15.0, 15.0 and 15.0 kg ha^{-1} of K_2O at planting; 0.0, 22.5, 36.0 and 49.5 kg ha^{-1} of K_2O at two and nine months; and 0.0, 30.0, 48.0 and 66.0 kg ha^{-1} of K_2O at 14 months using potassium chloride as a source. The residual of K_2O doses were evaluated after the first harvest in the second eucalyptus cycle.

2.4. Evaluations

2.4.1. Soil Chemical Analysis

Four soil samples were collected from each plot at the end of the first eucalyptus cycle seventy-six months after seedling plantation. The samples were collected between planting lines (crown projection—perpendicular to planting line at a distance of 0.50 m from plant)

except in experiment with P, in which samples were collected from the planting rows at a depth of 0–20 cm through a mug auger. These samples were homogenized to form a composite sample that was dried, passed through a 2 mm sieve and placed in labeled plastic bags. The chemical analysis followed the methodology described by Raij et al. [9]. The OM content in the soil was estimated by the Walkley–Black method. The amounts of P in the soil were estimated by an ion-exchange resin procedure with B in hot water and Cu, Fe, Mn, and Zn in DTPA. The concentration of P, Al, and B in the soil extracts was quantified by a colorimetric method. The Ca, Mg, Cu, Fe, Mn, and Zn concentrations were determined by an atomic absorption spectrophotometer (AAS) (VARIAN SpectrAA 220FS, NJ, USA) and the K using a flame-photometer (METEOR NAK-II, Stone, Staffordshire, UK). The available amount of S-SO$_4$ was estimated using a solution of calcium phosphate (Ca (H$_2$PO$_4$) 0.01 mol L^{-1}) and the quantification was determined by turbidimetry. The exchangeable aluminum was extracted with a 1 M KCl solution and determined by titration with 0.025 M of NaOH. The total acidity (H + Al) was extracted with a buffer solution of calcium acetate with a pH of 7.0 and determined by titration with ammonium hydroxide (0.025 M). From these values, the sum of bases (SB) {SB = Ca^{2+} + Mg^{2+} + K$^+$}, the total cation exchange capacity (CEC) at a pH of 7.0 (CEC = SB + (H + Al)), the saturation of exchangeable cations (V%) {V% = SB × 100)/CEC}, and the aluminum saturation (m%) {m% = (Al^{3+} × 100) / (SB + Al^{3+})} were obtained.

2.4.2. Leaf Litter

The collection of eucalyptus litter (forest waste that remained in the area after the first cycle harvest of eucalyptus) was carried out in July 2018. The litter samples were taken with the aid of a square wooden frame (0.5 × 0.5 m, totalizing 0.25 m^2). The frame was randomly thrown on the ground in each plot with three repetitions, the litter samples were brought together to form a composite sample.

The material obtained by frame was carefully dried and segregated to avoid soil impurities. Subsequently, the fractions were dried in an air-forced oven at 65 °C for 72 h and weighed on a precision scale (0.1 g). Litter productivity was estimated from litter dry mass (g) and values and are expressed in kg ha^{-1}.

After weighing, the samples of litter fractions were ground in a Willey mill and chemical analyses were subsequently carried out to determine the concentration of nutrients (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn and Zn) according to the methodology described by Malavolta et al. [11]. The determination of the N-total content occurred by sulfuric digestion followed by distillation by the micro-Kjeldahl method. After wet digestion of the dry material with nitric (HNO$_3$) and perchloric acid (HClO$_4$), the micronutrient concentration by atomic absorption spectrometry was used for Cu, Fe, Mn, and Zn determination. The azomethine H colorimetric method was used for B analysis.

2.4.3. Leaf Nutrients Diagnosis

Mature leaves of representative trees were collected from branches located in the middle part of crowns directed towards the four cardinal points as recommended by Haag et al. [12]. The collection of these leaves were carried out in March 2019 (five months after eucalyptus sprouts) in each plot. The leaves were dried, ground in a Willey mill and analyzed for the determination of leaf concentration of N, P, K, Ca, Mg, S, B, Cu, Fe, Mn and Zn according to the methodology of Malavolta et al. [11].

2.4.4. Measurements of DBH and Height of the Plant to Estimate Total Wood Volume

The measurement of circumference at breast height (CBH) at 1.30 m height of plants was carried out with the aid of a measuring tape in useful areas of all plots. Subsequently, the diameter at breast height (DBH) was obtained by means of Equation (1), while plant height was measured by Forestor Vertex hypsometer, USA, five months after sprouting (in March 2019). The wood volume with bark was estimated using DBH and plant height data using Equations (2) and (3), according to the methodology followed by Gazola et al. [13].

$$DBH = \frac{CBH}{\pi} \tag{1}$$

$$VW_i = \frac{\pi(DBH_i)^2 \cdot \text{ff} \cdot \text{Hi}}{4} \tag{2}$$

$$VW_B = \sum \frac{VW_i}{A_t} 1000 \tag{3}$$

where: VW_i = volume of wood with bark from each tree; A_t = useful area of plot; VW_B = total volume with bark (m^3 ha^{-1}); DBH_i = DBH from each tree (m); ff = form of factor—in this case, it is regionally defined for the clone used and a value of 0.5 was assigned; and H_i = total height of each tree (m).

2.5. Statistical Analysis

The results of the three experiments were statistically analyzed by analysis of variance (F test). The regression analysis for the effects of residual doses of N, P_2O_5 and K_2O were analyzed by SISVAR statistical program, Federal University of Lavras, Brazil [14]. The graphs were designed and plotted in Sigma Plot 12.5, Chicago, IL, USA.

3. Results

3.1. Soil Chemical Analysis

The soil nutrient contents at a depth of 0–20 cm after seventy-six months of eucalyptus plantation as a function of N, P_2O_5 and K_2O fertilization doses are shown in Tables 1 and 2. There was no residual effect of N dose on macronutrient (P, S, K, Ca and Mg) contents of the soil at a depth of 0–20 cm. The residual doses of P_2O_5 increased linearly the P content in the soil (Figure 2a).

Table 1. Mean soil macronutrient contents at a depth of 0–20 cm after seventy-six months of eucalyptus plantation as a function of N, P_2O_5 and K_2O fertilization doses.

N dose (kg ha^{-1})	P	S	K	Ca	Mg
	mg dm^{-3}			mmol$_c$ dm^{-3}	
0	5.33 [ns]	2.83 [ns]	0.33 [ns]	2.33 [ns]	1.67 [ns]
70	3.17	2.67	0.28	2.00	1.67
105	5.33	3.00	0.35	3.17	1.83
140	2.83	3.17	0.27	1.50	1.33
CV (%)	[†] 14.07	19.59	27.56	[†] 14.96	28.55
P$_2$O$_5$ dose (kg ha^{-1})					
0	1.83 *	3.00 [ns]	0.27 [ns]	2.00 [ns]	1.33 [ns]
40	3.33	2.50	0.27	1.83	1.50
70	2.83	3.17	0.27	1.50	1.33
100	9.17	2.67	0.35	2.50	1.67
CV (%)	[†] 22.54	19.29	26.57	[†] 12.44	27.40
K$_2$O dose (kg ha^{-1})					
0	4.00 [ns]	3.83 [ns]	0.23 [ns]	2.00 *	1.50 [ns]
90	9.50	2.67	0.30	3.83	2.67
135	5.00	2.83	0.33	2.67	2.00
180	2.83	3.17	0.27	1.50	1.33
C.V. (%)	[†] 27.91	[†] 14.34	15.84	[†] 16.13	[†] 16.86

* = significant at 5% level by F test; [ns] = not significant at 5% level by F test. [†]: Data corrected by equation $(x + 0.5)^{0.5}$.

Table 2. Mean soil micronutrient contents at a depth of 0–20 cm at seventy-six months after eucalyptus plantation as a function of N, P_2O_5, and K_2O fertilization rates.

N dose (kg ha^{-1})	B	Cu	Fe	Mn	Zn
	mg dm^{-3}				
0	0.26 [ns]	4.87 [ns]	15.50 *	5.83 [ns]	1.33 [ns]
70	0.23	1.85	16.67	4.57	1.35
105	0.31	6.20	18.17	4.90	1.42
140	0.32	1.53	14.50	4.10	1.32
CV (%)	14.01	[†] 30.72	7.03	28.47	[†] 12.26
P_2O_5 dose (kg ha^{-1})					
0	0.26 [ns]	2.18 [ns]	16.50 [ns]	5.07 [ns]	0.82 *
40	0.29	6.58	17.50	4.40	1.30
70	0.32	1.53	14.50	4.10	1.32
100	0.29	2.05	20.50	3.98	2.32
CV (%)	11.54	[†] 53.63	20.38	18.46	[†] 14.98
K_2O dose (kg ha^{-1})					
0	0.29 [ns]	0.82 [ns]	16.33 [ns]	3.00 [ns]	1.87 [ns]
90	0.27	2.18	16.67	4.63	2.32
135	0.27	1.97	20.67	7.35	1.23
180	0.32	1.53	14.50	4.10	1.32
CV (%)	14.37	[†] 33.14	14.21	[†] 12.82	[†] 20.27

B: determined in hot water; Cu, Fe, Mn and Zn: determined in DTPA. * = significant at 5% level by F test; [ns] = not significant at 5% level by F test. [†]: Data corrected by equation $(x + 0.5)^{0.5}$.
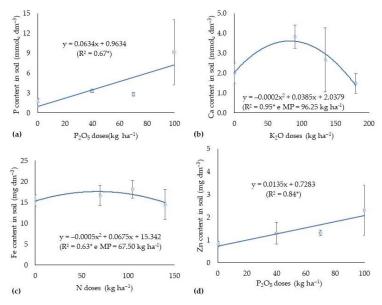

Figure 2. (**a**) Soil P content (0–20 cm) as a function of residual P_2O_5 dose. (**b**) Soil Ca content (0–20 cm) as a function of residual K_2O dose. (**c**) Soil Fe content (0–0.20 m) as a function of residual N dose. (**d**) Soil Zn content (0–0.20 m) as a function of residual P_2O_5 dose. Each point located on each graphic is a mean of five replications. * = significant at 5% level by F test.

3.2. Nutrient Contents in Leaf Litter and Leaves

The soil Ca content increased as a function of K_2O fertilization (Figure 2b), with the maximum optimal point (PM), which represents the highest soil Ca content (mmol$_c$ dm^{-3}), estimated at 96.25 kg ha^{-1} of K_2O.

The soil Fe content was adjusted to a quadratic function with an increasing N residual up to an estimated dose of 67.50 kg N ha^{-1} (Figure 2c). The other micronutrients (B, Cu, Mn and Zn) did not show regression adjustments with residual N doses.

The soil Zn content linearly increased with increasing residual P_2O_5 dose (Figure 2d). There is non-competitive inhibition between Zn and P in plants; however, increasing residual P_2O_5 dose in conjunction with plant litter favored an increase in soil Zn content. The contents of other micronutrients (B, Cu, Fe, and Mn) at a soil depth of 0–20 cm were not influenced by increasing residual doses of K_2O.

3.2.1. Leaf Litter

The macronutrient contents in eucalyptus leaf litter as a function of residual doses of N, P_2O_5 and K_2O are shown in Table 3. The residual N doses provided an adjustment to a quadratic function for N, Mg and S contents in leaf litter up to a maximum optimal dose of 68.83, 66.88 and 76.25 kg N ha^{-1}, respectively (Figure 3a). In addition, an increase in residual N doses also linearly increased K content in eucalyptus leaf litter (Figure 3b).

The residual doses of P_2O_5 was adjusted to increase the linear regression only for the K content of leaf litter (Figure 3e). For example, K content in eucalyptus litter was increased with increasing P dose. The other macronutrients (N, P, Ca, Mg, S) did not show regression adjustments following residual doses of P_2O_5.

The content of K in the litter showed a linear relationship with increasing residual doses of K_2O (Figure 3f). On the other hand, the Ca content in leaf litter was decreased with increasing residual K_2O doses (Figure 3g), confirming an antagonistic effect through competitive inhibition between these exchangeable bases during absorption.

Table 3. Macronutrient contents in eucalyptus leaf litter as a function of residual dose of N, P_2O_5 and K_2O.

N dose (kg ha^{-1})	N	P	K	Ca	Mg	S
	g kg^{-1}					
0	5.27 **	0.30 ns	3.03 **	6.63 ns	1.67 **	0.67 *
70	7.70	0.50	3.43	6.80	1.97	1.00
105	5.93	0.43	4.07	5.63	1.97	0.83
140	6.43	0.43	4.67	6.13	1.57	0.87
CV (%)	12.15	21.17	14.38	12.32	5.34	11.72
P_2O_5 dose (kg ha^{-1})						
0	5.50 ns	0.33 ns	2.67 **	6.17 ns	1.53 ns	0.77 ns
40	5.37	0.33	2.73	6.30	1.73	0.73
70	6.43	0.43	4.67	6.13	1.57	0.87
100	6.10	0.40	4.43	7.07	1.83	0.83
CV (%)	15.15	23.09	20.62	20.64	25.16	22.92
K_2O dose (kg ha^{-1})						
0	6.43 ns	0.47 ns	3.63 **	7.60 *	2.07 ns	0.90 ns
90	6.53	0.43	3.53	6.77	1.63	0.90
135	7.50	0.50	4.83	6.50	2.23	0.87
180	6.43	0.43	4.67	6.13	1.57	0.87
CV (%)	11.71	26.47	8.43	11.26	4.44	9.98

* and ** = significant at 5 and 1% level by F test, respectively; ns = not significant at 5% level by F test.

The contents of micronutrients in eucalyptus litters were increased with residual N fertilization doses (Table 4). The graph trend for B, Fe and Zn was adjusted to regression under N fertilization (Figure 4a–c). The increase in residual N doses showed quadratic regression adjustment to B content in leaf litter (Figure 4a) until the maximum optimal N dose of 75.19 kg ha^{-1}, where the highest B content in the litter is noted. While Zn and Fe contents in leaf litter of eucalyptus were also adjusted by a quadratic function under N fertilization (Figure 4b,c). The highest Fe content was obtained with increasing residual N doses up to an estimated dose of 78.22 kg N ha^{-1}, whereas the highest Zn content in the leaf litter of eucalyptus was observed at an estimated optimal N dose of 64.75 kg ha^{-1}.

The micronutrient contents in eucalyptus leaf litter as a function of residual P_2O_5 dose are shown in Table 4. There were no regression adjustments of micronutrients with P_2O_5 dose. However, increasing residual doses of K_2O linearly decreased B and Fe contents in eucalyptus leaf litter (Figure 4d,e).
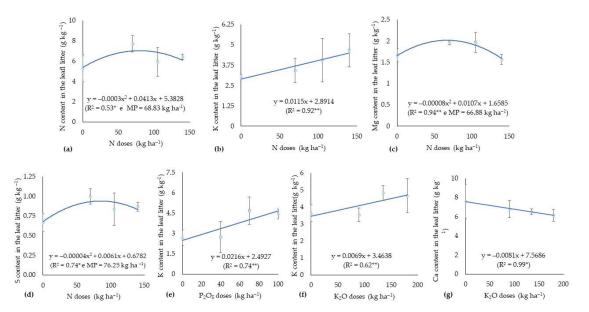

Figure 3. (**a**) Nitrogen, (**b**) potassium, (**c**) magnesium and (**d**) sulfur content in eucalyptus leaf litter as a function of residual N dose. (**e**) Potassium content in eucalyptus leaf litter as a function of residual P_2O_5 dose. (**f**) Potassium and (**g**) calcium content in eucalyptus leaf litter as a function of residual K_2O dose. Each point located on each graph is the mean of five replications. * and ** = significant at 5 and 1% level by F test, respectively.

Table 4. Micronutrient contents in eucalyptus leaf litter as a function of residual dose of N, P_2O_5 and K_2O.

N dose (kg ha^{-1})	B	Cu	Fe	Mn	Zn
	mg kg^{-1}				
0	28.00 *	11.67 [ns]	215.00 *	684.33 [ns]	11.33 **
70	41.00	12.00	496.67	739.67	14.67
105	32.00	13.00	318.33	755.33	15.00
140	33.00	13.33	337.33	702.00	9.67
CV (%)	13.21	[†] 16.68	29.92	14.65	13.22
P_2O_5 dose (kg ha^{-1})					
0	31.00 [ns]	11.00 [ns]	415.33 [ns]	763.00 [ns]	12.00 [ns]
40	37.33	12.33	216.00	757.33	9.67
70	33.00	13.33	337.33	702.00	9.67
100	35.00	12.67	380.00	786.67	14.00
CV (%)	13.26	[†] 21.48	25.26	24.33	[†] 23.61
K_2O dose (kg ha^{-1})					
0	46.67 **	10.67 [ns]	482.33 *	703.33 [ns]	9.00 [ns]
90	29.67	8.67	333.33	759.33	9.33
135	34.00	8.00	247.67	742.33	15.67
180	33.00	13.33	337.33	702.00	9.67
CV (%)	9.20	[†] 33.32	21.13	27.35	18.26

* and ** = significant at 5 and 1% level by F test, respectively; [ns] = not significant at 5% level by F test. [†] Data corrected by the equation $(x + 0.5)^{0.5}$.
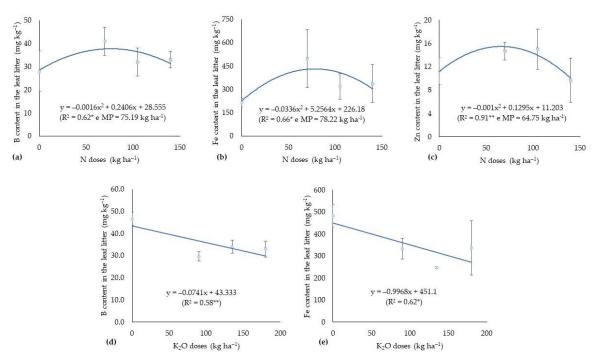
Figure 4. (**a**) Boron, (**b**) iron and (**c**) zinc content in eucalyptus leaf litter as a function of residual N dose. (**d**) Boron and (**e**) iron content in eucalyptus leaf litter as a function of residual K_2O dose. Each point located on each graph is the mean of five replications. * and ** = significant at 5 and 1% level by F test, respectively.

3.2.2. Leaf Nutrients Analysis

Leaf macronutrient content as a function of residual N, P_2O_5 and K_2O doses are shown in Table 5. There were no regression adjustments as a function of residual N doses for leaf macronutrients. The leaf Mg content in eucalyptus leaves decreased with an increasing dose of P_2O_5 (Figure 5a). The same relationship was observed between leaf Mg content and K_2O dose (Figure 5b).

Table 5. Macronutrient analysis in the leaves of eucalyptus at five months after shoot sprouting as a function of residual doses of N, P_2O_5 and K_2O.

N dose (kg ha^{-1})	N	P	K	Ca	Mg	S
	g kg^{-1}					
0	17.32 ns	1.22 ns	5.72 ns	6.52 ns	3.42 ns	1.40 ns
70	21.05	1.42	6.40	7.12	3.65	1.65
105	18.68	1.20	5.72	6.62	3.35	1.40
140	19.72	1.42	5.98	6.35	3.12	1.68
CV (%)	11.91	11.87	18.09	7.66	10.54	14.45
P_2O_5 dose (kg ha^{-1})						
0	20.80 ns	1.40 ns	6.70 ns	7.08 ns	3.40 *	1.52 ns
40	20.22	1.48	6.12	6.22	3.48	1.60
70	19.72	1.42	5.98	6.35	3.12	1.68
100	19.48	1.38	6.30	5.90	3.05	1.38
CV (%)	12.64	10.12	15.77	11.94	8.00	14.00
K_2O dose (kg ha^{-1})						
0	18.42 ns	1.28 ns	5.60 ns	7.58 ns	3.92 **	1.58 ns
90	18.85	1.32	5.58	6.92	3.50	1.58
135	19.38	1.30	6.35	6.75	3.42	1.50
180	19.72	1.42	5.98	6.35	3.12	1.68
CV (%)	9.26	11.08	19.00	13.11	9.23	16.67

* and ** = significant at 5 and 1% level by F test, respectively; ns = not significant at 5% level by F test.
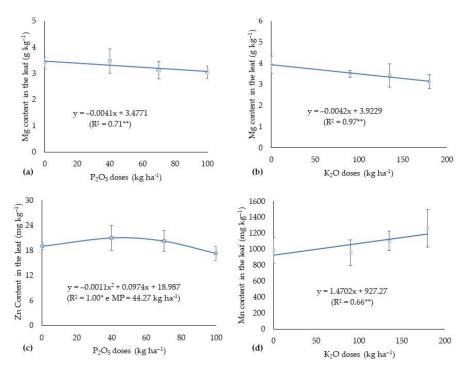
Figure 5. (**a**) Magnesium content in eucalyptus diagnosis leaves as a function of residual P_2O_5 dose. (**b**) Magnesium content in eucalyptus diagnosis leaves as a function of residual K_2O dose. (**c**) Leaf Zn content in eucalyptus diagnosis leaves as a function of residual dose of P_2O_5. (**d**) Leaf Mn content in eucalyptus diagnosis leaves under residual doses of K_2O. Each point located on each graph is the mean of five replications. * and ** = significant at 5 and 1% level by F test, respectively.

The leaf micronutrients contents as a function of residual doses of N, P_2O_5 and K_2O are shown in Table 6. There was a significant effect on leaf Zn content with residual doses of P_2O_5 up to 44.27 kg P_2O_5 ha^{-1} (Figure 5c). In addition, leaf Mn content increased linearly with increasing residual K_2O dose (Figure 5d).

Table 6. Micronutrient contents in the leaves of eucalyptus at five months after the definition of the sprouts as a function of the residual doses of fertilization with N, P_2O_5 and K_2O.

N dose (kg ha^{-1})	B	Cu	Fe	Mn	Zn
	mg kg^{-1}				
0	38.00 [ns]	5.50 [ns]	59.50 [ns]	1064.75 [ns]	17.50 [ns]
70	42.25	6.75	53.50	979.50	18.75
105	48.00	5.75	54.50	1185.00	17.25
140	39.50	6.00	62.50	1261.50	20.25
CV (%)	16.29	11.11	13.72	17.26	7.68
P_2O_5 dose (kg ha^{-1})					
0	43.50 [ns]	6.50 [ns]	53.75 [ns]	1295.25 [ns]	19.00 *
40	35.50	6.25	68.00	1288.00	21.00
70	39.50	6.00	62.50	1261.50	20.25
100	39.75	5.75	66.25	1062.00	17.25
CV (%)	15.93	11.22	21.00	13.86	9.46
K_2O dose (kg ha^{-1})					
0	44.00 [ns]	7.00 [ns]	54.00 [ns]	985.00 **	20.25 [ns]
90	38.75	5.75	49.75	956.00	18.75
135	38.50	5.25	63.00	1102.00	19.00
180	39.50	6.00	62.50	1261.50	20.25
CV (%)	9.89	15.71	19.23	7.52	8.09

* and ** = significant at 5 and 1% level by F test, respectively; [ns] = not significant at 5% level by F test.

3.3. Analysis of Initial Growth (Diameter at Breast Height, Height and Total Wood Volume)

The initial growth of eucalyptus was evaluated ten months after the first cycle of harvesting (or after five months of eucalyptus shoot sprouting) by quantifying plant height, DBH and estimated wood volume as a function of residual doses of N, P_2O_5 and K_2O (Table 7). There was no regression adjustment for growth assessments as a function of N dose and K_2O dose.

Table 7. Initial growth of eucalyptus after five months of eucalyptus shoot sprouting, diameter at breast height (DBH), plant height (H) and total wood volume (VW_B) as a function of residual dose of N, P_2O_5 and K_2O.

N dose (kg ha^{-1})	DBH	H	VW_B
	cm	m	m^3 ha^{-1}
0	3.60 ^{ns}	4.90 ^{ns}	6.70 ^{ns}
70	3.67 ^{ns}	5.04 ^{ns}	7.24 ^{ns}
105	3.43 ^{ns}	4.90 ^{ns}	6.06 ^{ns}
140	3.61 ^{ns}	4.98 ^{ns}	6.81 ^{ns}
CV (%)	6.45	5.32	† 16.33
P_2O_5 dose (kg ha^{-1})			
0	3.53 ^{ns}	4.80 *	6.29 *
40	3.55 ^{ns}	4.80	6.69
70	3.61 ^{ns}	4.98	6.81
100	3.99 ^{ns}	5.26	8.90
CV (%)	10.26	4.63	24.24
K_2O dose (kg ha^{-1})			
0	3.44 ^{ns}	4.54 ^{ns}	6.06 ^{ns}
90	3.39	4.65	6.38
135	3.56	4.83	6.59
180	3.61	4.98	6.81
CV (%)	19.13	14.47	22.50

* and ** = significant at 5 and 1% level by F test respectively; ^{ns} = not significant at 5% level by F test. † Data corrected by equation $(x + 0.5)^{0.5}$.

Plant height and wood volume of eucalyptus showed an increasing linear adjustment with increasing P fertilization (Figure 6a,b). Therefore, plant height and total wood volume of eucalyptus plants increased with an increasing dose of P_2O_5.
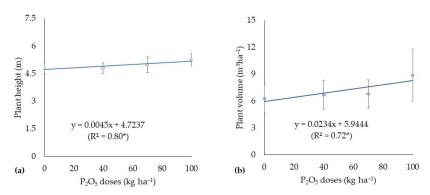

Figure 6. (**a**) Height of eucalyptus five months after definition of eucalyptus shoots as a function of residual P_2O_5 doses. (**b**) Total volume of eucalyptus wood five months after definition of eucalyptus sprouts as a function of residual P_2O_5 dose. Each point located on each graph is the mean of five replications. * and ** = significant at 5 and 1% level by F test, respectively.

4. Discussion

4.1. Soil Chemical Analysis

Soil nutrient analysis at the end of the first cycle, seventy-six months after plantation, under residual doses of N showed that residual N fertilization did not interfere with soil macronutrient contents. This is probably due to the complex dynamics of N in the soil and the fact that the greatest residual effects of nitrogen fertilization have been found in leaf litter (Figures 3g and 4), i.e., associated with carbon compounds. Therefore, N doses do still have an effect in this second eucalyptus production cycle.

An experiment with residual P doses showed a linear increase in soil P content with increasing P_2O_5 doses. The critical levels of P in soil in the initial phase is harmful for eucalyptus development, interfering with growth and harming later phases. The demand of P for eucalyptus decreases with increasing age. The average soil P content for eucalyptus ranges from 6 to 8 mg dm^{-3} [15]. Therefore, the P content was above this average content only at a residual P_2O_5 dose of 100 kg ha^{-1}, while the lower or higher doses could harm the initial growth of shoots in Experiment 2.

The availability of P in soil can stimulate greater formation of fine roots (effective root system) [16]. Thus, these effective roots can favor absorption of other nutrients that may be below the adequate levels in soil for initial development of eucalyptus plants.

The residual doses of K_2O fertilization positively influenced soil Ca content at seventy-six months after plantation with an increase in residual K_2O dose of 96.25 kg ha^{-1} (Figure 2b). Dick et al. [17] reported that *Eucalyptus dunnii* stand in a dystrophic red Ultisol at five years of growth duration showed similar soil Ca contents to those obtained at the end of our experiment with K_2O fertilization. The average soil Ca contents were 3 mmol$_c$ dm^{-3} in the 0–20 cm layer (Table 1) which is considered a very low level for the development of eucalyptus [16]. On the other hand, Gazola et al. [18] found that the soil K contents in the eucalyptus planting row at the superficial layer (0.00–0.20 m) at 24, 36, and 66 months after planting and from 0.20 to 0.40 m at 24 months were influenced by the dose of K_2O (0, 90, 135, and 180 kg ha^{-1}).

Among the micronutrients, only soil Fe content presented regression adjustment with residual N doses. The soil Fe content in the N experiment was found at high levels, considering the range of interpretation established by Raij et al. [15]. Iron is an important micronutrient for plant life maintenance that is related to various metabolic activities of plants, such as the formation of enzymes involved in respiration, photosynthesis, N_2 fixation, and electron transfer. The excess of Fe in the soil may deteriorate several processes of plants and can even become toxic; however, some plant species such as *Eucalyptus* spp. demonstrate tolerance to an excess of this micronutrient in soil [19].

Similarly, Godoi et al. [7], in their research on the second production cycle of eucalyptus in the Brazilian Cerrado region, verified that mineral fertilization (doses of formula 06-30-06 + 1% Ca + 3% S + 1% Mg + 1.5% Cu + 1% Zn) affects the chemical attributes of the soils at depths of 0–1.00 m and largely provides higher P and B contents.

4.2. Nutrient Contents in Leaf Litter and Leaf

4.2.1. Leaf Litter

The concentration of leaf litter in the forest site of eucalyptus contributes to the protection and nutritional maintenance of soil through the cycling of nutrients [20]. There was an increase in litter N content with increasing residual N doses up to 68.83 kg ha^{-1} of N. The organic supply of N provides nutrients for the next growing cycle of eucalyptus that were necessary for sprout generation. A 5-year-old eucalyptus forest site provided 41 kg ha^{-1} N in litter with a decomposition rate of about 40%, thus contributing to the next crop rotation [21].

In the experiment with residual K_2O doses, the Ca content in leaf litter decreased with increasing doses of K_2O. The behavior of increasing soil K content with increasing K_2O fertilization has impaired absorption of Ca from the previous eucalyptus cycle, which consequently decreased litter Ca content. This is due to the antagonistic effect of competitive

inhibition where K and Ca compete for absorption sites in root cells, meaning that more K availability in the root rhizosphere led to reduced Ca absorption in eucalyptus. In contrast, Bellote et al. [22] verified the opposite behavior in the litter of *Eucalyptus grandis* where high levels of soil Ca impaired K absorption, decreasing K content in the litter of forest sites. However, it is important to emphasize that plants well supplied with K present greater water use efficiency, which would result in an increase in the lifetime of leaves [23,24], which is very important in tropical regions that have high temperatures and sandy soils, such as those found in this research.

4.2.2. Leaf Nutrients Analysis

The concentrations of N, P, Ca and Mg in eucalyptus leaves were considered within the adequate range for the initial growth phase except N treatments, where the plants had a N deficiency. Dell et al. [25] proposed the following ranges; N from 18 to 30 g kg^{-1}, P from 1 to 3 g kg^{-1}, K from 6 to 18 g kg^{-1}, Ca from 3 to 8 g kg^{-1}, Mg from 1 to 3 g kg^{-1} and S from 1.5 to 3 g kg^{-1} for initial growth and development of eucalyptus plants. There was also a K deficiency in eucalyptus in most of the treatments in experiments with residual N and K_2O fertilization. In addition, the content of S in eucalyptus leaves was deficient only in the treatments without N application or the highest dose of P application. However, in general, S contents in the current study were adequate, as suggested by Dell et al. [25].

The concentrations of micronutrients in the leaves of eucalyptus were assessed as being in the adequate range for Cu, Fe, Mn and Zn, whereas B was recorded above the range considered "adequate" by Dell et al. [25] for the initial growth phase. These authors proposed the following ranges of micronutrients for the initial growth and development phase; B from 15 to 27 mg kg^{-1}, Cu from 2 to 11 mg kg^{-1}, Zn from 15 to 50 mg kg^{-1}, Mn from 60 to 2300 mg kg^{-1} and Fe from 25 to 130 mg kg^{-1}. The content of B in soil was within the range considered average for eucalyptus [15] in all three experiments evaluated that had contributed to maintaining an appropriate range of leaf B contents. In Brazilian Cerrado soils that have low organic matter content, boron fertilization is of great concern, as this micronutrient is commonly applied in the planting furrow, and occasionally B application via leaves has been employed in regions suffering prolonged dry periods in order to attenuate the effect of the lower B uptake by the roots during this period [26,27]. Therefore, we consider the results obtained for B important.

Soil nutrient contents from the residual fertilization of N, P_2O_5 and K_2O, along with litter nutrient cycling, contributed to the maintenance of an adequate nutrient content range in eucalyptus leaves, even in soil nutrients that were considered below adequate by Raij et al. [15]. For example, S and K content was below the considered adequate range only in the experiment with residual N doses as previously mentioned.

4.3. Analysis of Initial Growth (Diameter at Breast Height, Height and Total Wood Volume)

The initial growth attributes (DBH, height and total wood volume) did not respond to residual N doses. This can be explained partly by the presence of litter in the forest site [28] and partly by the greater mobility of N in soil, mainly in the form of nitrate in relation to P and K. Gazola et al. [18] evaluated clonal eucalyptus plantation and observed that N fertilization positively influenced the growth and stem diameter of eucalyptus trees up to a maximum dose of 63 kg ha^{-1} at the age of eighteen months.

There was a linear increase in eucalyptus height with an increase in P_2O_5 fertilization. There is a positive correlation between eucalyptus height and phosphate fertilization [29]. Total wood volume linearly increased with increasing P_2O_5 doses. It was also reported in a previous study that *Eucalyptus dunnii* at 6 years of age in an Oxisol soil showed an increase in wood productivity with increasing P_2O_5 fertilization where increasing doses resulted in a quadratic equation with an optimal dose of 93.4 g of P_2O_5 per tree [30].

Soil P content linearly increased with the P_2O_5 dose. The soil P content at the highest dose (100 kg ha^{-1}) of P_2O_5 was considered above the average content [15], which subsequently contributed to a range of leaf P content within the appropriate range for the initial

phase of eucalyptus. All these factors contributed to greater wood volume of eucalyptus with an increase in residual doses of P_2O_5 fertilization.

There was no significant regression adjustment for growth attributes under residual K_2O doses. Teixeira et al. [31] observed an increase in the height of eucalyptus seedlings in a greenhouse experiment with increasing K_2O fertilizer up to the maximum dose in Brazil. Gazola et al. [18] reported that potassium fertilization linearly increased the biomass yield of eucalyptus plants at 66 months (in the first cycle), the K content in the deposition of senescent leaves, K transfer to the soil, the accumulation of K, Ca, Mg, and S in the aerial parts of the plant, the N use efficiency, and the K concentration in the soil. The response of eucalyptus' height as a function of K_2O dose may vary (may increase, decrease, or even not change significantly), as in the case of the present research that evaluated a residual effect of K_2O doses in sandy soils. The K content in soil as a function of K_2O doses is far below the level considered adequate for K in the soil in the range of 0–2 $mmol_c$ dm^{-3} [15]. Therefore, this deficit of exchangeable K in soil may be the reason for the lack of response to DBH, height and wood volume as a function of K_2O dose. However, the trend is that at the beginning of the eucalyptus biogeochemical cycle the maintenance and supply of nutrients to the plants is important [24,32], thus it is likely that the residual K_2O and N doses will still have an effect in this second eucalyptus production cycle.

5. Conclusions

Residual N doses ranging between 64 and 75 kg ha^{-1} provided higher soil Fe content and higher N, K, Mg, S, B, Fe and Zn content in leaf litter of a first eucalyptus cycle. However, leaf nutrient contents and initial growth of eucalyptus were not influenced by increases in residual N fertilization in sandy soil.

The increase in residual doses of P_2O_5 increased the contents of P and Zn in soil, K content in leaf litter, decreased leaf Mg content and increased initial growth (height and estimated volume of eucalyptus wood).

The residual K_2O doses positively influenced soil Ca content, increased K content in leaf litter and leaf Mn and Zn content, but decreased the contents of Ca, B and Fe in leaf litter and Mg in leaves. Residual K_2O fertilization did not significantly influence the initial growth of eucalyptus in the Cerrado region of Brazil.

Therefore, we conclude that there is a positive residual effect of fertilization with N, P_2O_5 and K_2O from the first productive cycle over the second eucalyptus cycle, even in a sandy soil in a tropical region. For the initial growth phase of eucalyptus, the residual phosphate fertilization was more beneficial, but we believe that based on our results of soil, leaf litter and plant nutrient contents, the residual of K_2O and N doses will still have an effect in this second eucalyptus production cycle. Thus, in the future, mineral fertilization may be reduced in eucalyptus forests managed by the coppice system.

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