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Potassium Fertilization of *Eucalyptus* in an Entisol in Low-Elevation Cerrado

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ABSTRACT: Potassium (K) is one of the most highly accumulating nutrients in *Eucalyptus* and, consequently, is heavily exported by the harvesting of wood. Moreover, its availability in the soil in most Brazilian plantation areas is very low, especially in the regions of the Cerrado biome, which has soils with low natural fertility and marked water deficits, implying a lack of nutrient supply and, consequently, a less efficient water use. Our objective was to evaluate the effects of K fertilization on *Eucalyptus* biomass yield, the addition of nutrients to the soil by leaf deposition, nutrient use efficiency, and soil K availability. The experiment was conducted with clone I144 (*Eucalyptus urophylla*) in the municipality of Três Lagoas/MS, in a *Neossolo Quartzarênico Órtico* (Entisol). The experimental design was a randomized block with four treatments and five replicates. The treatments consisted of four K doses (0, 90, 135, and 180 kg ha^{-1} of K_2O) as KCl. Plant biomass production (leaves, branches, trunk, and bark), senescent leaf deposition, leaf nutrient concentrations, nutrient accumulation in the different plant compartments, nutrient use efficiency, addition of nutrients to the soil by leaf deposition, and soil K availability were evaluated. Potassium fertilization increased the biomass yield of *Eucalyptus* plants, senescent leaf K content, the transfer of K to the soil, the accumulation of K in the aerial plant parts, and the K content in the soil. However, it did not influence senescent leaf deposition yield or plant K use efficiency.

Keywords: senescent leaf nutrients, fertilization, biomass, macronutrients, nutritional efficiency.

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INTRODUCTION

Areas of forestation with *Eucalyptus* species have occupied new regions of Brazil in addition to the traditional ones, such as the south and southeast (Santana et al., 2008). These new regions present soils of low natural fertility, in addition to high and frequent water deficits, such as in the Cerrado biome (Gava et al., 1997; Oliveira Neto et al., 2010; Alves, 2011). Moreover, anthropogenic activities such as extensive livestock farming have resulted in the long-term impoverishment of these soils, with decreased nutrient amounts and, consequently, negative impacts on the newly forested areas (Gazola et al., 2015).

Potassium (K) is one of the nutrients that most limits the *Eucalyptus* yield in Brazil, and its application is relevant to successive rotations (Gava, 1997; Silveira and Malavolta, 2000). Among the nutrients demanded by different species of *Eucalyptus*, K plays a major role, and K fertilization has allowed significant increases in yield in most of the planted areas due to the low levels of K available in soils (Almeida et al., 2007).

Several studies report responses of *Eucalyptus* in soil with K contents below 1.0 $mmol_c\ dm^{-3}$. Gava (1997), in plantations of *Eucalyptus grandis* with K contents of 0.4 $mmol_c\ dm^{-3}$, Almeida et al. (2010), in *E. grandis* with K levels of 0.2 $mmol_c\ dm^{-3}$, Melo (2014), in clonal eucalypt plantations under different soil and climatic conditions with K contents between 0.3 and 0.4 $mmol_c\ dm^{-3}$, and Gazola et al. (2015), in *Eucalyptus urophylla* stands in *Neossolo Quartzarênico* (Entisol) with initial K contents of 0.2 $mmol_c\ dm^{-3}$. Thus, the responses of *Eucalyptus* to K application are not consistent when K contents of the soil are higher; positive responses were obtained only in soils whose K contents did not exceed 1.0 $mmol_c\ dm^{-3}$ (Silveira and Malavolta, 2000).

In addition to soil conditions, it is considered that the crop presents a high accumulation of K in the trunk and in the total aerial parts (N > Ca > K > Mg > P) (Silveira et al., 2005; Andrade et al., 2006; Faria et al., 2008; Benatti, 2013), which demonstrates the great requirement of *Eucalyptus* for this nutrient. This explains the high demand for this nutrient in later cycles of the crop due to its removal from the soil by extraction and, consequently, its export by wood harvesting. This demand varies between genetic materials (species clones or *Eucalyptus* hybrids); cultivars with a higher nutritional efficiency require lower amounts of nutrient to produce the same amount of biomass in relation to the less efficient ones.

The clone I144 (*Eucalyptus urophylla*), used in this study, is more productive and more efficient in the uptake and use of N, P, K (Faria et al., 2008; Pinto et al., 2011). This characteristic is desirable because these clones can be established in soils with less availability of these nutrients without compromising biomass production. This finding is of great importance because it is desirable to establish certain materials (species clones or eucalyptus hybrids) that are compatible with soil conditions, which are among the most limiting factors for crop development.

Regarding the crop response to K fertilization throughout the crop cycle, Gazola et al. (2015) found that the response obtained with a higher dose at 21 months in relation to previous evaluations was associated with a higher requirement for this nutrient during the crop cycle. The research conducted by Melo et al. (2016), studied the nutrition and fertilization of clonal *Eucalyptus* plantations under different edaphoclimatic conditions, the authors verified that the K requirement increased with age in all evaluated locations. Similarly, Gonçalves et al. (2008) found that the application of K led to increases in the responses with aging of the culture, as opposed to the applications of N and P, where diminished responses were observed with age. These findings, according to Barros et al. (1990), were due to the increase in the critical level of K in the soil over time.

Ideally, *Eucalyptus* crops are fertilized before canopy closure, and after this period, there is practically no response from the crop to fertilization, due to the beginning of the biogeochemical cycle. This cycle is responsible for the maintenance and supply of nutrients to the plants through the deposition of leaves, branches, and other parts of the plant on the soil, which form the litter layer, providing nutrients through decomposition (Laclau et al., 2003; Silva, 2011; Benatti, 2013).

The increase in the fertilizer dose led to higher yields and nutrient cycling in a *Eucalyptus* crop (Silva et al., 2013). The understanding of nutrient removal from the soil by its extraction and, consequently, the export of nutrients upon wood harvesting is of great importance to the understanding of the inputs and outputs of the nutrients during the crop cycle (nutrient balance). To maintain and improve the soil chemical properties in *Eucalyptus* plantations, the nutrient balance should be adequately monitored, mainly by fertilization and the correct management of crop residues (Silva, 2011).

Our objective was to evaluate the effects of K fertilization on biomass yield, nutrient accumulation in aerial part compartments, the transfer of nutrients to the soil by leaf deposition, and the efficiency of nutrient use by a *Eucalyptus* crop in the Cerrado, as well as the availability of soil K at different ages and depths.

MATERIALS AND METHODS

The experiment was conducted from September 2011 to July 2017 at the Renascença Farm (Fazenda Renascença), an agricultural fund managed by Cargill Agrícola S/A, located in the municipality of Três Lagoas, state of Mato Grosso do Sul, Brazil. According to the Köppen system, the climate of the region is classified as Aw, defined as humid tropical with a rainy season in the summer and a dry season in the winter. The rainfall data recorded during the execution of the experiment are presented in figure 1.

The experimental area was occupied by natural vegetation (plants of the Cerrado biome); prior to the implementation of the experiment, the area consisted of degraded pasture, with a slope of 4 %. The soil presented a sandy texture with only 8 % clay, classified as *Neossolo Quartzarênico Órtico* (Entisol) (Santos et al., 2013).

Before the experiment, soil samples were collected at layers of 0.00 to 0.20 and 0.20 to 0.40 m to determine the soil chemical properties, according to the method described by van Raij et al. (2001). The chemical properties at the layer of 0.00-0.20 m were as follows: pH($CaCl_2$) 4.2; 7.4 g dm^{-3} of organic matter (OM); 1 mg dm^{-3} P in resin; K^+, Ca^{2+}, Mg^{2+}, H+Al, and Al^{3+} contents of 0.2, 4.2, 1.9, 17.0, and 4.3 $mmol_c$ dm^{-3}, respectively; and a base saturation (V) of 27 %. At the layer of 0.20-0.40 m, we measured the following parameters: pH($CaCl_2$) 4.2; 6.8 g dm^{-3} of OM; 1 mg dm^{-3} P in resin; K^+, Ca^{2+}, Mg^{2+}, H+Al, and Al^{3+} contents of 0.3, 1.6, 1.1, 18.0, and 4.5 $mmol_c$ dm^{-3}, respectively; with a V level of 14 %.

The experimental design was a randomized block with four treatments and five repetitions, where four doses of K (0, 90, 135, and 180 kg ha^{-1} of K_2O) were applied in the planting groove and in the cover. The study of these doses was based on the following recommendations for *Eucalyptus* fertilization under the soil conditions of this research. According to Gonçalves et al. (1997), the dose of 50 kg ha^{-1} of K_2O is ideal for soils with a clay content <15 % and a K content <0.7 $mmol_c$ dm^{-3}. However, based on economical considerations, the adequate dose in soils with K contents between 0 and 1.0 $mmol_c$ dm^{-3} is in the range of 120 to 180 kg ha^{-1} of K_2O (Silveira and Malavolta, 2000). This range was selected in our study because it is in accordance with the practices adopted by forestry companies.

Seedlings of *Eucalyptus urophylla* hybrids (clone I144) were planted in January 2012 with a spacing of 3.0 × 2.5 m. Each plot contained 56 plants, distributed in seven rows of eight plants each, totaling 420 m^2. Only 30 plants in the center of the plots were considered, resulting in a total effective sampling area of 225 m^2. In September 2011,

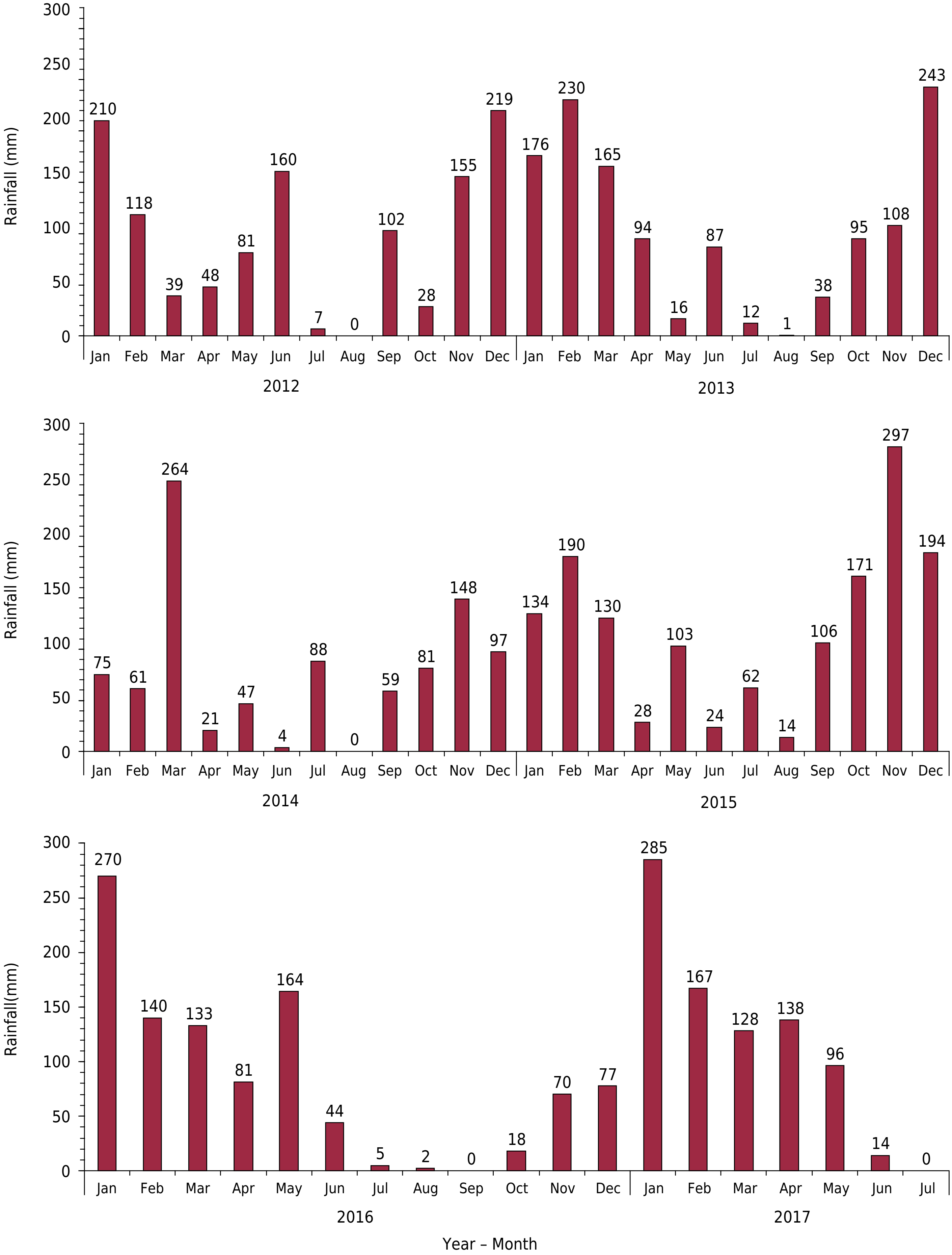

Figure 1. Monthly accumulations of rainfall registered at the Três Lagoas Automatic Meteorological Station, 2012/17.

1,500 kg ha^{-1} of limestone of PRNT 80 % and 500 kg ha^{-1} of gypsum were applied by broadcasting over the total area.

The plantation fertilization involved 70 kg ha^{-1} of P_2O_5 (triple superphosphate) and 15 kg ha^{-1} of N (urea), with 37.5, 37.5, and 50 kg ha^{-1} of N in the cover (at 2, 9, and 14 months, respectively) as ammonium nitrate. The treatments of K fertilization were 0 kg ha^{-1} K_2O (control); 90 kg ha^{-1} K_2O (15.0, 22.5, 22.5, and 30.0 kg ha^{-1} K_2O); 135 kg ha^{-1} K_2O (15.0, 36.0, 36.0, and 48.0 kg ha^{-1} K_2O), and 180 kg ha^{-1} of K_2O (15.0, 49.5, 49.5, and 66.0 kg ha^{-1} of K_2O), respectively, at planting and at 2, 9, and 14 months after planting. The following micronutrients were applied at planting in all treatments: 1 kg ha^{-1} of B (boric acid), 1 kg ha^{-1} of Zn (zinc sulphate), and 1 kg ha^{-1} of Cu (copper sulphate). In the cover fertilizations with N and K, carried out at 9 and 14 months after planting, 1 kg ha^{-1} of B (boric acid) was applied to all treatments.

To quantify senescent leaf deposition, sombrite-type screens were fixed onto four *Eucalyptus* plants per row and between rows, with three collectors per plot distributed within the useful plot area. The collections were carried out quarterly from 30 to 66 months after planting. The data presented correspond to the total amount deposited in this period (accumulated over 36 months).

Samples of fallen leaves were taken to form the composite sample, oven-dried (65 °C for 72 h), and milled in a Willey mill for the chemical nutrient analysis according to the method described by Malavolta et al. (1997). The data presented correspond to the mean nutrient contents in the 12 collection periods. The addition of nutrients to the soil by leaf deposition in the period from 30 to 66 months was estimated by multiplying the senescent leaf deposition by the nutrient content in the leaf. At 66 months after planting, four trees in the useful area of each plot of one block were cut, where one tree was representative of the small-diameter class, two represented the intermediate-diameter class, and one was representative of the large-diameter class, according to the method described by Silva (2011). Samples of all components of the trees (leaves, branches, and trunk) were collected manually for the determination of the moisture in the laboratory and the subsequent quantification of the dry biomass. Prior to drying, the samples obtained from the trunk were separated into bark and wood.

The plant samples of the different tree components were oven-dried (65 °C for 72 h), weighed, and ground in a Willey mill. Chemical analysis was performed to determine the macronutrient content according to the method described by Malavolta et al. (1997). To measure the nutrients in the wood and the bark, the average content obtained in discs collected at the base and the diameter at breast height (DBH) and at 10, 30, 50, and 70 % of the total height were considered. Using the values of the contents in each compartment, the contents in the different components of the trees (mineral mass) were estimated. Nutrient use efficiency was evaluated according to the method presented by Barros et al. (1986) as the ratio between the dry biomass of the trunk and the mineral mass of the nutrient accumulated in the trunk.

At 24, 36, 48, 60, and 66 months after planting, four soil samples were collected per plot in the planting line at layers of 0.00-0.20 and 0.20-0.40 m and in the interline (plant canopy projection - perpendicular to the planting line at a distance of 0.50 m from the plant, where K cover fertilization was carried out) at layers of 0.00-0.20 and 0.20-0.40 m (or layers of 0.40-0.60 and 0.60-0.80 m only in the last evaluation), using an auger. The samples were homogenized and an aliquot of each sample was used to form a composite sample; available K levels in the soil were determined according to the method described by van Raij et al. (2001).

Data were analyzed using a regression analysis for the doses of K_2O and an analysis of variance (test F) and Tukey's test at 5 % probability to compare the soil K availability levels among the five evaluation periods (at 24, 36, 48, 60, and 66 months after planting). The SISVAR software (Ferreira, 2008) was used for statistical tests.

RESULTS AND DISCUSSION

Potassium fertilization positively influenced leaf and wood biomass production as well as the total biomass of the aerial parts after 66 months (Figures 2a and 2b). The dose of 180 kg ha^{-1} of K_2O provided the highest leaf and wood biomass values and the highest total biomass values, with an increase of 31.5, 17.8, and 18.2 %, respectively, in relation to the control (0 kg ha^{-1} of K_2O). Silva (2011) evaluated the impacts of fertilization doses and rates in *Eucalyptus* plantations in the initial growth phase in *Neossolo Quartzarênico* (Entisol) and found that the biomass production increased with increasing fertilizer doses, at all ages evaluated. At 24 months, the group receiving the highest fertilizer dose had 50 % more biomass compared to the other groups.

In a study carried out in Cerrado soil, Almeida (2009) concluded that *Eucalyptus grandis* responds to K fertilization in its leaf area index. Christina et al. (2015) evaluated the effects of K deficiency and water deficit on yield and light use efficiency in *E. grandis* plantations and found that the plants that did not receive K application had a 64 % lower leaf area index than the plants fertilized with K. In this sense, K fertilization favors an increase in leaf area, which results in a greater intensity of the interception of sunlight and the photosynthetic processes, which in turn results in greater growth. This effect is also due to the functions performed by K in the plant, including the regulation of the osmotic potential of plant cells, thus controlling the opening and closing of the stomata, resulting in a higher water use efficiency (Siddiqui et al., 2008; Taiz and Zeiger, 2013). Therefore, plants spend less energy during periods of water deficit, which are common in the study region (Figure 1).

On average, the biomass distribution in the different components of the aerial part of the *Eucalyptus* plants at 66 months after planting presented the following magnitudes: wood (86 %) > bark (6 %) > leaf (4 %) = branch (4 %). Verão et al. (2016) evaluated the nutrient content in *Eucalyptus urophylla* × *Eucalyptus grandis* at 84 months in an Ultisol

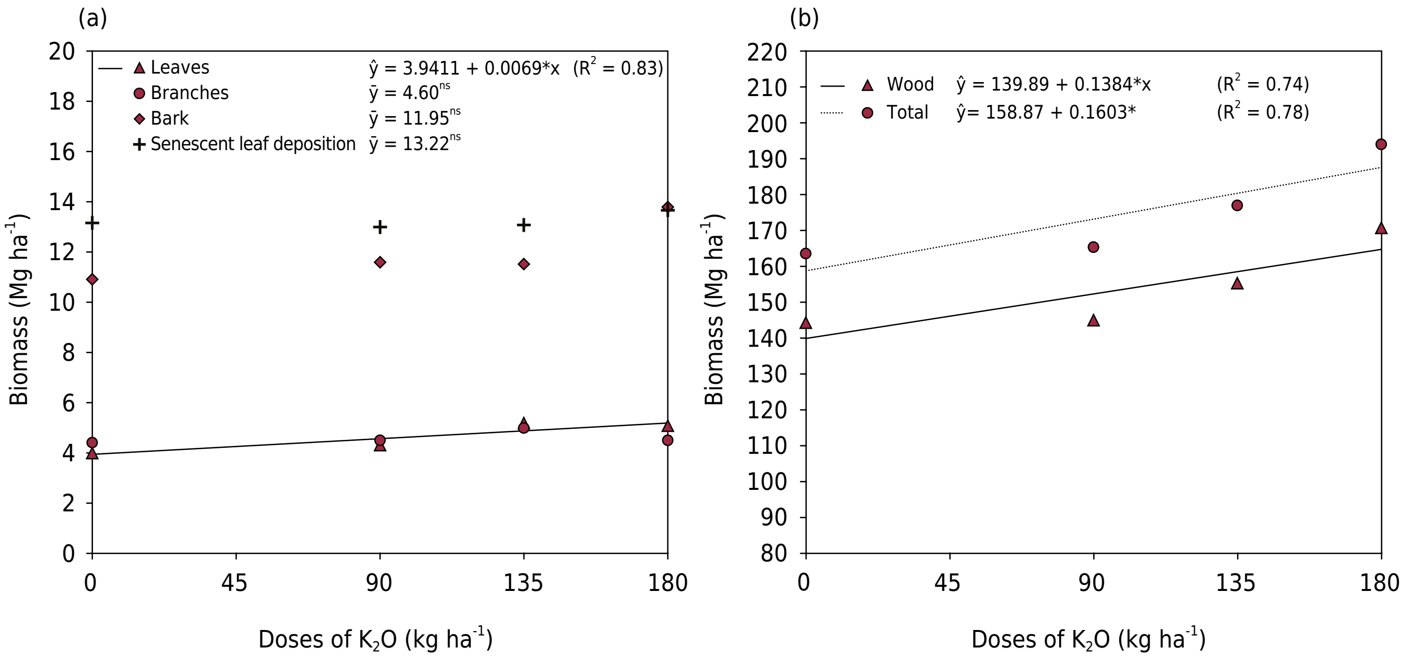

Figure 2. Biomass of leaves, branches, bark, senescent leaf deposition (a), wood and total of the aerial part (b) of *E. urophylla* hybrid, evaluated at 66 months after planting, as a function of doses of K_2O.

from low to medium fertility and found that wood (89.4 %) and bark (8.20 %) are the most representative aerial part biomass fractions. Faria et al. (2008), investigating the same hybrid used in this study at 57 months in an Oxisol, found that under the conditions of dominance of the closed Cerrado ecosystem, the plants tended to allocate, on average, a larger percentage of trunk biomass (92.3 %) in relation to the plant canopy (7.7 %).

Total senescent leaf deposition yield was not influenced by K fertilization in the period from 30 to 66 months after planting, with a mean yield of 13.2 Mg ha^{-1} during that period (Figure 2a). Silva (2011) found that more than 3.5 Mg ha^{-1} of senescent leaf deposition were produced from 12 to 24 months by clones of the hybrid *Eucalyptus urophylla* x *grandis* without NPK fertilization, while 7.1 Mg ha^{-1} were produced with the highest fertilizer dose. This higher production in the initial phase of the *Eucalyptus* growth is due to the reduced residence time of the leaves at the eucalyptus branches due to the addition of fertilizers, which accelerates the growth of the trees after anticipating the intra-specific competition for light and water due to the mutual shading of the plant canopy. This process accelerates leaf senescence. At the later stages of the crop cycle, this competition decreases, resulting in lower senescent leaf deposition.

Eucalyptus is not a deciduous genus; however, in the dry season, it loses leaves to reduce water consumption. This mechanism is caused by drought to increase ethylene synthesis, which results in leaf abscission. As a stress response, abscisic acid levels are increased; this plant hormone regulates the opening and closing of the stomata, especially when the plant is under environmental stress, reducing the loss of water by transpiration (Florence, 2004; Taiz and Zeiger, 2013). Therefore, plants that are well supplied with K present greater water use efficiency, which would result in an increase in the lifetime of leaves (Silva et al., 2002; Laclau et al., 2009). This explains the finding that K fertilization increased the production of leaf biomass and did not influence senescent leaf deposition.

The increase in K_2O led to an increase in K content and a decrease in Mg in the leaves (Figure 3a), and this behavior was verified for the K and Mg contents in the deposited senescent leaves (Figure 3e). The probable cause of the decrease in Mg content is the "dilution effect" of these nutrients on the leaf because with increasing K doses, there was a higher leaf biomass production (Figure 2a), resulting in a lower content of this nutrient. In addition, these macronutrients compete for the same absorption site; that is, the competitive inhibition of Mg may have occurred in parts (Malavolta, 2006; Marschner, 2012).

Silva (2011) evaluated the effects of fertilization levels and fertilization rates (NPK) on *Eucalyptus* plantations in the initial phase of growth and found that the differences in K concentration occurred in all compartments of the trees; further, the treatment without fertilization presented the lowest content. The decrease in foliar content of Mg as a function of the increase in K was also reported by Silveira (2000) in *E. grandis* progenies grown in nutrient solution.

The lowest contents of nutrients were observed in the wood compartment (Figure 3c), while the highest contents of N, P, K, and S were observed in the leaves (Figure 3a). The higher Ca content was found in the bark (Figure 3d) and the Mg content in the leaves and bark which were very close values (Figures 3a and 3d). The highest contents of N, P, K, and Mg in the leaves are due to the high mobility of these nutrients in the plant and to the presence of Ca in the bark due to its low mobility or immobility in the plant (Malavolta, 2006; Marschner, 2012). In addition, the main metabolic activities occur in the leaves, and consequently, leaves show a greater nutrient demand (Viera et al., 2013). Verão et al. (2016) also found higher N, P, K, Mg, and S contents in the leaves and lower contents in the trunk in *E. urophylla* x *E. grandis* at 84 months.

Potassium fertilization positively and linearly influenced the accumulation of K (leaves, bark, and total), Ca (wood, bark, and total), Mg, and S (total) (Figures 4a, 4c, 4d, and 4e).

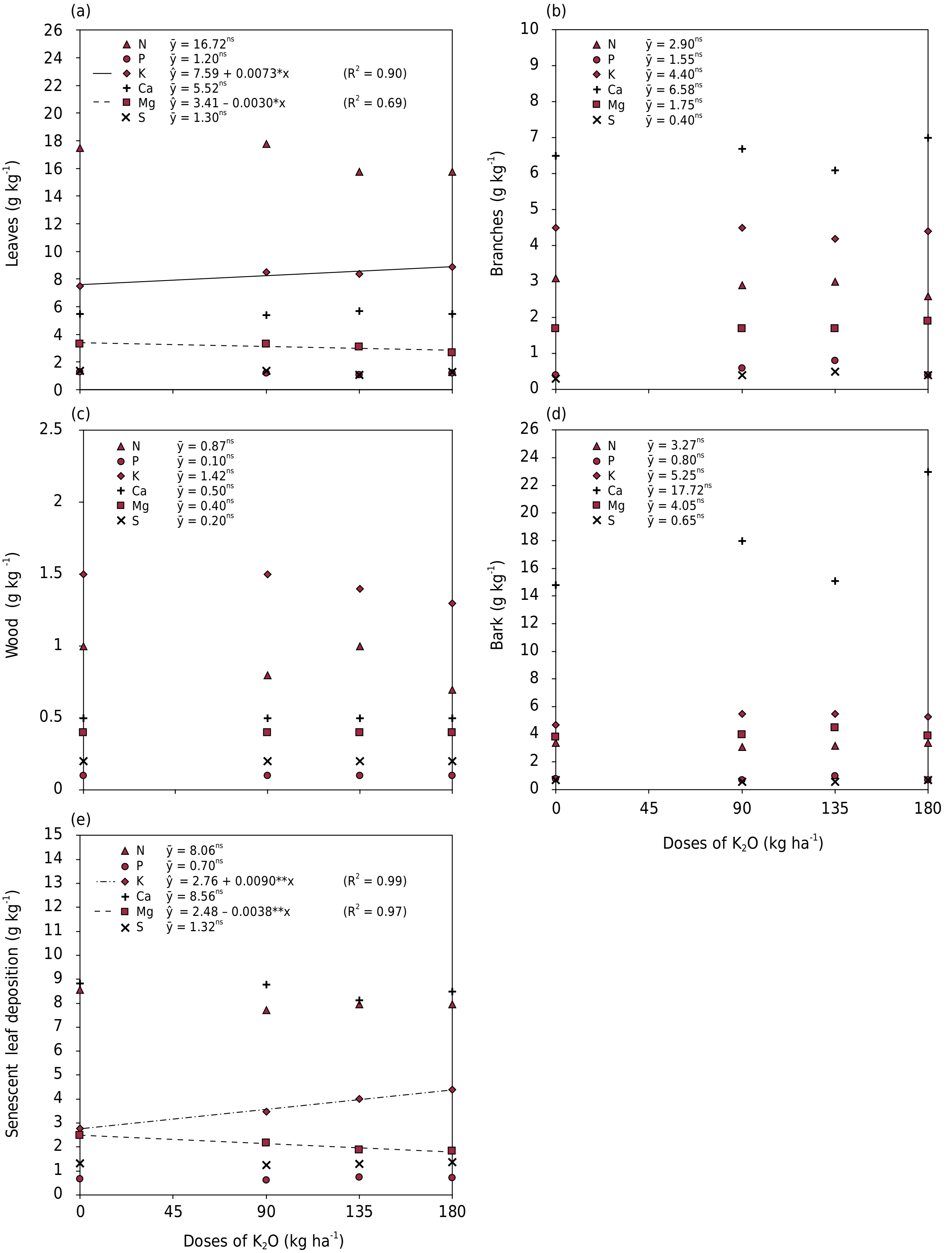

Figure 3. Contents of nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur in the different compartments of *Eucalyptus* plants (leaves, branches, wood, and bark, respectively, a, b, c, and d) and senescent leaf deposition mean (e), as a function of doses of K_2O.

Higher doses of fertilizers had a positive effect on mineral mass production (nutrients accumulated in biomass) for *E. urophylla* x *E. grandis* at 12 and 24 months of age (Silva, 2011). This result corroborates those obtained in the present research. With increasing K_2O levels, the content of K increased linearly in leaves, bark, and the total plant. There was also an increase in the stock of Ca in the wood and bark compartments and in the total aerial part. In turn, the increases in Mg and S in the aerial part were 21.2 and 23.4 %, respectively (of the highest dose of K in relation to the control).

Regarding the compartments, in the wood, the nutrient stocks of the *Eucalyptus* plants at 66 months after planting followed the order K > N > Ca > Mg > S > P. In the aerial part of the Eucalyptus plants, the order was Ca > K > N > Mg > S > P. Of the total nutrients stored in the aerial part, approximately 66 % of Ca were accumulated in the bark and 89 % of K in the trunk, being 18 % in bark and 81 % in wood. According to Santana et al. (2002), Ca is the most abundant nutrient in the bark, whereas K is the most abundant nutrient in the wood; these are the most exported nutrients by harvesting the trunk (wood + bark). In this sense, debarking the trunk is a practice that reduces the export of nutrients, mainly of Ca, and minimizes the export of other nutrients contained in this compartment.

Similar to the K and Mg contents in senescent leaf depositions, the amounts of these nutrients transferred to the soil increased and decreased, respectively (Figure 4f). With increasing doses of K_2O, the amounts of K transferred to the soil increased by 66 % (57.5 kg ha^{-1} of K), while those of Mg decreased by 23 % when comparing the highest dose of K with the control. This finding is associated with the increased supply of K to the plant, which, as reported, increased the K contents in leaf tissues and decreased Mg (Figure 3e), since the senescent leaf deposition yield was not influenced by the doses of K_2O (Figure 2a). The amount of K transferred via senescent leaf deposition in the control was 34.6 kg ha^{-1} of K (Figure 4f), and the difference between the highest potassium dose and the control was 22.9 kg ha^{-1} of K (or 27.5 kg ha^{-1} of K_2O), which means that 15.3 % of K applied by mineral fertilization were recycled by fallen leaves during the period from 36 to 66 months.

Silva (2011) found that from 12 to 24 months, the amounts of N, K, Ca, Mg, and S transferred via senescent leaf deposition by *Eucalyptus urophylla x grandis* were higher in the treatments with fertilizer application, mainly due to the higher senescent leaf deposition yield of these treatments.

The addition of macronutrients by senescent leaf deposition between 30 and 66 months followed the order Ca > N > K > Mg > S > P, with the following quantities: Ca = 113.9 kg ha^{-1}; N = 107.5 kg ha^{-1}; K = 47.8 kg ha^{-1}; Mg = 27.3 kg ha^{-1}; S = 17.4 kg ha^{-1}, and P = 9.2 kg ha^{-1}. The same sequence was also found in other studies with different species of *Eucalyptus* at different ages (Silva, 2011; Salvador et al., 2014). Potassium is the third-most transferred nutrient by senescent leaf deposition; however, because it is not part of any plant structure or organic molecule and rather occurs as a free cation (monovalent), it becomes available for plants more quickly. Moreover, the leaf fraction is the most notable litter component in forest soil in terms of deposited K, and this nutrient presents the highest intensities of biochemical and biogeochemistry cycling (Cunha et al., 2005; Meurer, 2006; Caldeira et al., 2008; Salvador et al., 2014).

Potassium fertilization influenced the efficiency of nitrogen use by *Eucalyptus* plants (Figure 5a). The efficiency of nutrient use in genotypes of *Eucalyptus* spp. was evaluated by Faria et al. (2008), the authors found that clone I144 (*Eucalyptus urophylla*), at 57 months of cultivation, showed a higher N use efficiency. In the present study, K fertilization increased the efficiency of N use as the doses of K_2O increased. Such efficiency in the increase of biomass production per kilogram of N stored can be explained by the role of K in controlling the opening and closing of the stomata (Taiz and Zeiger, 2013). Therefore, with a higher K_2O dose, plants spend less energy during periods of water deficit (a typical

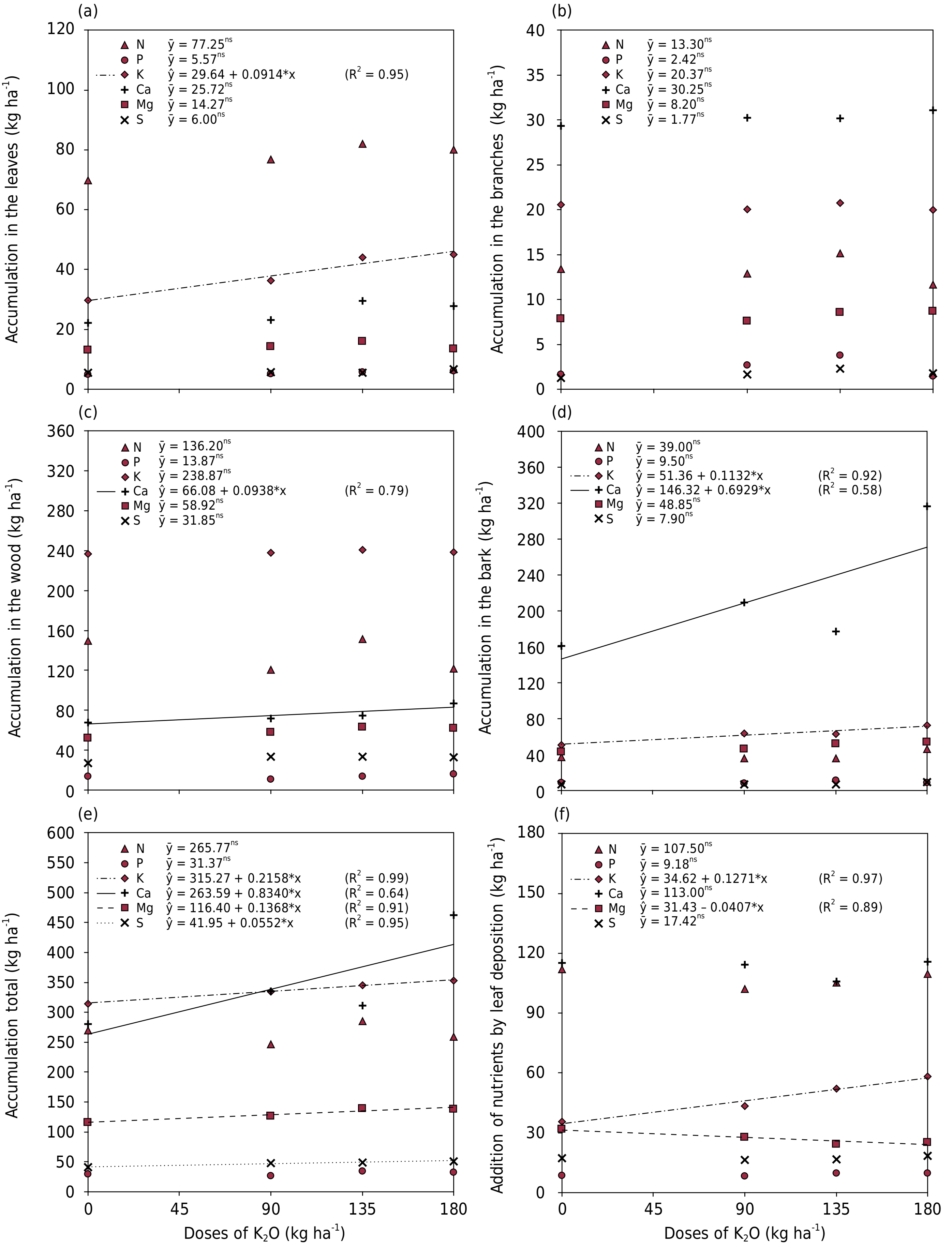

Figure 4. Accumulation of nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur in the different compartments of *Eucalyptus* plants (leaves, branches, wood, bark, and total, respectively, a, b, c, d, and e) and addition of nutrients by leaf deposition (f), as a function of doses of K_2O.

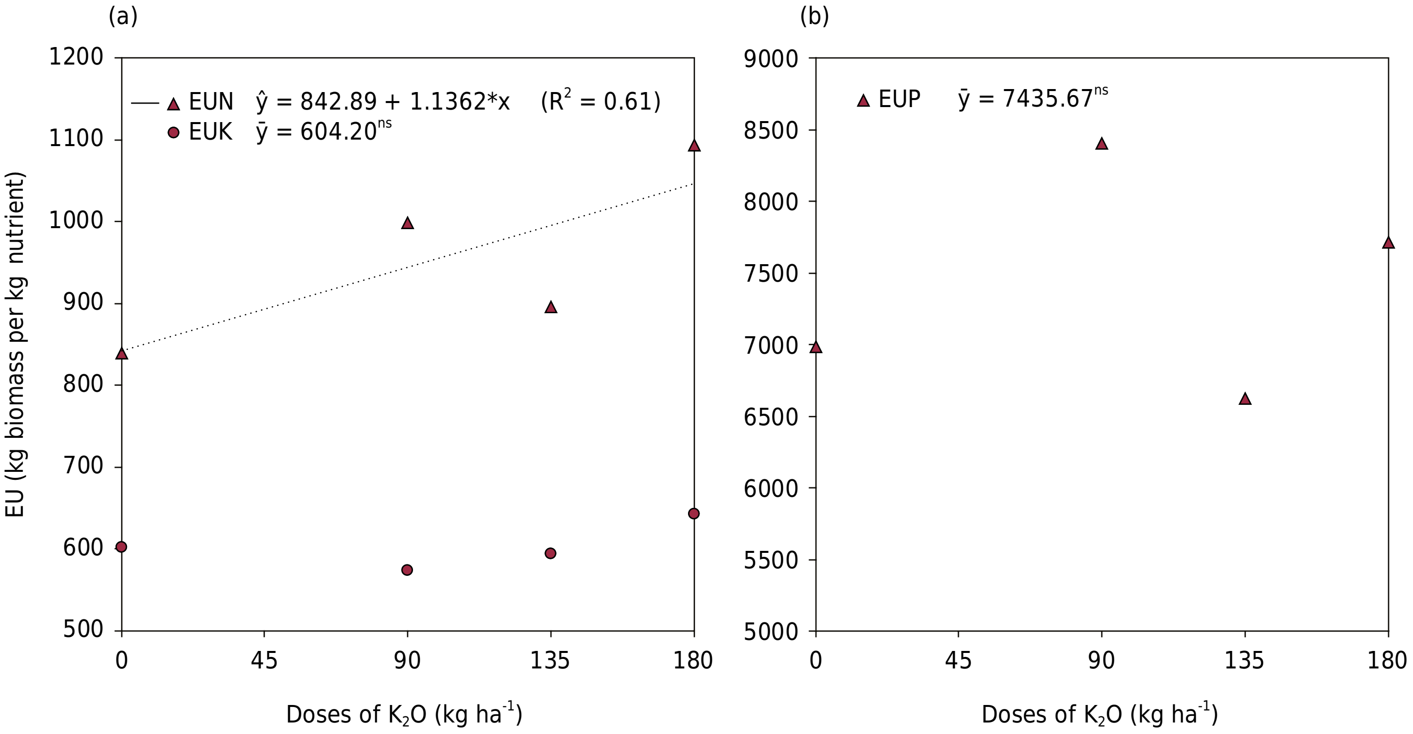

Figure 5. Efficiency of use of nitrogen (EUN), potassium (EUK) (a), and phosphorus (EUP) (b) of *E. urophylla* hybrid, evaluated at 66 months after planting, as a function of doses of K_2O.

condition of the study region) (Figure 1), which is best used for N metabolism (Xu et al., 2002), for example, in the assimilatory reduction of nitrate, by the participation of K in nitrate reductase activation (Marschner, 2012).

The non-efficiency of the use of K as a function of K fertilization was probably due to the increase in wood biomass production (Figure 2b) and K accumulation in the bark (Figure 4d) because nutrient use efficiency is calculated by the relationship between the dry trunk biomass (wood + bark) and the nutrient accumulated in the trunk. Therefore, an increase in biomass and the accumulation of K in the trunk as a function of the increase in K_2O dose did not alter this relationship.

The soil K levels in the planting row at the superficial layer (0.00-0.20 m) at 24, 36, and 66 months and from 0.20 to 0.40 m at 24 months were influenced by the doses of K_2O, which was also observed for the nutrient contents in the inter-row area in the layer of 0.0 to 0.20 m at 24 months and in the subsurface layer at all evaluation times (Table 1). These contents increased linearly with increasing K_2O doses (Figures 6a, 6b, 6c, and 6d). However, only in the inter-row area at the two depths in the second year, we observed contents above 1 $mmol_c$ dm^{-3} K at doses of 135 and 180 $mmol_c$ dm^{-3} of K_2O. These contents would be classified as low (0.8-1.5 $mmol_c$ dm^{-3}), according to the interpretation limits established by van Raij et al. (1997).

In subsequent evaluations, the highest levels of K in the soil were obtained with the highest dose of K_2O; however, they were similar to those found in the initial soil analysis (0.2 and 0.3 $mmol_c$ dm^{-3} of K); these contents would be classified as very low, which indicates the high absorption of this nutrient by *Eucalyptus* due to the large accumulation of K in the biomass (Figure 4e). In this sense, higher K levels in the soil [values of K classified from medium to high according to van Raij et al. (1997)] would be observed in the initial phases of the development of the culture, in the period of K application.

Regarding the availability of K between 24 and 66 months after planting, the highest level occurred in the first evaluation (Table 1). Between 24 and 36 months, K levels

Table 1. Potassium levels in the soil in the planting line and in the interline of *E. urophylla* hybrid at layer of 0.00-0.20 and 0.20-0.40 m, evaluated at 24, 36, 48, 60, and 66 months after planting, as a function of doses of K_2O

Doses of K_2O	**24th month**	**36th month**	**48th month**	**60th month**	**66th monnth**
			K^+ levels		
kg ha^{-1}			mmol$_c$ dm^{-3}		
			Line of 0.00-0.20 m		
0	0.23^{*}	0.10^{*}	0.30^{ns}	0.27^{ns}	0.26^{*}
90	0.43	0.20	0.26	0.29	0.33
135	0.50	0.17	0.30	0.33	0.40
180	0.73	0.33	0.33	0.35	0.40
mean	0.48 a	0.20 c	0.30 bc	0.31 bc	0.35 b
D.M.S. (5 %)	0.12				
C.V. (%)	8.99	7.47	12.42	16.59	5.06
			Line of 0.20-0.40 m		
0	0.17^{*}	0.10^{ns}	0.20^{ns}	0.19^{ns}	0.20^{ns}
90	0.20	0.13	0.23	0.26	0.30
135	0.20	0.13	0.20	0.21	0.23
180	0.33	0.20	0.23	0.22	0.23
mean	0.23 a	0.14 b	0.22 a	0.22 a	0.24 a
D.M.S. (5 %)	0.07				
C.V. (%)	4.65	4.56	20.35	21.51	4.68
			Interline of 0.00-0.20 m		
0	0.30^{*}	0.17^{ns}	0.20^{ns}	0.19^{ns}	0.20^{ns}
90	0.70	0.17	0.30	0.27	0.27
135	1.17	0.20	0.30	0.27	0.27
180	1.50	0.17	0.26	0.22	0.20
mean	0.92 a	0.18 b	0.27 b	0.24 b	0.23 b
D.M.S. (5 %)	0.29				
C.V. (%)	17.52	4.78	10.83	10.44	14.29
			Interline of 0.20-0.40 m		
0	0.30^{*}	0.10^{*}	0.17^{*}	0.15^{**}	0.15^{*}
90	0.63	0.10	0.20	0.14	0.10
135	1.13	0.47	0.23	0.21	0.20
180	1.30	0.34	0.27	0.24	0.23
mean	0.84 a	0.25 b	0.22 b	0.18 b	0.17 b
D.M.S. (5 %)	0.34				
C.V. (%)	20.39	10.16	25.51	13.93	18.89

Means followed by the same letter in the line do not differ by the Tukey test, 5 % probability. ns, *, ** = not significant, significant at 5 and 1 % by the F test, respectively. The K^+ was extracted by the ion exchange resin method, according to the method described by van Raij et al. (2001).

were greatly reduced by 80 to 70 % in the inter-row area at depths of 0.00-0.20 and 0.20-0.40 m, respectively, and by 58.3 and 39.1 % in the planting row at layers of 0.00-0.20 and 0.20-0.40 m, respectively. These findings evidence the high K absorption by *Eucalyptus* as early as in the first few years of cultivation.

In addition, the sandy soil presents a favorable condition for nutrient leaching. Soil K levels in the surface layer of the last evaluation were higher than those in the layers of 0.20-0.40, 0.40-0.60, and 0.60-0.80 m (Table 2), demonstrating that K leaching was probably reduced by the instalment of K fertilization, which shows that the main process responsible for the decrease in K availability was the high uptake of this nutrient by the crop. Studies evaluating potassium fertilization in *Eucalyptus* plantations on *Neossolo*

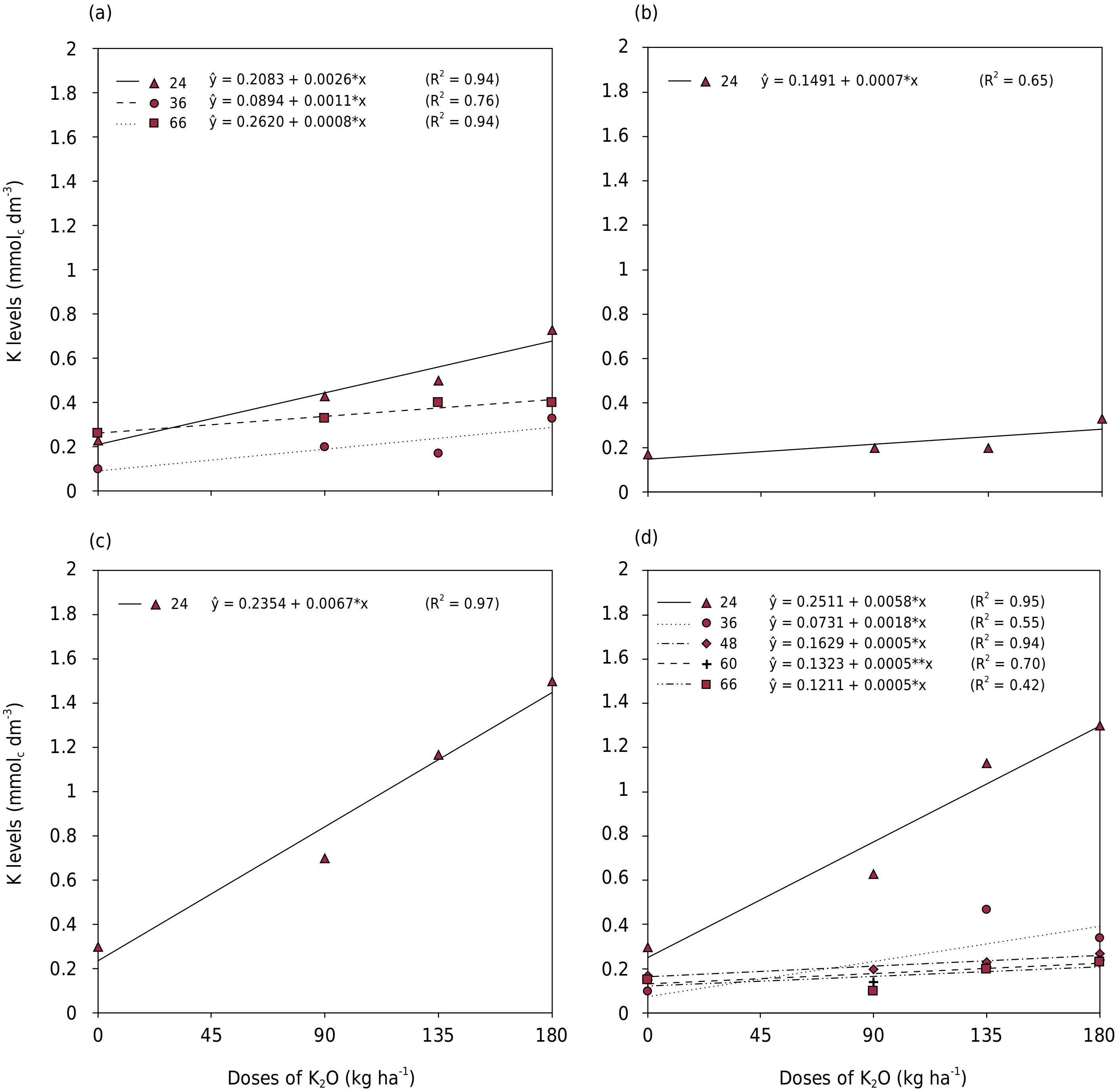

Figure 6. Potassium levels in the soil in the line (0.00-0.20 and 0.20-0.40 m) and interline (0.00-0.20 and 0.20-0.40 m) of the *E. urophylla* hybrid, evaluated at 24, 36, 48, 60, and 66 months after planting (respectively, a, b, c, and d), as a function of doses of K_2O.

Quarztzarênico (Entisol) show that K splitting reduces its leaching in the soil, with the fast K absorption by the crop being the main factor responsible for its decrease in the soil (Silva et al., 2013; Melo, 2014).

The K contents in the surface layer of the planting row increased by 75 % between 36 and 66 months. Such an increase can be explained by biogeochemical cycling process, mainly because K was the third-most transferred nutrient to the soil via senescent leaf deposition (Figure 4f). Melo (2014) found that K increased between 24 and 48 months in one forest site and attributed this to the nutrient cycling process arising from the deposition of branches and leaves. According to Gonçalves et al. (2008), this process starts in the second year of the *Eucalyptus* crop cycle, when the closure of the forest canopy occurs, and is responsible for the mineralization of the nutrients contained in the litter.

Table 2. Potassium levels in the soil in the interline of *E. urophylla* hybrid at depths of 0.00-0.20, 0.20-0.40, 0.40-0.60, and 0.60-0.80 m, evaluated at 66 months after planting, as a function of doses of K_2O

Layers	**Doses of K_2O**				**Mean**
	0 kg ha^{-1}	**90 kg ha^{-1}**	**135 kg ha^{-1}**	**180 kg ha^{-1}**	
m			mmol$_c$ dm^{-3}		
0.00-0.20	0.20 a	0.27 a	0.27 a	0.20 ab	0.23 a
0.20-0.40	0.15 a	0.10 b	0.20 a	0.23 a	0.17 b
0.40-0.60	0.10 a	0.13 b	0.17 a	0.13 ab	0.13 b
0.60-0.80	0.10 a	0.10 b	0.17 a	0.10 b	0.12 b
D.M.S.$_{\text{doses x depths}}$			0.11		
D.M.S.$_{\text{layers}}$			0.05		
C.V. (%)			29.34		

Means followed by the same letter in the column do not differ by the Tukey's test at 5 % probability.

However, the phase that precedes the harvest is characterized by the intense recycling of nutrients, either through internal retranslocation (biochemical cycle) or through the biogeochemical cycle responsible for the maintenance and supply of nutrients to the plants (Laclau et al., 2003; Silva, 2011; Benatti, 2013).

CONCLUSIONS

Potassium fertilization linearly increased the biomass yield of *Eucalyptus* plants at 66 months, 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.

Between the second and the third year of cultivation, soil K was greatly reduced, with levels being lower compared to those at harvest time. Such an increase in soil K availability at later stages was facilitated by the K transfer via senescent leaf deposition, independent of the K dose applied. The largest stocks of N, P, K, Mg, and S were found in the wood, while Ca accumulated more in the bark.

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