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Establishment of critical nutrient levels in soil and plant for eucalyptus

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ABSTRACT: The adoption of more productive and nutrient-demanding genotypes, in addition soils with low availability of nutrients of soils under forest plantations, lead high fertilizer demand and justify research that seeks to rationalize the use of these inputs. Therefore, we aimed with this research to determine classes of interpretation of soil fertility using boundary line (BL) and estimate macronutrient sufficiency ranges for eucalyptus. Fertility classes and sufficiency ranges were obtained using a database of areas cultivated with eucalyptus in the Central-East region of Minas Gerais, Brazil, totaling 689 plots, containing information on yield, leaf contents, and soil chemical properties. Scatter plots were drawn relating the mean annual increment (MAI) in trunk volume (relative) with soil organic matter (OM), phosphorus (P), potassium (K⁺), calcium (Ca²⁺), and magnesium (Mg²⁺) of the 0.00-0.20 m layer. Those graphs and equations were used to estimate soil fertility classes. Leaf contents of N, P, K, Ca, and Mg were plotted with soil contents of OM, P, K⁺, Ca²⁺, and Mg²⁺. Using the Quadrant Diagram of the plant-soil Relationship (QDpsR) method, horizontal and vertical lines were drawn separating the cloud of points in four quadrants. With the points at the quadrants III and I, regression equations were fitted. To obtain foliar sufficiency ranges, soil values of critical and optimal levels of OM, P, K⁺, Ca²⁺, and Mg²⁺, obtained by BL, were substituted in the equations generated by the QDpsR method. The appropriate soil content ranges determined by BL for productivity of 47.7 m³ ha⁻¹ yr⁻¹ were: 24.75-38.28 g kg⁻¹ of OM, 8.5-14.6 mg dm⁻³ of P, 100.0-150.35 mg dm⁻³ of K⁺, 0.77-1.47 cmol_c dm⁻³ of Ca²⁺, and 0.25-0.43 cmol_c dm⁻³ of Mg²⁺. Leaf content ranges determined by QDpsR are: 19.4-21.3 g kg⁻¹ of N, 1.0-1.2 g kg⁻¹ of P, 8.5-10.6 g kg⁻¹ of K, 4.8-6.1 g kg⁻¹ of Ca, and 1.9-2.4 g kg⁻¹ of Mg. The critical levels of nutrients in the soil, obtained by the BL method, and the leaf sufficiency ranges, obtained using the QDpsR method, are similar to those existing in the literature. This indicates that this methodology is reliable in establishing standards and that the critical levels obtained can be used to improve the recommendation of fertilizers for eucalyptus.

Keywords: boundary line, fertility classes, sufficiency ranges.

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INTRODUCTION

The average yield of eucalyptus plantations throughout Brazil has increased by almost fourfold in the last decades, from $10 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in 1970 to $36 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in 2018 (Binkley et al., 2017; Iba, 2019). Such an increase of yield was achieved because of the advances in genetic improvement and the perfecting of silvicultural practices, including the more efficient management of nutrition and fertilization of forest plantations.

Most eucalyptus plantations in Brazil are established in Cerrado (tropical savanna ecosystem) whose soils, despite having favorable physical properties for plant growth, are highly weathered and leached and also show low natural fertility and high acidity (Gonçalves et al., 2008, 2013). These soils, in general, have low contents of potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), which are insufficient to maintain the productive capacity of the eucalyptus along its cultivation cycle (Reatto et al., 1998).

In addition to the natural poverty of these soils in terms of fertility, eucalyptus cultivation in successive rotations contributes even more to the depletion of soil nutrient stocks, which makes fertilization an indispensable practice to maintain high yields (Leite et al., 2010). These fertilizers should be applied at the appropriate time and in sufficient quantities to meet the nutritional requirements of the plants, besides promoting high yields with lower cost and lower environmental impacts (Silva et al., 2013).

Fertilizer recommendation for crops is based on soil analysis, and the diagnosis of fertility is made based on recommendation tables (Cantarutti et al., 2007). However, even when the analysis indicates adequate contents of nutrients in the soil, there is no guarantee that plants will be adequately supplied because factors such as limited moisture, compacted soils, among others, compromise the transport of nutrients in the soil and their absorption by plants.

Leaf analysis is a practice commonly adopted in the forestry field, complementary to soil chemical analysis. It aims to evaluate the nutritional condition of plants and contribute to adjustments in fertilization. The use of foliar analysis is based on the three basic assumptions proposed by Malavolta et al. (1997), who state that there must be, within certain limits, a direct relationship: a) between nutrient supply (by fertilizer) and production; b) between fertilizer dose and leaf content; and c) between leaf content and production.

The planting of new genetic materials, more productive and probably more demanding in terms of nutrients, and the introduction of new silvicultural techniques or cultivation in new environments make it necessary to conduct new studies to determine critical levels of nutrients in both soil and leaves. These studies serve as a basis for adequate fertilizer recommendations, which is extremely relevant for eucalyptus given the lack of more current information (Gazola et al., 2015), since the critical levels in the soil for the eucalyptus were determined in the 1980s (Novais et al., 1986).

To estimate nutrient critical levels and optimal ranges, it would be necessary to set up calibration experiments, that are long-lasting in the case of eucalyptus (Wadt et al., 1998). An alternative to obtain them without the need to set up calibration experiments is to employ the boundary-line (BL) method (Webb, 1972; Bhat et al., 2012; Bhat and Sujatha, 2013; Ali, 2018), associated with the Quadrant Diagram of the plant-soil Relationship (QDpsR) method (Deus et al., 2018; Sousa et al., 2018), which have as an advantage the possibility of using data from high-yielding commercial plantations.

Therefore, this study aimed to establish availability ranges of soil chemical attributes for eucalyptus, using the BL method, and to determine sufficiency ranges for foliar diagnosis of macronutrients for eucalyptus, using the QDpsR method.

MATERIALS AND METHODS

Study areas and database

Soil fertility classes and nutritional sufficiency ranges in leaves for the eucalyptus were obtained using a database containing information on yield, contents of macronutrients nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) in the leaf, bark, wood, and branch, and soil chemical properties (OM, P, K^+ , Ca^{2+} , and Mg^{2+}) in the 0.00-0.20 m layer. These data come from areas cultivated with *Eucalyptus grandis*, with ages varying from 72 to 153 months, planted at 3 × 2 m spacing, in six localities: Cocais - CO (19° 23' 41" S/42° 47' 11" W, 950 m), Piracicaba - PI (19° 39' 02" S/43° 01' 07" W, 880 m), Rio Doce - RD (19° 09' 34" S/42° 25' 07" W, 480 m), Sabinópolis - SA (18° 41' 09" S/42° 56' 56" W, 880 m), Santa Bárbara - SB (20° 00' 29" S/43° 21' 50" W, 820 m) and Virginópolis - VI (18° 40' 03" S/42° 30' 08" W, 860 m), in the Central-East region of Minas Gerais, Brazil, totaling 689 plots.

Data of the plots were distributed by localities as follows: Cocais (n = 129 plots), Piracicaba (n = 143), Rio Doce (n = 36), Sabinópolis (n = 138), Santa Bárbara (n = 121), and Virginópolis (n = 122). Due to differences between localities and plantation ages, it was decided to work with the yield on a relative scale, as adopted in studies on calibration for evaluating soil fertility.

According to Köppen's classification system, the predominant climate in the region of CO is Cwb, mesothermal of dry winter and mild summer, with temperatures below 22 °C. The region of RD has a predominant Aw climate, tropical with rainy summer and dry winter from May to September. In the regions of SB, PI, VI, and SA, the climate is Cwa, rainy temperate-mesothermal, in which the average temperature of the coldest month is less than 18 °C and that of the warmest month exceeds 22 °C, with rains occurring predominantly in the summer and winter with low levels of precipitation (Cenibra, 2001).

For the determination of leaf contents, samples of mature leaves (fully expanded) were collected from the middle third of the canopy and middle third of the branches, following the management adopted by the company. Nitrogen concentration was determined by the Kjeldahl method after sulfuric digestion. After digestion nitro-perchloric acid solution, P was determined by the ascorbic acid method (Braga and Defelipo, 1974); K by flame emission photometry; Ca and Mg by atomic absorption spectrophotometry (Malavolta et al., 1997).

Soil samples were collected in the 0.00-0.20 m layer at the end of the rotation and, subsequently, were air-dried and passed through a 2-mm-mesh sieve. These samples were analyzed for P and K^+ , extracted with Mehlich-1, Ca^{2+} and Mg^{2+} extracted with KCl 1 mol L⁻¹ (Claessen, 1997) and organic carbon by the Walkley-Black method (Walkley and Black, 1934).

To estimate the contents of P, K^+ , Ca^{2+} , and Mg^{2+} in soil (0.00-0.20 m), which existed in the area at the beginning of planting, the contents obtained in the soil chemical analysis (end of rotation) were summed with those estimated from the quantity of nutrients accumulated in plant shoots at the end of the rotation, as presented below (Figure 1).

To convert the accumulations of nutrients in the shoots to contents in soil in the 0.00-0.20 m layer (Figure 1), the trunk volume (TRV) was initially obtained by multiplying the mean annual increment (MAI) of the plot by its respective age. The nutrient content in the trunk (NCTR) was calculated by summing the content in the bark (NCDMBark) with the content in the wood (NCDMWood), considering the partition obtained by Gatto et al. (2011). Trunk dry mass (TRDM) was obtained by multiplying trunk volume (TRV) by trunk density (TRD) and then multiplied by the nutrient content in the trunk to obtain the accumulation in the respective organ (NATR).



Figure 1. Flowchart of the steps used to obtain the estimated contents of nutrients (P , K^+ , Ca^{2+} , and Mg^{2+}) in the soil in the 0.00-0.20 m layer before planting.

The dry masses of leaves (LDMest) and branches (BDMest) were estimated considering their proportion relative to the trunk and the partition obtained by Gatto et al. (2011). Subsequently, this mass was multiplied by their respective contents to estimate the accumulations in the leaves (NALest) and branches (NABest). These were summed with the accumulations of the trunk to obtain the nutrient accumulation in the shoots (NASest).

After dividing the nutrient accumulation in the shoots by the recovery rate of the plant (RRpl) and multiplying the result by the recovery rate of the extractor (RRext), the nutrient content recovered by the extractor was obtained (NutRext). This was divided by two (P and K) and also by the atomic mass (Ca and Mg) to convert $kg\ ha^{-1}$ to $mg\ dm^{-3}$ and to $cmol_c\ dm^{-3}$, respectively, obtaining the estimated nutrient content in the soil (NCSest), corresponding to the accumulation in the shoots. By summing the estimated content with that shown in the chemical analysis (NCSdet) (end of rotation), it was possible to estimate the contents of P , K^+ , Ca^{2+} , and Mg^{2+} existing in the soil before planting (Figure 1).

Obtaining soil fertility classes for eucalyptus

To estimate soil fertility classes by the BL method, scatter diagrams were constructed relating the relative MAI (relative MAI = MAI of each plot/highest MAI of all plots \times 100), obtained in each plot (y), with the soil contents of OM, P, K^+ , Ca^{2+} , and Mg^{2+} in the 0.00-0.20 m layer, in the respective plot (x), with correction for outliers. Then, the computer application "Boundary Fit" in development at the Federal University of Viçosa (UFV), was used to select the pairs of points (y, x) from the region of the upper boundary of the cloud of points.

The selected points were used to obtain regression equations, selecting the best fit based on the significance of the model, its biological meaning and the coefficient of determination (R^2). After that, these equations were used to estimate the soil fertility classes: Low (relative MAI <70 %), Medium (70 % \leq relative MAI <90 %), Adequate (90 % \leq relative MAI \leq 100 %), High (100 % > relative MAI \geq 90 %, to the right of maximum), Very High (relative MAI <90 %, to the right of maximum).

Obtaining leaf sufficiency ranges for eucalyptus

After the soil fertility classes were obtained, the leaf contents of N, P, K, Ca, and Mg (y) were plotted with the soil contents of OM, P, K^+ , Ca^{2+} , and Mg^{2+} , respectively (x), in a Cartesian coordinate system. Subsequently, the QDpsR method (Sousa et al., 2018) was used. This method consisted of separating into four quadrants (I, II, III, and IV) the set of points originating from the relationship between leaf content and soil content, using horizontal and vertical dashed lines (Figure 2).

The horizontal line, perpendicular to the ordinate axis (y), was drawn using as a criterion the average leaf contents of the database (19.15; 1.04; 8.07; 4.36; and 1.93 g kg^{-1} , respectively of N, P, K, Ca, and Mg). The vertical line, perpendicular to the abscissae axis (x), was drawn using the critical levels (relative MAI = 90 %) obtained for each nutrient in the soil and the OM content by the BL method, as proposed by Sousa et al. (2018).

The leaf response curve of the relationship between leaf content (y) and soil content (x) for each nutrient and OM, using the QDpsR method, was determined considering only the quadrants III and I (positive quadrants), because these are the ones in which there is the positive response of foliar nutrient content and, consequently, of yield (Deus et al., 2018; Sousa et al., 2018). Subsequently, regression equations were fitted to the pairs of points (y, x) located in quadrants III and I (highlighted in green).

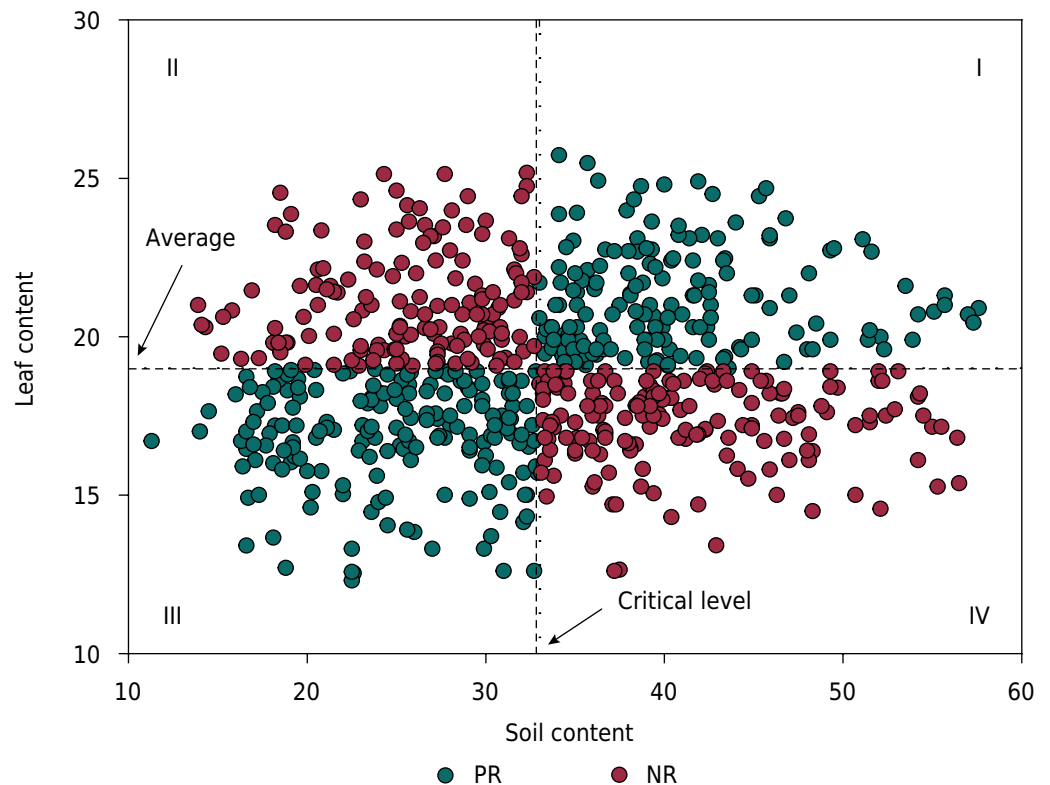


Figure 2. Scatter diagram illustrating the application of the Quadrant Diagram of the plant-soil Relationship (QDpsR) method, obtained from the relationship between nutrient concentrations in the leaf (y) and in the soil (x). PR: Positive response; NR: Neutral response.

To obtain the leaf sufficiency ranges for eucalyptus, the soil contents corresponding to the critical levels (relative MAI = 90 %) and optimal levels (relative MAI = 100 %) of the OM, P, K⁺, Ca²⁺, and Mg²⁺, obtained by the BL, were substituted in the equation generated by the QDpsR method. These ranges were then confronted with the adequate leaf contents found in the literature for the eucalyptus.

RESULTS

The descriptive analysis of eucalyptus yield, of some soil chemical properties and leaf contents of macronutrients, are presented in table 1. The yield of the plots used to obtain the relationships, based on the MAI, ranged from extremely low to very high (Gonçalves et al., 2012), with values higher than the national average that is around 35 m³ ha⁻¹ yr⁻¹. The soils had OM contents varying from low to good. The available P ranged from very low to very good, considering that the soils of the study areas, in general, have clayey/very clayey texture. The available K⁺ ranged from low to very good, the exchangeable Ca²⁺ ranged from very low to good and the exchangeable Mg²⁺ ranged from very low to medium (Alvarez V et al., 1999).

Regarding the leaf nutritional status of the plots used to obtain the relationships, it was observed that the N contents varied from tending to sufficient to tending to excessive (Table 1). Phosphorus and K contents ranged from deficient to excessive (Galdino, 2015). Calcium and Mg contents ranged from deficient to tending to excessive (Fernandes, 2010). The highest variability of soil chemical properties was observed in contents of Ca²⁺ and Mg²⁺. For plant characteristics, the highest variability occurred for the MAI and the leaf contents of K and Ca (Table 1).

The relationship of the relative MAI of the eucalyptus trunk with the OM content of the soil is presented in figure 3a. In the cloud of points of the relationship, the ones found on the upper edge (highlighted in green) were selected to establish the boundary line (BL) and, subsequently, based on these points, a second-degree polynomial regression model was fitted to evaluate the single effect of OM content on eucalyptus yield (Figure 3a).

Table 1. Summary of the descriptive statistics for mean annual increment (MAI), contents of organic matter (OM) and macronutrients in the soil estimated for the start of planting and leaf contents of macronutrients in eucalyptus plants

Variable	Minimum	Maximum	Mean	SD	CV
MAI (m ³ ha ⁻¹ yr ⁻¹)	2.2	47.7	25.76	9.61	37.32
Soil content					
OM (g kg ⁻¹)	11.20	57.00	32.90	9.64	29.31
P (mg dm ⁻³)	1.21	21.47	8.56	3.75	43.79
K ⁺ (mg dm ⁻³)	8.80	227.35	85.09	40.89	48.06
Ca ²⁺ (cmol _c dm ⁻³)	0.03	3.00	0.51	0.47	91.42
Mg ²⁺ (cmol _c dm ⁻³)	0.01	0.80	0.25	0.16	62.85
Leaves content					
N (g kg ⁻¹)	12.30	31.40	19.15	2.76	14.42
P (g kg ⁻¹)	0.43	4.65	1.04	0.28	26.67
K (g kg ⁻¹)	2.50	29.47	8.07	3.04	37.70
Ca (g kg ⁻¹)	0.78	10.90	4.36	1.56	35.76
Mg (g kg ⁻¹)	0.31	3.86	1.93	0.61	31.66

OM: 1.724 × OC - Walkley and Black Method; P and K⁺: extracted by Mehlich-1; Ca²⁺ and Mg²⁺: extracted by KCl 1 mol L⁻¹; N: determined by the Kjeldahl method; P: by the ascorbic acid method (Braga and Defelipo, 1974); K: by flame emission photometry; Ca and Mg: by atomic absorption spectrophotometry. SD: standard deviation; CV: coefficient of variation.

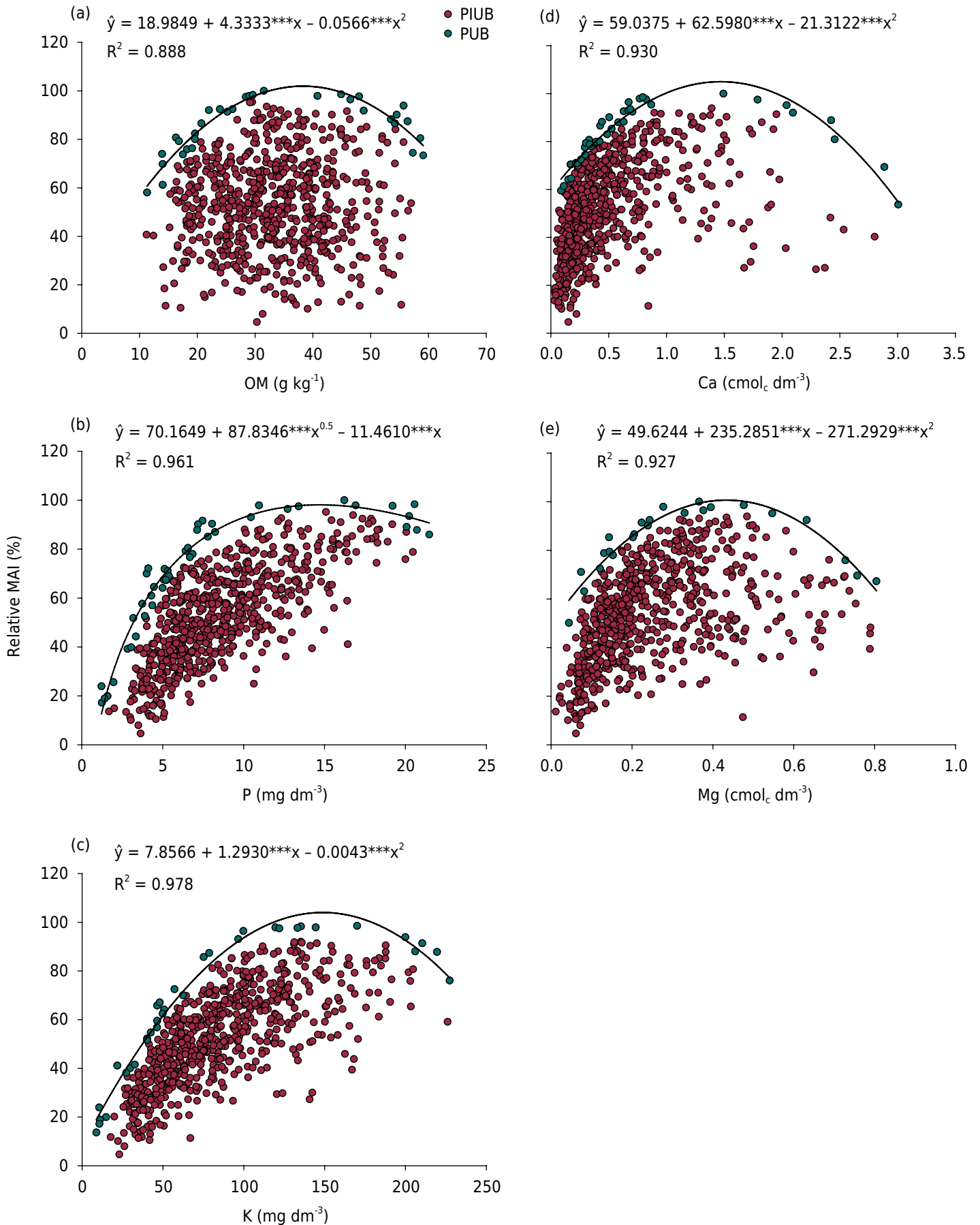


Figure 3. Scatter diagram and the boundary line of the relationship between the relative MAI of eucalyptus and OM (a), available P (b), available K^+ (c), exchangeable Ca^{2+} (d), and exchangeable Mg^{2+} (e) content in the soil (0.00-0.20 m). PIUB: points lower than the upper boundary; PUB: points of the upper boundary.

To establish the availability ranges of soil OM for eucalyptus plants (Table 2), the equation obtained by the BL approach (Figure 3a) was derived and the first derivative was made equal to zero ($dy/dx = 0$). The derivative was used to obtain the values of OM corresponding to the critical level (90 % of the relative MAI) and the yield of maximum physical efficiency (100 % of the relative MAI), as well as the other classes. Through the BL method, it was established that the ideal range of OM contents in the soil to obtain maximum eucalyptus yield ranged from 24.75 to 38.28 $g\ kg^{-1}$ (Table 2).

The scatter diagram showing the relationship between the relative MAI (yield) of eucalyptus and the P content available in the soil (0.00-0.20 m) is presented in figure 3b. The response curve obtained by the BL method indicates that eucalyptus trunk yield (relative MAI) increased along the range of P contents available in the soil, reaching a plateau from which there are no more increments, even with an increase in the content of the nutrient in soil (Figure 3b).

The relationship of the relative MAI (relative yield) of eucalyptus with soil P content and the BL approach (Figure 3b) was used to obtain the regression equations employed to define the critical level (90 % of the relative MAI), which corresponds to the upper limit of the Medium class, and the available ranges of the nutrient in the soil for this forest species. By the BL method, it is observed that the maximum yield was obtained with P contents in the soil ranging from 8.5 to 14.6 $mg\ dm^{-3}$ (Table 2).

The scatter diagram and BL equation, relating the relative MAI of eucalyptus with the K^+ content available in the soil (0.00-0.20 m) are presented in figure 3c. Based on the dispersion of the points, which represent the K^+ content available in each plot, it can be observed that most of them are below the BL and that the contents of this nutrient in the soil are grouped in a very wide range, indicating great variability in the soil of the evaluated areas, in terms of K^+ availability (Figure 3c).

According to the BL method for the relationship between the relative MAI of eucalyptus and the available K^+ content in the soil (0.00-0.20 m), it is observed that the yield was maximized within a wide range, between K^+ contents from 100.0 to 150.35 $mg\ dm^{-3}$ (Figure 3c; Table 2). Outside this range, eucalyptus yield was compromised in response to changes in soil K^+ content.

The response curve of the relative MAI (yield) of eucalyptus as a function of the Ca^{2+} content in the soil is presented in figure 3d. Based on the distribution of the data set in the scatter diagram, it can be observed that most of the plots have Ca^{2+} contents lower than 1.0 $cmol_c\ dm^{-3}$. The BL of the relationship indicates that there was a positive effect of the increase of Ca^{2+} content in soil on the yield; however, after reaching an optimal value, it was negatively affected (Figure 3d).

Table 2. Classes of interpretation of contents of organic matter (OM), phosphorus (P), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the soil estimated for the start of planting (0.00-0.20 m) for eucalyptus

Relative MAI	OM	P	K^+	Ca^{2+}	Mg^{2+}	Classes of interpretation
%	$g\ kg^{-1}$	$mg\ dm^{-3}$		$cmol_c\ dm^{-3}$		
< 70	< 15.25	< 4.9	< 65.0	< 0.25	< 0.10	Low
70 - 90	15.25 - 24.75	4.9 - 8.5	65.0 - 100.0	0.25 - 0.77	0.10 - 0.25	Medium ⁽¹⁾
90 - 100	24.75 - 38.28	8.5 - 14.6	100.0 - 150.35	0.77 - 1.47	0.25 - 0.43	Adequate
100 - 90	38.28 - 51.75	14.6 - 22.6	150.35 - 199.0	1.47 - 2.17	0.43 - 0.62	High
< 90	> 51.75	> 22.6	> 199.0	> 2.17	> 0.62	Very High

OM: $1.724 \times OC$ - Walkley and Black Method; P and K^+ : extracted by Mehlich-1; Ca^{2+} and Mg^{2+} : extracted by KCl 1 mol L^{-1} ; ⁽¹⁾ The upper limit of the class indicates the critical level.

The availability ranges of Ca^{2+} in the soil, obtained based on the BL equation, are presented in table 2. By deriving the BL equation and making it equal to zero, it was obtained the soil Ca^{2+} content that maximizes the relative MAI ($1.47 \text{ cmol}_c \text{ dm}^{-3}$). Subsequently, the relative MAI, obtained with this Ca^{2+} content in the soil, was multiplied by 0.9 to obtain the nutrient content in the soil corresponding to the critical level ($0.77 \text{ cmol}_c \text{ dm}^{-3}$).

The relationship of relative yield (relative MAI) of eucalyptus trunk with the Mg^{2+} content has a high dispersion of the points as a function of the availability of the nutrient in the soil (Figure 3e). The regression equations fitted by the BL method (Figure 3e) were used to calculate the Mg^{2+} availability ranges in the soil and the nutrient content which caused maximum economic efficiency or critical level (90 % of the relative MAI) and maximum physical efficiency or optimal level (100 % of the relative MAI), which corresponded to 0.25 and $0.43 \text{ cmol}_c \text{ dm}^{-3}$, respectively (Table 2).

The leaf contents of N and P in eucalyptus plants responded positively to the increase in soil contents of OM and available P. For the N contents in the leaf tissue, there is a tendency of stabilization from the content of 40 g kg^{-1} of OM in the soil (Figure 4a). To estimate the leaf sufficiency range of N, the critical and optimal levels (24.75 and 38.28 g kg^{-1}) of OM in the soil were substituted in the QDpsR equation and the range from 19.4 to 21.3 g kg^{-1} of N was obtained as ideal.

The QDpsR equation (Figure 4b) and the critical and optimal levels of P in the soil (8.5 and 14.6 mg dm^{-3}) were used to obtain the adequate range of leaf P contents in *Eucalyptus grandis* plants, which ranged from 1.0 to 1.2 g kg^{-1} of P.

The leaf K content was directly related to the content of this nutrient in soil (Figure 4c). The response curve, fitted to the data of quadrants III and I by an exponential model, indicates that the greater availability of K^+ in the soil was translated, within certain limits, into higher contents of the nutrient in eucalyptus leaves, obeying one of the basic assumptions so that foliar diagnosis can be used (Malavolta et al., 1997).

The range of adequate K contents in the leaf tissue of eucalyptus plants, obtained based on the QDpsR equation (Figure 4c) and the critical and optimal levels of K^+ in the soil (100.0 and $150.35 \text{ mg dm}^{-3}$) was 8.5 and 10.6 g kg^{-1} of K.

The contents of Ca and Mg in eucalyptus leaves showed a positive relationship with the contents of Ca^{2+} and Mg^{2+} in soil (Figure 4). The fit of the curves to the points of the quadrants III and I by an exponential model, similar to the behavior of the Mitscherlich's law or the law of diminishing returns, demonstrates that the leaf contents of Ca and Mg tend to reach a plateau and show small increments with soil contents higher than 2.5 and $0.6 \text{ cmol}_c \text{ dm}^{-3}$ of Ca^{2+} and Mg^{2+} , respectively (Figures 4d and 4e).

Leaf sufficiency ranges of Ca and Mg were obtained using the equations established by the QDpsR method (Figures 4d and 4e). By using the critical and optimal levels of Ca^{2+} (0.77 and $1.47 \text{ cmol}_c \text{ dm}^{-3}$) and Mg^{2+} (0.25 and $0.43 \text{ cmol}_c \text{ dm}^{-3}$) in the soil, and substituting in the equations, it was possible to find the ranges from 4.8 to 6.1 g kg^{-1} for Ca and from 1.9 to 2.4 g kg^{-1} for Mg, as ideal for *Eucalyptus grandis*.

DISCUSSION

The BL can be interpreted in terms of the Liebig's law of the minimum, which establishes that the yield is determined by the factor found in the lowest quantity and that this yield will vary with changes in this attribute until it is no longer limiting (Shatar and McBratney, 2004). The BL represents the limiting effect of an independent variable, understood in this case as the soil OM content, on a dependent variable, represented by the relative yield of eucalyptus (Figure 3a). Thus, it is assumed that all plots with

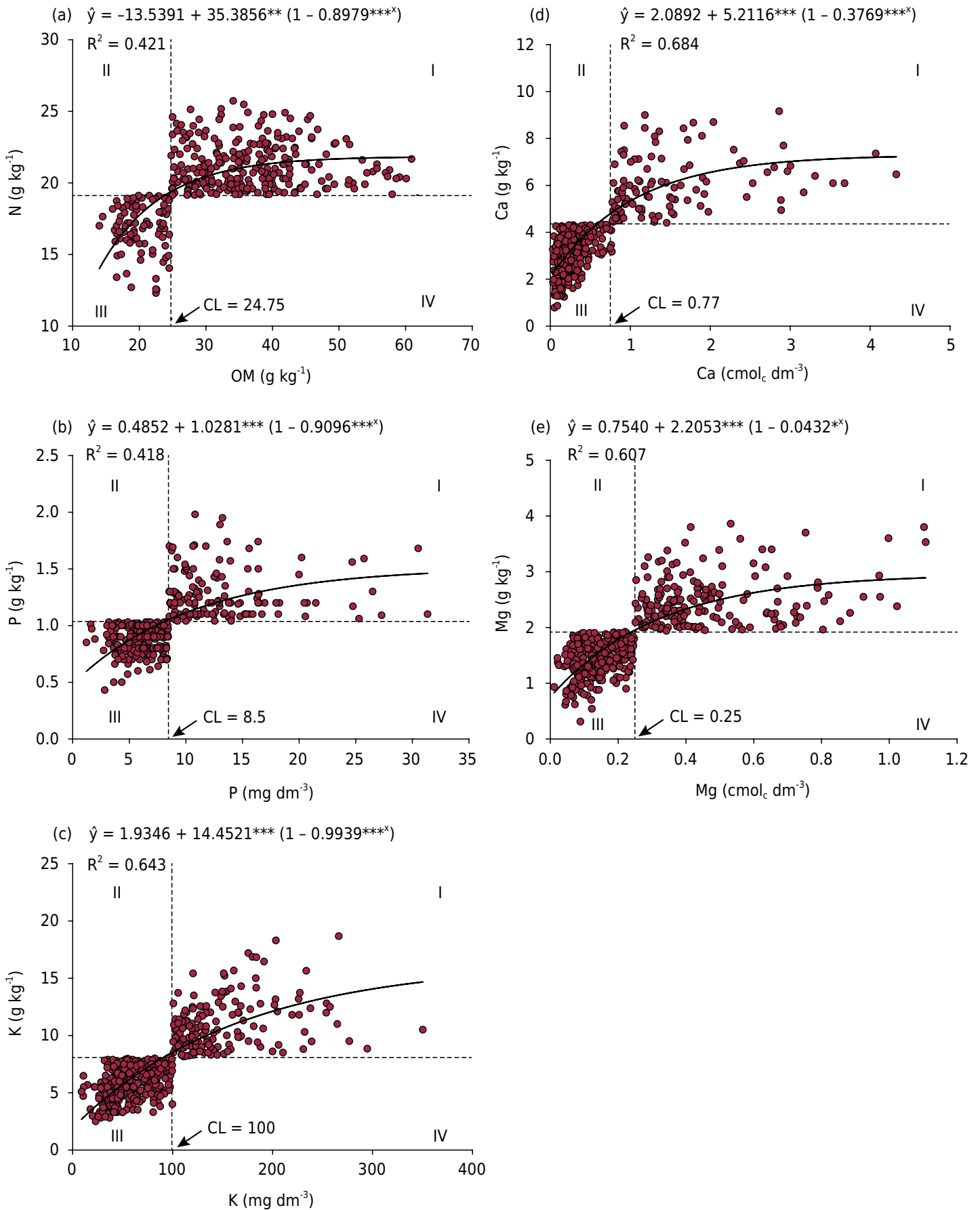


Figure 4. Relationship between N (a), P (b), K (c), Ca (d), and Mg (e) contents in eucalyptus leaves as a function of OM, P, K⁺, Ca²⁺, and Mg²⁺ contents in soil (0.00-0.20 m), respectively, obtained by the Quadrant Diagram of the plant-soil Relationship (QDpsR) method. CL: critical level.

yield values (relative MAI) below the BL are being influenced by another independent variable or by the combination of other independent variables (Webb, 1972; Blanco-Macías et al., 2010).

The values of OM obtained in this work (Table 2) are within the range from 24.25 to 38.93 g kg⁻¹ of OM obtained based on the study of Gava (2005), who evaluated the relationships between soil properties and the yield of *Eucalyptus grandis* plantations, with ages ranging from 6.5 to 7.0 years. These are within the range from 21 to 40 g kg⁻¹, classified as medium by the Soil Fertility Commission of Minas Gerais State - CFSEMG (Alvarez V et al., 1999).

Soil organic matter (OM) under forest plantations has great importance in supplying nutrients to plants, showing good correlation with N availability and yield (Gonçalves et al., 2013; Pulito et al., 2015). Because of this good correlation with N contents, Gonçalves et al. (2008) proposed the expected response classes and the recommendation of N fertilization in eucalyptus plantations using the OM content as reference. According to these authors, soils with OM contents below 20 g kg⁻¹, from 21 to 50 g kg⁻¹ and higher than 50 g kg⁻¹, exhibit high, moderate, and no response to N fertilization, respectively.

Considering that the maximum MAI of these plots is 47.7 m³ ha⁻¹ yr⁻¹ (Table 1) and that they generally have clayey/very clayey soils, this value of P critical maintenance level (Table 2) is higher than the 4.5 mg dm⁻³ defined for the eucalyptus, considering a MAI of 50 m³ ha⁻¹ yr⁻¹ (Novais et al., 1986). However, it should be noted that the critical level (8.5 mg dm⁻³) obtained in this study is within the availability range (8.0 to 12.0 mg dm⁻³) established for clayey/very clayey soils in the state of Minas Gerais, Brazil (Alvarez V et al., 1999).

According to the K⁺ response curve in the soil, it is possible to note that the yield is much more affected by K⁺ deficiency than by its excess (Figure 3c). These points (plots) located along the BL represent cases in which the factors influencing yield have optimal values and the yield is influenced only by K⁺ content. Those located below the BL indicate that one or more determinants of yield were not optimized, and the production level did not depend only on K nutrition (Izsáki, 2017). The value of the critical level of K⁺ (90 % of the relative MAI), which encompasses the upper limit of the Medium class (Table 2), is close to the 90 mg dm⁻³ of K⁺ proposed by Novais et al. (1986) for MAI of 50 m³ ha⁻¹ yr⁻¹.

The increase of K⁺ availability in the soil above the range considered adequate for the best development of the plants resulted in reductions in eucalyptus yield (Figure 3c; Table 2). Reductions in eucalyptus yield, due to greater availability of K⁺ in the soil, were also observed by Gazola et al. (2015). These authors found that higher K doses in the soil led to increasing in the leaf content of the nutrient and reduced Ca and Mg contents, which agrees with Malavolta et al. (1997) and Marschner (2012), who affirm that the K⁺ at high contents in soil affects the absorption of Ca²⁺ and Mg²⁺ and, consequently, the yield.

The information in table 2 for fertilizer recommendation will be used as follows. The recommended dose (RD) of the nutrient is obtained by the difference between the critical level (CL) of the nutrient for the eucalyptus (Table 2) and the nutrient content available in the soil (NUTav), considering the nutrient recovery rate by the extractor (RRext), using the formula $RD = [(CL - NUTav) / RRext] \times 2$. Thus, considering a soil K⁺ content of 70 mg dm⁻³ and an extractor recovery rate of 80 %, the recommended dose for eucalyptus will be 75 kg ha⁻¹ of K, i.e., $RD = [(100 - 70) / 0.8] \times 2$.

The value of Ca²⁺ critical level in the soil (Table 2), obtained by the BL method for a MAI of 47.7 m³ ha⁻¹ yr⁻¹ is close to the 0.80 cmol_c dm⁻³ proposed by Novais et al. (1986) for an expected yield of 50.0 m³ ha⁻¹ yr⁻¹. The BL can reveal potential maximum yields for a given crop in a given environment. These can sometimes represent the maximum yields obtained under management conditions or locally attainable yield (Tittonell and Giller, 2013).

When soil Ca^{2+} contents were above $1.47 \text{ cmol}_c \text{ dm}^{-3}$, it was observed that eucalyptus yield was compromised (Figure 3d; Table 2). High Ca^{2+} contents in soil reduce the contents of K^+ and Mg^{2+} , due to the antagonism between Ca^{2+} , K^+ , and Mg^{2+} , competing for the same cationic exchange sites, a result found by Chatzistathis et al. (2015). These authors found that the increase of Ca^{2+} contents in the soil, due to the application of limestone (calcitic), also reduced the soil and leaf contents of Cu, Mn, and Fe, essential elements to plant growth. According to Walworth et al. (1986), the advantage of the second-degree polynomial curve derived from the BL method is that it can be used to isolate the influence of a single production factor from data in which yield was affected by multiple factors (Webb, 1972).

The Mg^{2+} critical level in soil (Table 2) obtained by the BL method is higher than the $0.19 \text{ cmol}_c \text{ dm}^{-3}$ suggested as ideal to obtain yields of $50 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in eucalyptus plantations (Novais et al., 1986). The second-degree polynomial equation of the BL indicates that the increase in soil Mg^{2+} content initially caused a positive response with increments of yield (Figure 3e). Higher contents of the Mg^{2+} in the soil led to a reduction in growth, indicating that under this condition other factors would also be limiting the yield.

The database used in this study allowed relating the soil contents OM, P, K^+ , Ca^{2+} , and Mg^{2+} with the relative MAI (relative yield) of eucalyptus using the BL method (Figures 3a to 3e). These relationships were obtained by the fitting of second-degree polynomial regression equations, that were highly significant ($p < 0.0001$) and with high R^2 values (0.88 to 0.97), indicating that the BL method can be used to determine the availability ranges of soil chemical properties, as evidenced in other studies (Evanylo and Sumner, 1987; Schnug et al., 1996; Bhat et al., 2012; Deus et al., 2018; Sousa et al., 2018).

The mineralizable N from soil OM in eucalyptus plantations is the main source of the nutrient for plants, which justifies the relationship between leaf N content and soil OM content (Barreto et al., 2010). However, OM mineralization and N availability for plants are strongly affected by climatic conditions and soil texture (Pulito et al., 2015) and, thus, this relationship may not always occur.

The leaf contents of N (Figure 4a) are close to those estimated by Malavolta et al. (1997) for *Eucalyptus grandis* plantations and within the range established by Bellote and Silva (2000) and by Galdino (2015) for eucalyptus plantations in Brazil, but below the range suggested by Gonçalves (2011) for the most planted *Eucalyptus* species in the country (Table 3). The leaf contents range of P (Figure 4b) corroborates those obtained by Bellote and Silva (2000), Gonçalves (2011), and Galdino (2015), but is below the one suggested by Malavolta et al. (1997) for high-yielding plants (Table 3).

For leaf P contents, the tendency of stabilization due to the higher availability of the nutrient in the soil was less pronounced (Figure 4b), indicating that plants cultivated in

Table 3. Adequate ranges of leaf macronutrient contents for eucalyptus

Macronutrient	Authors			
	Malavolta et al. (1997) ⁽¹⁾	Bellote and Silva (2000) ⁽²⁾	Gonçalves (2011) ⁽³⁾	Galdino (2015) ⁽⁴⁾ ; Fernandes (2010) ⁽⁵⁾
N (g kg^{-1})	21.0-23.0	20.0-22.0	21.0-30.0	14.8-20.9
P (g kg^{-1})	1.3-1.4	0.9-1.4	1.0-1.3	0.82-1.22
K (g kg^{-1})	9.0-10.0	7.5-8.3	5.5-8.5	5.6-8.8
Ca (g kg^{-1})	5.0-6.0	3.8-6.0	3.5-6.0	3.68-5.9
Mg (g kg^{-1})	2.5-3.0	2.6-6.2	2.0-3.0	1.39-2.57

⁽¹⁾ *Eucalyptus grandis* plantations of high yield; ⁽²⁾ *Eucalyptus* plantations in general; ⁽³⁾ Most planted *Eucalyptus* species in Brazil; ⁽⁴⁾ N, P, K; ⁽⁵⁾ Ca and Mg in *Eucalyptus* plantations in Brazil obtained by the boundary line.

soils with high contents of this nutrient, or supplied by fertilization, must have high P contents in the leaf tissue, even if it does not translate into higher yield. These results are in agreement with Melo et al. (2016), who observed that phosphate fertilization caused an increase in the leaf P content of eucalyptus plants.

A positive relationship between leaf K content and soil K⁺ content (Figure 4c) has also been observed by Almeida et al. (2010), Silva et al. (2013), and Gazola et al. (2015), who found that the increase in K doses applied to the soil caused an increase in leaf K contents in eucalyptus plants.

The leaf K contents obtained by the QDpsR method are higher than those established by Bellote and Silva (2000), Gonçalves (2011), and Galdino (2015) and are close to those suggested as adequate by Malavolta et al. (1997) for *Eucalyptus grandis* plantations (Table 3).

The leaf Ca and Mg contents increased with greater availability of Ca²⁺ and Mg²⁺ in soil (Figure 4). These results corroborate those obtained by Simonete et al. (2013), who found that liming (calcitic limestone) caused an increase in Ca and Mg contents in the soil and leaf tissue of *Eucalyptus saligna* plants.

These ranges for Ca (Figure 4d) are consistent with those obtained in the literature for the eucalyptus by several authors (Table 3). In the case of Mg (Figure 4e), the contents obtained in the present study are only within the range proposed by Fernandes (2010) and below that proposed by the other authors (Table 3). The differences observed between the ranges proposed in this study and those of other authors can be attributed to the different calculation methods used (BL and QDpsR), the area covered by the plantations, the *Eucalyptus* species used to determine the standards and the edaphoclimatic conditions in the different sites.






CONCLUSIONS




The Boundary Line method allowed estimating the availability ranges of OM, P, K⁺, Ca²⁺, and Mg²⁺ in the soil for the eucalyptus. The adequate range of soil chemical properties obtained by the BL was 24.75-38.28 g kg⁻¹ of OM; 8.5-14.6 mg dm⁻³ of P; 100.0-150.35 mg dm⁻³ of K⁺; 0.77-1.47 cmol_c dm⁻³ of Ca²⁺; and 0.25-0.43 cmol_c dm⁻³ of Mg²⁺. The QDpsR method allowed relating leaf contents with the nutrient contents in the soil and estimating reliable sufficiency ranges. The ideal range of leaf contents for *Eucalyptus grandis* obtained by the QDpsR method is 19.4-21.3 g kg⁻¹ of N; 1.0-1.2 g kg⁻¹ of P; 8.5-10.6 g kg⁻¹ of K; 4.8-6.1 g kg⁻¹ of Ca; and 1.9-2.4 g kg⁻¹ of Mg. The critical levels of nutrients in the soil, obtained by the BL method, and the leaf sufficiency ranges, obtained using the QDpsR method, are similar to those existing in the literature. This indicates that this methodology is reliable in establishing standards and that the critical levels obtained can be used to improve the recommendation of fertilizers for eucalyptus.




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