

Division - Soil Use and Management | Commission - Soil Fertility and Plant Nutrition

Relationship between Coffee Leaf Analysis and Soil Chemical Analysis

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ABSTRACT: Research focused on adequate nutrition of plants is essential in modern coffee production to increase yield and develop more efficient management strategies with greater environmental and economic sustainability. The objectives of this study were to establish critical and optimal levels of soil fertility properties for high yielding Arabica coffee crops using the Boundary Line method and, then, relate the macronutrient contents in the diagnostic leaf of coffee to the macronutrients available in the soil using the Quadrant Diagram of the Plant-Soil Relationship (QDpsR). The study made use of a soil chemical analysis database, leaf macronutrient contents, and Arabica coffee yield from five representative coffee-growing regions in Minas Gerais. An analysis of data consistency was performed, and relative fruit yield (RFY) was related to the soil organic matter (SOM), P, K, Ca, and Mg contents in the soil, establishing the boundary line (BL) in each graph. Equations were adjusted from the BL points, and the equation that best fit was selected. Using the QDpsR method, the response plane was divided into four quadrants, where the total leaf contents of N, P, K, Ca, Mg, and S were plotted as a function of the contents of SOM, P, K, Ca, and Mg in the soil, on the y and x axes of the Cartesian coordinate system. The regression equations were adjusted to the pairs of points (y, x) of quadrants III and I and were used to estimate the macronutrient sufficiency ranges from the critical and optimal levels in the soil. The BL method was used to determine the class of good soil fertility for SOM, P, K, Ca, and Mg. The QDpsR method allows determination of response curves for leaf content as a variable of soil contents, making it possible to estimate the sufficiency ranges in the diagnostic leaf of coffee: 33.4-35.8 g kg⁻¹ of N, 1.4-1.6 g kg⁻¹ of P, 24.4-27.0 g kg⁻¹ of K, 11.9-13.6 g kg⁻¹ of Ca, 3.8-4.5 g kg⁻¹ of Mg, and 1.4-1.8 g kg⁻¹ of S; which were consistent with the sufficiency ranges considered suitable for the crop. This study demonstrated the importance of leaf analysis as a tool for evaluation of the nutritional status of Arabica coffee since the technique is consistent with the theoretical principles underlying it.

Keywords: *Coffea arabica* L., leaf nutrient content, soil nutrient content, nutritional management.

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INTRODUCTION

Modern coffee production aims to increase crop yield, and, at the same time, to develop more efficient management strategies that allow environmental and economic sustainability of the crop (Pretty, 2008; Guimarães and Reis, 2010). The rational use of inputs in agricultural production is essential in this scenario, especially in an increasingly demanding market, both in product quality and in terms of farmers commitment to good farming practices, and in the face of the high costs of these inputs.

Research aimed at adequate plant nutrition becomes even more necessary to make the coffee sector more competitive by increasing yield, especially in the Brazilian *Cerrado* (Brazilian tropical savanna) (Guimarães and Reis, 2010; Fernandes et al., 2012).

Mineral fertilizers constitute a considerable part of the costs of coffee production, which makes it essential to monitor the nutritional status of crops through leaf chemical analysis for the purpose of recommendation of more balanced and economically appropriate applications of fertilizers (Bataglia et al., 2004).

The use of nutrient content in leaf tissue to evaluate the nutritional status of plants was originally proposed by Lagatu and Maume (1934). It was based on the assumption that the plant itself is used as a soil nutrient extractor and, within certain limits, there is a relationship between the supply of nutrients, either from the soil or the fertilizer, and leaf nutrient contents; increases in leaf nutrient content are related to higher yields, and decreases to lower yields (Bataglia and Santos, 2001).

Evaluation of the nutritional status of plants by leaf tissue analysis indicates the nutritional status of the plant at a given moment and allows detection of deficiency, sufficiency, or toxicity of nutrients (Cantarutti et al., 2007). It also serves as a guide to adjust or redirect the fertilization program to correct nutritional imbalances to achieve higher crop yield (Malavolta et al., 1997; Wadt, 2011).

Different diagnostic methods in the literature, however, fail to provide direct information on the amount of nutrients to be supplied to plants (Wadt, 2011). This information is limited mainly by the lack of systematic studies on the relationship between leaf chemical analysis and nutrient availability in the soil or properties of soil fertility, and their relationship, in turn, with coffee yield.

This knowledge gap results from the difficulty of studying an isolated nutrient under field conditions, in which several uncontrolled factors simultaneously affect the rate of nutrient accumulation and dry matter production of crops (Fageria et al., 1991) and make this kind of study expensive. However, methods such as the Boundary Line (BL), together with a new approach to analysis of the plant-soil relationship, the Quadrant Diagram of the Plant-Soil Relationship (QDpsR) (Sousa, 2016), are useful tools to overcome this problem. The methods are used to confirm and improve the criterion of use of leaf analysis to adjust fertilization recommendations for the coffee crop and provide adequate nutrition and higher yields.

The BL method was originally proposed by Webb (1972). It considers that the line defining the best performance in the population is at the edge of any body of data, and occurs whenever there is a cause-effect relationship between two variables. This line represents the limiting effect of the variable analyzed, considered as independent (x), on the variable considered as dependent (y) and, therefore, it can be assumed that all values below this boundary result from the influence of other variables or of the combination of variables that are possibly limiting the dependent variable.

This approach has been widely used to determine optimal nutrient levels and relationships between contents for plant nutritional diagnosis, as well as to establish critical nutrient levels in the soil (Evanylo and Sumner, 1987; Njukeng et al., 2013; Almeida et al., 2016, Maia and Morais, 2016).

The objectives of this study were to establish the critical and optimal levels of soil fertility properties for high yielding Arabica coffee crops using the BL method and, to relate the macronutrient contents in the diagnostic leaf of coffee to macronutrients available in the soil using the Quadrant Diagram of the Plant-Soil Relationship (QDpsR).

MATERIALS AND METHODS

Characteristics of the database and study regions

This study used a database containing information of physical and chemical soil analysis and leaf nutrient contents from coffee plantations from the Cerrado (Patrocínio), southern Minas Gerais (Guaxupé and São Sebastião do Paraíso), and Zona da Mata (Manhuaçu and Viçosa) regions, which are considered representative of coffee production in the state of Minas Gerais.

Coffee plantations were selected in each region and sampling units (SUs) were defined. A total of 44 plantations were sampled in Patrocínio, 30 in Guaxupé, 17 in São Sebastião do Paraíso, 36 in Manhuaçu, and 41 in Viçosa, constituting 168 SUs in the five regions from 1996 to 1999, comprising three crop years, 96/97, 97/98, and 98/99.

Sampling units

In each farm, uniform field plots in regard to management practices were selected for SUs: without irrigation (rainfed system); plant density (3000-5000 plants ha⁻¹); cultivar (Catuaí); crop age (5-9 years); soil texture; fertilization practices, soil liming; pest and disease control; land slope; and yield records from the last two or three harvest seasons.

The size of the SUs ranged from 0.5 to 1.0 ha. These units were marked off by stakes, and a layout was drawn to locate them. The farmers agreed to harvest the SUs separately and record the yields in the next two crop seasons. They also answered a questionnaire on management history and yield for each SU.

Sampling of soil and leaf analyses

Soil samples were collected under the canopy projection area, where fertilization is usually applied, during the reproductive period of the coffee tree, specifically when the fruits were at the pinhead stage. Sample collection was carried out with the help of coffee cooperatives such as Cooxupé and Cooparaíso, the Heringer Fertilizers company, and research and extension institutes such as Epamig and Emater-MG.

Soil samples were composed of 20 subsamples taken at 20 different locations within the SU from layers of 0.00-0.05, 0.05-0.20, and 0.20-0.50 m. After mixing the subsamples together, approximately 0.5 dm³ of the material was transferred to a plastic bag, labeled, and sent to the routine analysis laboratory of the Department of Soils of the *Universidade Federal de Viçosa*. Physical and chemical characterization of the soil samples was made of the air-dried fine-earth fraction: particle size analysis by the pipette method; pH(H₂O), soil:solution at 1:2.5; Al, Ca, and Mg using 1 mol L⁻¹ KCl extractor (Claessen, 1997); P, K, Cu, Zn, Fe, Mn using the Mehlich-1 extractor; and soil organic matter (SOM) contents by the modified Walkley-Black method (Defelipo and Ribeiro, 1997).

Leaf samples were collected when the fruit was in the pinhead stage, between the flowering phase and the first phase of rapid fruit expansion, from November to mid-January, by removing newly mature leaves with petioles from the 3rd or 4th pairs of leaves from the apex of the branch, in the middle part of the plants, from all cardinal directions. In each SU, 20 plants were chosen at random, and two pairs of leaves were removed from each plant, for a total of 80 leaves per uniform plot.

Samples were collected between 6 and 10 a.m. in the morning, washed with tap water, rinsed with filtered water, packed in paper bags, and sent to the Plant Mineral Nutrition Laboratory of the Department of Plant Science of the *Universidade Federal de Viçosa*.

In the laboratory, the leaf samples were dried in a forced-air-circulation oven at 70-75 °C to constant weight, ground in a Wiley mill to pass through 0.85-mm (20-mesh) screen, and subjected to mineralizations and analyses.

Contents were determined as follows: organic N by the Nessler method (Jackson, 1958); nitrate (N-NO₃⁻) by the Cataldo method (Cataldo et al., 1975); K by flame photometry; P by molecular absorption spectrophotometry, vitamin C method, modified by Braga and Defelipo (1974); and S by sulfate turbidimetry (Blanchar et al., 1965). The contents of Ca, Mg, Cu, Fe, Mn, and Zn were determined by atomic absorption spectrophotometry, and B by colorimetry using the Azometin-H method (Malavolta et al., 1997).

Soil and leaf samplings were carried out on the same day, at least one month after any fertilization or spraying, and they were labeled for location, sampling time, fertilization applied, and the nutrients and properties to be determined.

Data analysis by the Boundary Line

With information from the database, the crops were separated in regard to yield observed in each SU in accordance with the biennial production of the coffee crop. In this study, only the crops from crop years that had highest yields were considered, based on the assumption that higher yielding plants come from optimal production conditions, including balanced nutrition. Consistency analysis of the data on soil and plant chemical analysis was performed, as well as on yield, which showed normal distribution ($p < 0.0643$) and yields ranging from 1.02 to 6.16 t ha⁻¹, with an average of 2.90 t ha⁻¹.

From the nutrient content in soil chemical analysis at layers of 0.00-0.05 and 0.05-0.20 m, a weighted average of the nutrients at these two layers was calculated to obtain a single value for the 0.00-0.20 m layer. Scatter plots related the relative fruit yield from high production years, RFY [as %, where relative fruit yield = (yield of each crop/yield of the highest yielding crop) × 100], on the y-axis, to the contents of SOM, K, Ca, and Mg at the layer of 0.00-0.20 m, on the x-axis.

Relative phosphorus (RP, %), which is the P content relative to its critical level, was calculated in an attempt to eliminate the effect of soil phosphate buffer capacity. This calculation took into account the phosphorus content available in the soil (*caP*) and its critical level (*c/P*) and was performed using the following formula: $RP (\%) = 100 \times (caP/c/P)$. Relative phosphorus was calculated using the *cl* of 9.0 mg dm⁻³ of P, constant in the table of fertilization recommendation for coffee in production for the state of Minas Gerais (Guimarães et al., 1999), considering a soil with 46 % clay (average clay content of the soils used in this study).

The boundary line approach was used, which provides an optimal relationship between RFY and the levels of SOM and macronutrients in the soil. The software Boundary Fit, in development at the *Universidade Federal de Viçosa* (UFV), was used to select the pairs *yx*, which define the upper population regarding RFY (*y*) for each *x* (soil content) of the cloud of points. Equations were adjusted to the data pairs, and the equation that best fit was selected.

Once the respective equations were obtained, the critical (*cl*) and optimal (*ol*) levels of SOM, P, K, Ca, and Mg in the soil were calculated, corresponding to 90 and 100 % of the estimated RFY, respectively. In order to determine the optimal levels, the first derivative of the BL equations was calculated by equating it to 0 ($dy/dx = 0$), and the maximum RFY (100 %) was estimated from the optimal levels. The critical levels were calculated by multiplying the maximum RFY by 0.90 and replacing these values in the BL equations to obtain the contents corresponding to 90 % of the maximum RFY.

Data analysis by QDpsR

Macronutrient contents (N, P, K, Ca, Mg, and S) in the diagnostic leaf of coffee, in high production years, and their levels available in the soil at the layer of 0.00-0.20 m were plotted on the y and x axes, respectively. The relationship for leaf N and S contents was obtained as a function of the SOM content.

In the method Quadrant Diagram of the Plant-Soil Relationship (QDpsR) (Sousa, 2016), horizontal dashed lines and vertical lines were drawn perpendicular to the axes of the ordinates and abscissae, respectively, on the cloud of points of the relationship between the leaf macronutrient content and SOM and soil macronutrient contents, in order to separate the population of points into four quadrants (I, II, III, and IV) (Figure 1).

The marker used to draw the horizontal dashed line, perpendicular to the y-axis, was the mean leaf content in the index leaf of Arabica coffee crops ($\bar{y} = \Sigma Y/n$). The vertical line, perpendicular to the x-axis, used the critical levels of SOM and macronutrients at the layer of 0.00-0.20 m determined by the boundary line method.

The calibration curve of the leaf contents of N and S, P, K, Ca, and Mg as a function of the contents of MO, P, K, Ca, and Mg in soil, respectively, were adjusted only to the quadrants III and I. It was assumed that in these quadrants there is a positive response of leaf nutrient content and productivity, representing the plant-soil relationship, analogously to the Mitscherlich's law, or the law of decreasing increments (Rajj, 1981).

Regression equations were adjusted to the pairs of points (yx) of the crop populations present in quadrants III and I to obtain the best fit.

To determine the sufficiency ranges of macronutrients, the *cl* and *ol* of SOM and macronutrients in the soil at the layer of 0.00-0.20 m obtained by BL were substituted in the QDpsR equations to estimate the sufficiency ranges in the diagnostic leaf of coffee. These ranges were compared with those in the literature considered ideal for coffee (Mills and Jones Junior, 1996; Malavolta et al., 1997; Matiello, 1997; Guimarães et al., 1999; Martinez et al., 2003; Farnezi et al., 2009).

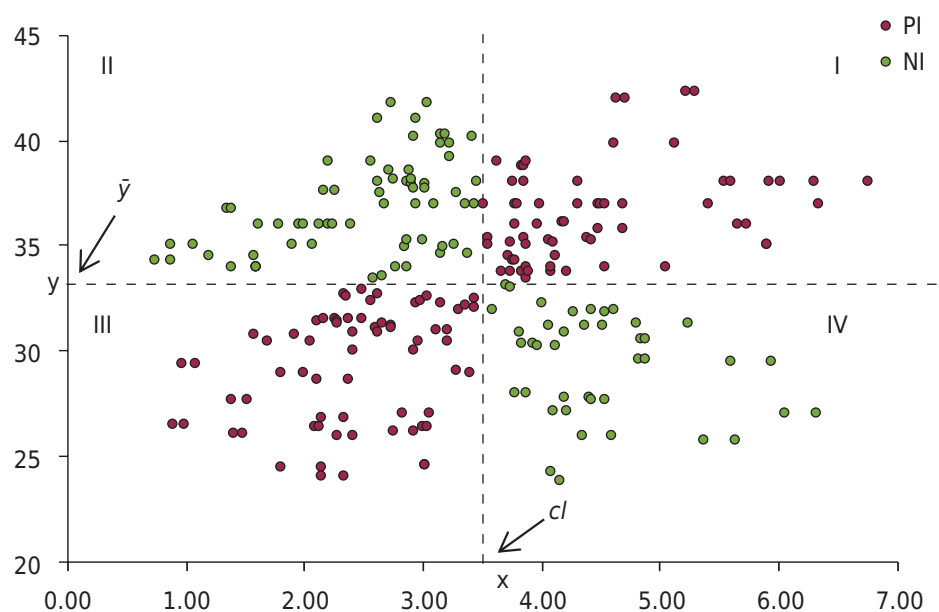


Figure 1. Quadrant Diagram of the Plant-Soil Relationship (QDpsR), y as a function of x. \bar{y} : average of the leaf contents in the diagnostic leaf of coffee; *cl*: critical level of soil fertility properties obtained by the Boundary Line approach; PI: positive increase; NI: neutral increase.

RESULTS AND DISCUSSION

The BL method applied to the relationship between coffee yield and soil fertility properties allowed the establishment of significant quadratic curvilinear models, with a good fit and high coefficients of determination (Figure 2).

The BL is based on the principle that crop yield has an upper limit of development or response in accordance with the direct effect of a nutrient or production factor, and the nonlinearity of the models that describe it allow critical and optimal levels or the range of nutrient availability in the soil to be achieved (Schnug et al., 1996; Haneklaus et al., 2007; Maia and Morais, 2016).

The increase in SOM contents provides a positive quadratic response in coffee yield (Figure 2a). This demonstrates its importance as a production factor, since it is known that SOM not only improves the physical, chemical, and biological properties of the soil, but also acts on the biogeochemical cycling processes of N, P, S, and other nutrients (Silva and Mendonça, 2007; Schmidt et al., 2011).

Maximum economic efficiency and maximum physical yield of coffee were observed in SOM contents of 32.27 and 52.45 g kg⁻¹, corresponding to *c* and *o*, respectively (Figure 2a and Table 1). According to the Soil Fertility Commission of the State of Minas Gerais - Cfssemg, this range of contents is in line with that indicated for the development of agricultural crops in general, and is considered to be from medium to good (Alvarez V. et al., 1999; Mesquita et al., 2016).

Coffee was responsive to increases in the levels of relative phosphorus (RP) in the soil during the production phase of the crops studied (Figure 2b). The RP that provided the maximum estimated RFY was 173.79 %, equivalent to 15.64 mg dm⁻³ of P in the soil; for 90 % of the maximum RFY, the PR was 82.59 %, corresponding to 7.43 mg dm⁻³ of P (Figure 2b and Table 1).

This difference in P values in the soil, that is, from 9.0 mg dm⁻³ of P, according to the Cfssemg (Guimarães et al., 1999), to 7.43 mg dm⁻³ of P obtained by BL, can be attributed to the different populations of soils and crops studied, to the different calculation procedures, and to the BL method used in this study.

The *c* obtained by the BL method may be closer to the actual growing conditions of a coffee tree in full production, since studies have shown that perennials have a tendency to require less P during development (Novais et al., 1982; Valadares et al., 2014). This may be one of the reasons for the low response of coffee trees in production to phosphate fertilization; hence, it is important to establish the critical levels of P for each stage of plant growth, aiming at rational management of fertilization for coffee and meeting its demand throughout the crop cycle (Guimarães and Reis, 2010).

The increase in available K levels in the soil resulted in a positive quadratic response for relative yield (Figure 2c). The RFY of maximum economic efficiency (90 % of the RFY) and the maximum RFY of Arabica coffee (100 % of RFY) were obtained at the contents of 76.40 mg dm⁻³ (*c*/K) and 127.19 mg dm⁻³ of K (*o*/K), respectively (Figure 2c and Table 1). The reduction in yield from *o*/K may be related to nutritional imbalance resulting from cation competition, Ca and Mg, because of the relationship between the cations in solution, which may interfere with K availability to plants (Marschner, 2012).

These levels are consistent with the ideal range for coffee, from 60 to 120 mg dm⁻³ of K (Guimarães et al., 1999; Mesquita et al., 2016) and are close to those found by Silva et al. (2000), ranging from 83.9 to 152.6 mg dm⁻³ of K for average production over four harvest seasons of cv. Catuaí Vermelho, corresponding to 90 and 100 % of the maximum production.

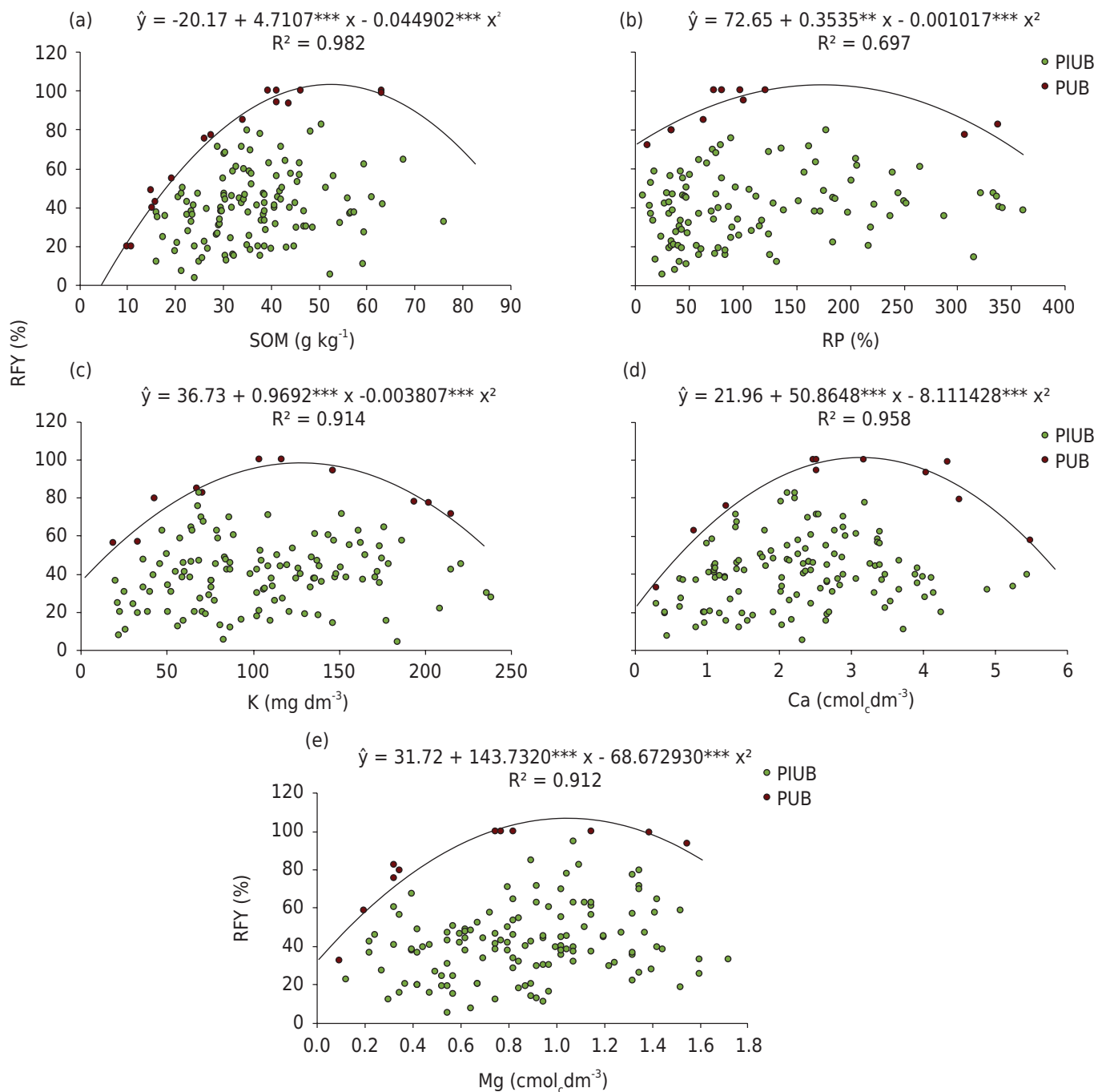


Figure 2. Relative fruit yield (RFY) as a function of the of SOM content (a) and relative P (b), K (c), Ca (d), and Mg (e) contents at the layer 0.00-0.20 m. PIUB: points lower than the upper boundary; PUB: points of the upper boundary. ** and *** significant at 1 and 0.1 % probability, respectively.

Table 1. Good availability class of soil fertility properties obtained by the Boundary Line (BL), and nutrient sufficiency range in the diagnostic leaf obtained by the Quadrant Diagram of the Plant-Soil Relationship (QDpsR) from coffee plantations in full production in the state of Minas Gerais

Property	Good availability class	Nutrient	Sufficiency range
SOM (g kg ⁻¹)	37.27-52.45	N (g kg ⁻¹)	33.4-35.8
P (mg dm ⁻³)	7.43-15.64	P (g kg ⁻¹)	1.4-1.6
K (mg dm ⁻³)	76.40-127.19	K (g kg ⁻¹)	24.4-27.0
Ca (cmol _c dm ⁻³)	2.01-3.13	Ca (g kg ⁻¹)	11.4-13.6
Mg (cmol _c dm ⁻³)	0.65-1.04	Mg (g kg ⁻¹)	3.8-4.5
		S (g kg ⁻¹)	1.4-1.8

Similar to the results of this study, Silva et al. (2001) found significant linear responses of potassium fertilization on soil K availability and a positive quadratic effect on coffee production. Likewise, Clemente et al. (2013) evaluated the effect of K rates in the nutrient solution on the growth, yield, and size of coffee beans and found a quadratic response on coffee bean production.

Potassium is demanded and exported in large quantities by coffee, especially in years of high yield, since it has a direct relation with production or with fruit load (Laviola et al., 2006; Clemente et al., 2013; Valadares et al., 2013). Because soil sampling was carried out at the pinhead stage, when there is low accumulation of fruit dry matter (Laviola et al., 2006), the soils with higher K levels resulted in higher yields, under conditions in which the only limiting factor was this nutrient.

The relative yield of the coffee tree was responsive to increases in exchangeable Ca and Mg in the soil, showing, in both cases, a significant quadratic response with high coefficients of determination by the BL method (Figure 2d and 2e). The classes of good availability, 90 and 100 % of the RFY, estimated by the equations were 2.01 to 3.13 and 0.65 to 1.04 $\text{cmol}_c \text{dm}^{-3}$ for Ca and Mg, respectively (Table 1).

Calcium and Mg contents are related to the degree of soil acidity and can serve as an interpretation criterion for the cation exchange complex. The nutrient contents in this study are classified as medium to good according to the Cfsemg (Alvarez V et al., 1999; Mesquita et al., 2016). Rajj (2011) assigns minimum desirable Ca and Mg contents, for crops in general, in the range of 0.4-0.7 and 0.5-0.8 $\text{cmol}_c \text{dm}^{-3}$, respectively, which only aligns with the contents of Mg obtained in this study. In accordance also with Favarin et al. (2013), who recommend a range of 0.8 to 1.2 $\text{cmol}_c \text{dm}^{-3}$ of Mg, due to the high rates of K usually applied on most coffee crops, which can cause an increase of the ionic competition between these two nutrients and consequently reducing the absorption of Mg by the plants, when the levels of K are elevated in soil (Hawkesford et al., 2012).

Calcium and Mg are usually applied via liming, which provides undeniable benefits to plant development, especially in correction of soil acidity, by increasing pH, decreasing aluminum toxicity, and making other improvements to the root environment (Sousa et al., 2007; Rajj, 2011).

For coffee trees, there are reports on the relationship between Ca availability and yield, where increasing exchangeable Ca contents in the soil lead to linear and significant increases in coffee bean production (Malavolta et al., 1979; Chaves et al., 1991). This is mainly associated with the role of Ca in formation of soil fertility, as well as Ca being the third nutrient most required by coffee (Guimarães and Reis, 2010).

Total contents of N (tcN) and S (tcS) in the diagnostic leaf of coffee were significantly affected by increases in organic matter contents ($cSOM$) in soils (Figures 3a and 3b). The tcN and tcS had a similar tendency to increase, and both fit the logarithmic model (base e) with R^2 of 0.467 and 0.486, respectively.

Leaf N and S contents and SOM contents showed no direct relationship, since the mineralization and release rates of these nutrients to the soil solution depend on the chemical composition of the residues and on the biotic and abiotic factors associated with soils (Carneiro et al., 2013).

Furthermore, organic matter has surface charges that contribute to an increase in cation exchange capacity (CEC) of the soil, and, due to the high reactivity of organic matter, it regulates the availability of several nutrients, acting as the quantity factor (Q) of the soil, mainly in Cerrado soils that have a high degree of weathering (Stevenson and Cole, 1985; Silva and Mendonça, 2007; Tiecher et al., 2012; Zandonadi et al., 2014).

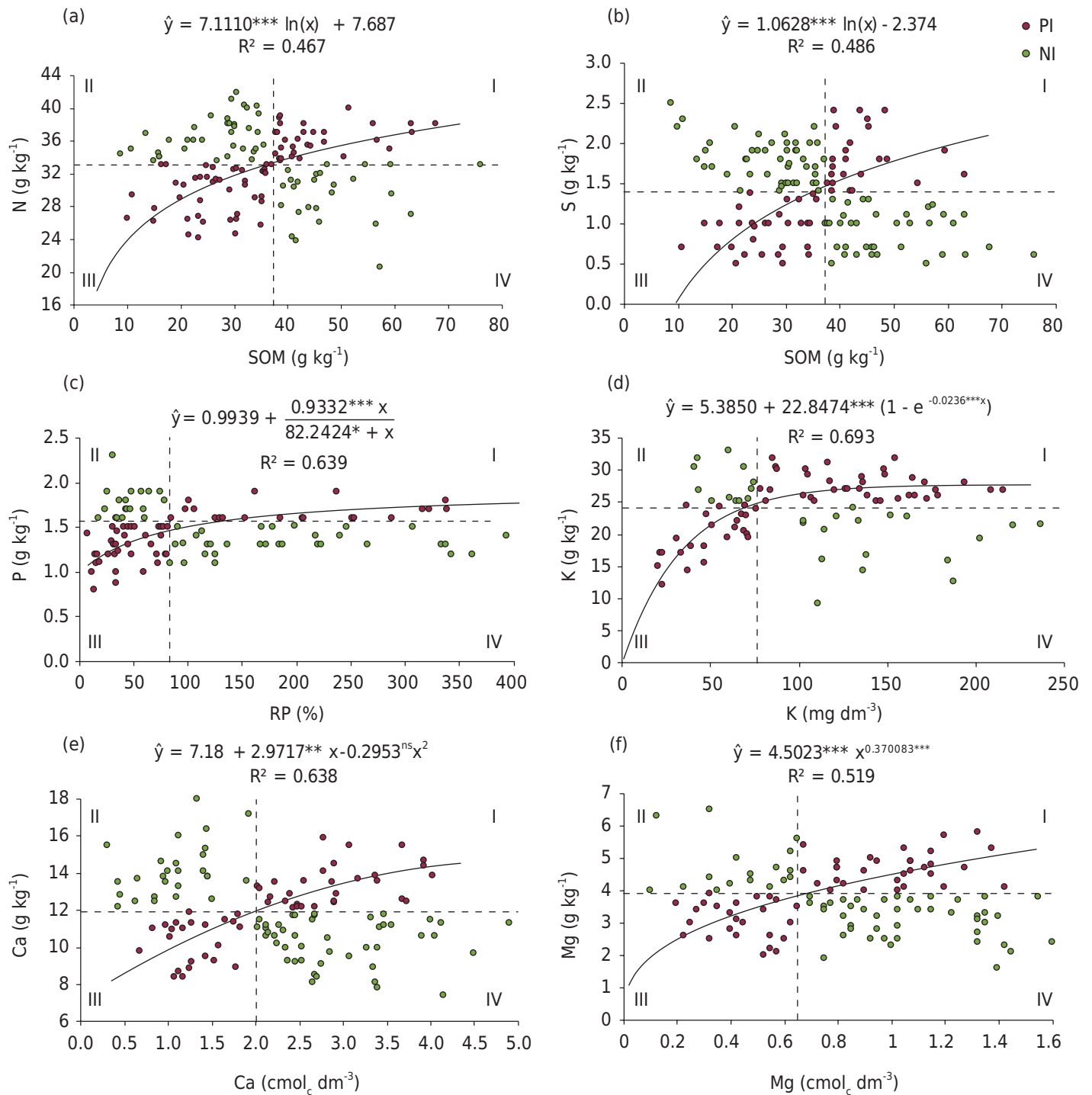


Figure 3. Relationship between leaf N (a), S (b), P (c), K (d), Ca (e), and Mg (f) contents in the coffee leaf as a function of organic matter (SOM), relative P (PR), K, Ca, and Mg at the layer 0.00-0.20 m. PI: positive increase; NI: neutral increase. ^{ns}, ^{*}, ^{**} and ^{***}: non-significant up to 10 %, and significant at 5, 1, and 0.1 % probability, respectively.

The exponential model best fit the data in the III and I quadrants, considering the relationship between the total contents of P in the diagnostic leaf of coffee and the contents of relative phosphorus (RP) in the soil (Figure 3c), wherein increases in P content in the soil provide small increases in leaf P content, with a tendency to stabilize around 1.7 g kg⁻¹. Reis et al. (2011) and Dias et al. (2015) reported a similar trend of increase in P content in the coffee leaf with increasing P in the soil, and leaf P content stabilized around 1.9 g kg⁻¹ in both studies at application rates of 270 and 300 kg ha⁻¹ of P₂O₅, respectively.

The leaf K contents increased in a positive and significant way with the increasing availability of K contents in the soil. Here, the exponential model ($R^2 = 0.693$) was the best

Table 2. Sufficiency ranges for macronutrient contents in coffee leaves, according to different authors

Macronutrient	Authors					
	1	2	3	4	5	6
N (g kg ⁻¹)	23.0-30.0	29.0-32.0	30.0-35.0	29.0-32.0	25.2-32.8	22.5-27.9
P (g kg ⁻¹)	1.2-2.0	1.6-1.9	1.2-2.0	1.2-1.6	1.1-1.9	1.8-2.2
K (g kg ⁻¹)	20.0-25.0	22.0-25.0	18.0-25.0	18.0-22.0	18.0-26.6	17.2-21.0
Ca (g kg ⁻¹)	10.0-25.0	13.0-15.0	10.0-15.0	10.0-13.0	8.7-14.1	12.6-15.1
Mg (g kg ⁻¹)	2.5-4.0	4.0-4.5	3.5-5.0	3.1-4.5	2.6-5.2	2.9-3.5
S (g kg ⁻¹)	1.0-2.0	1.5-2.0	1.5-2.0	1.5-2.0	1.3-2.5	1.3-3.2

1 = Mills and Jones Junior (1996); 2 = Malavolta et al. (1997); 3= Matiello (1997); 4= Guimarães et al. (1999); 5 = Martinez et al. (2003); 6 = Farnezi et al. (2009).

fit for the pairs of points from quadrants III and I (Figure 3d). Leaf K contents increased until reaching a plateau at around 28.1 g kg⁻¹ (maximum point), from 195 mg dm⁻³ of K in the soil. Considering the volume of soil contained in 1 ha and 0.20 m of depth, this would correspond to 468 kg ha⁻¹ of K₂O. Silva et al. (2001) obtained similar results when evaluating coffee yield and leaf nutrition response according to three application rates of K sources, with positive and significant responses for leaf K content, and yield benefitted from this relationship. In the same manner, Valadares et al. (2013), studying the effects of potassium fertilization on coffee yield and K contents in the diagnostic leaf, found positive effects on these response variables in accordance with the rates applied.

Calcium and Mg increased significantly in the diagnostic leaf along with increases in their exchangeable contents in the soil (Figures 3e and 3f). Silveira (1995) and Marques et al. (1999) evaluated the effects of combined applications of gypsum and limestone on the mineral nutrition of Arabica coffee and found similar trends. The authors obtained increases in the exchangeable Ca contents in the soil with the increase in the limestone and gypsum application rates. Application of limestone increased leaf Ca and Mg contents in a consistent manner, which was not observed from application of gypsum.

The sufficiency ranges of N, P, K, Ca, Mg, and S contents in the diagnostic leaf of coffee were estimated from the equations adjusted by the QDpsR method, based on the *cl* and *ol* of SOM, P, K, Ca, and Mg (Figure 3 and Table 1).

The estimated range for N is consistent, according to Matiello (1997), and higher than the adequate ranges, according to other authors (Tables 1 and 2). The estimated sufficiency ranges for P, K, Ca, and S are in agreement with those commonly reported in the literature for the coffee crop. For Mg, the sufficient range is above that established by Farnezi et al. (2009), and consistent with the other ranges (Tables 1 and 2).

The importance of using leaf analysis as a tool to evaluate the nutritional status of Arabica coffee is evident; it reflects the availability of nutrients in the soil, in view of the principles governing its use (Ulrich and Hills., 1967; Malavolta et al., 1997).

CONCLUSIONS

The boundary line method allowed us to obtain the content range of SOM, P, K, Ca, and Mg in the soil optimal for high yield coffee crops: 37.27-52.45 g kg⁻¹ of SOM; 7.43-15.64 mg dm⁻³ of P; 76.40-127.19 mg dm⁻³ of K; 2.01-3.13 cmol_c dm⁻³ of Ca; and 0.65-1.04 cmol_c dm⁻³ of Mg.

The Quadrant Diagram of the Plant-Soil Relationship applied to the study of the interrelation between leaf analysis and soil fertility properties allowed determination of the range of leaf content of N, P, K, Ca, Mg, and S adequate for the coffee tree: 33.4-35.8 g kg⁻¹ of N; 1.4-1.6 g kg⁻¹ of P; 24.4-27.0 g kg⁻¹ of K; 11.9-13.6 g kg⁻¹ of Ca; 3.8-4.5 g kg⁻¹ of Mg; and 1.4-1.8 g kg⁻¹ of S.

The sufficiency ranges indicated by the QDpsR method are consistent with those commonly reported in the literature for the coffee crop.

This study demonstrated the importance of using leaf analysis as a tool to evaluate the nutritional status of the coffee crop, since the technique is consistent with the theoretical principles underlying it.

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