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Modeling in the Adjustment of Fertilization Recommendation through Leaf Analysis in Fertigated 'Prata' Banana

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ABSTRACT: In banana cultivation, fertilization recommendations are almost exclusively based on soil chemical analysis, without considering leaf analysis and expected yield, which can help in the adjustment of fertilization programs. The aim of this study was to develop a method to recommend macronutrient fertilization rates which integrates data on leaf analysis, soil chemical analysis, and yield. Yield, soil chemical analysis, and leaf analysis data of fertigated plantations of 'Prata' banana were obtained for the first and second halves of the years from 2010 to 2015. Yield was correlated with soil organic matter (SOM) and soil contents of macronutrients (P, K, Ca, and Mg) to obtain the critical level ($_{CL}Nu_i$). Then, leaf nutrient contents were plotted on a dispersion graph as a function of soil contents using the method of Quadrant Diagram of the Plant-Soil Relationship (QDpsR). Based on leaf analysis, recommended rates were simulated for four plots and compared with rates recommended by other methods. The values of $_{CL}Nu_i$ obtained were 13.2 g dm^{-3} for SOM; 97.5 and 91.5 mg dm^{-3} for P and K; and 2.71 and 0.61 cmol$_c$ dm^{-3} for Ca^{2+} and Mg^{2+}. The rates recommended based on leaf analysis diverged from the recommendations of Ferticalc®-Bananeira and the Recommendation Table for Banana Fertilization; in plots for which recommendations were made, there were higher rates of P_2O_5 and Ca and lower rates of K_2O. However, in most cases, applications were not recommended, either because contents in leaves and soil were adequate or because yield was being limited by non-nutritional factors or, if nutritional, related to other nutrient(s). Leaf analysis satisfactorily adjusts the recommended rates of nutrients and has advantages if incorporated in nutritional balance models.

Keywords: *Musa spp.*, nutrient, critical level, boundary line, yield.

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INTRODUCTION

Fertilization recommendations for crops in general are made almost exclusively based on soil chemical analysis, without considering leaf analysis and expected yield, which can help in the adjustment of fertilization programs. Using soil chemical analysis alone, based on recommendation tables, may lead to errors because the nutrient content presented in the analysis is only an availability index and not the quantification of the nutrient actually available to the crop (Oliveira et al., 2005).

Nutrient contents indicated in soil chemical analysis may be taken up by plants but will not necessarily be absorbed and metabolized by them. In addition, uptake, absorption, and transport of nutrients in plants are related to interactions between various biotic and abiotic factors, and these interactions are not contemplated in fertilization recommendation tables (Deus, 2016).

To improve recommendation tables, researchers have developed nutritional balance models that estimate the nutrient application rate based on plant nutritional requirements, yield, and nutrient supply by the soil and other sources for eucalyptus (Barros et al., 1995), banana (Oliveira et al., 2005), soybean (Santos et al., 2008), pineapple (Silva et al., 2009), coconut (Rosa et al., 2011), ornamental plants (Alvarez V. et al., 2014), melon (Deus et al., 2015), and carrot (Dezordi et al., 2015). The advantages of nutritional balance models include the ease of incorporating new research results, which contributes to evolution and improvement of the recommendations.

The use of leaf analysis has increased in Brazil, especially in crops grown with higher technological levels because it allows one to know and evaluate plant nutritional conditions, thus identifying the existence of deficiency and/or excess of nutrients, in order to guide fertilization programs (Silva and Rodrigues, 2001; Deus et al., 2012). However, although leaf analysis helps in decision-making regarding fertilization recommendations, it has been underused because there is no method that directly employs this tool to recommend fertilization rates.

The hypothesis of this study was that leaf analysis is an important tool in nutritional management and that it can be directly used to recommend fertilization rates, and the aim was to develop a method for recommendation of macronutrient fertilization rates that integrates data from leaf analysis, soil chemical analysis, and expected yield.

MATERIALS AND METHODS

The study was conducted in the *Sítio Barreiras Fruticultura* company, in the municipality of Missão Velha, Ceará, Brazil, at the geographic coordinates 7° 35’ 90” S and 39° 21’ 17” W, at an altitude of approximately 442 m. The climate in the region is Aw - tropical, with a dry season in the winter and rains concentrated in the summer (Köppen-Geiger).

Database

The database contained data on fruit yield (Figure 1) and chemical analyses of soil and leaves relative to the first and second halves of the years from 2010 to 2015 in 66 plots of fertigated 'Prata' banana (*Musa spp*.), with a mean area of 3.26 ha per plot.

Fruit yield (t ha^{-1}) was calculated for six-month periods (January to June and July to December) to synchronize with the chemical analyses of soil and leaves, which were carried out twice a year (June and December). Relative yield was used to minimize possible differences in the yield of each plot in the first and second halves of the years, due to the seasons with and without rains, as well as throughout the years of evaluation.

Fertilization recommendation based on leaf analysis

Assumptions of studies on correlation and calibration similar to those employed in methods of soil chemical analyses were made for the fertilization recommendation based on leaf

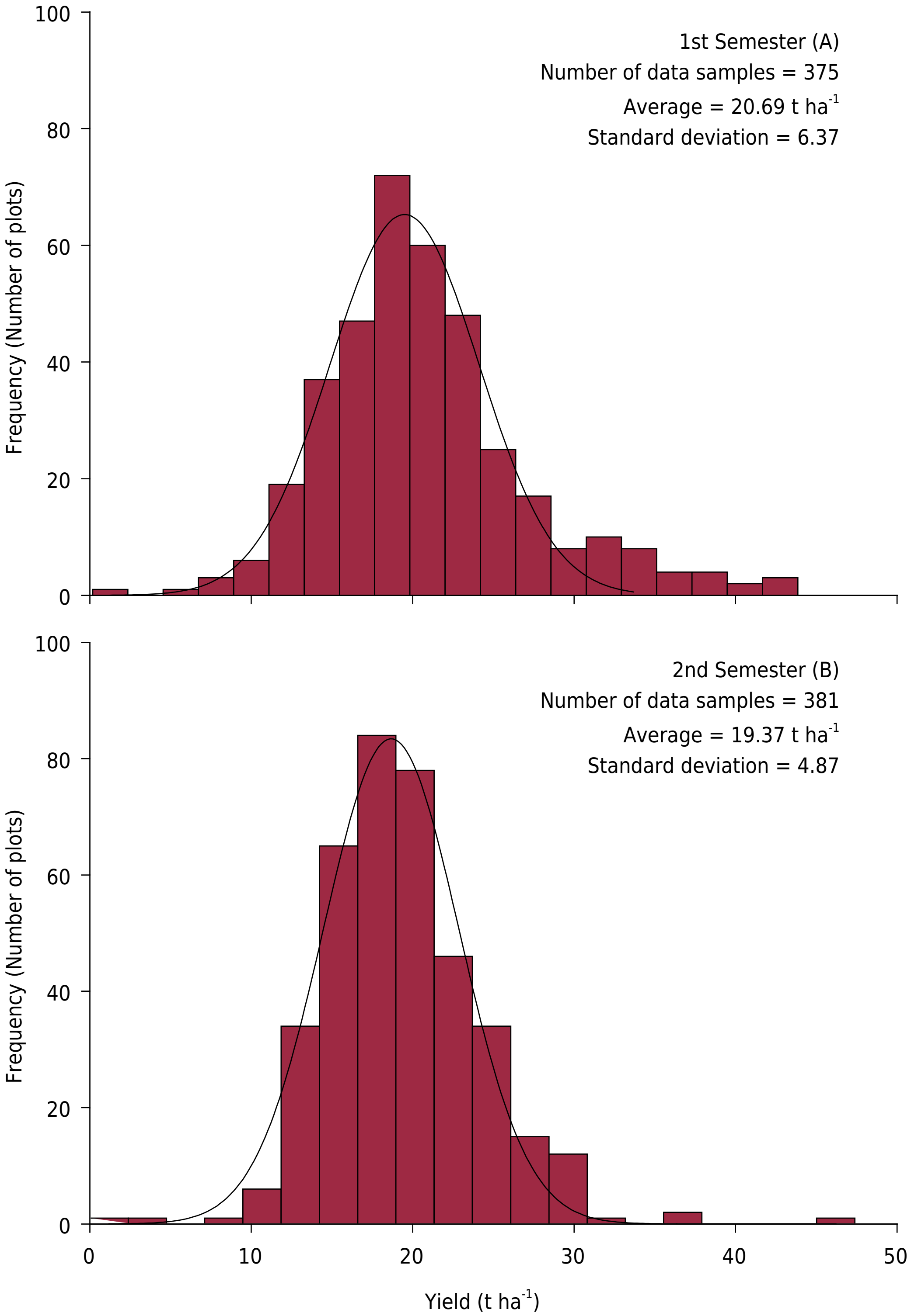

Figure 1. Histogram of distribution and normal curve of semiannual fruit yield in plots cultivated with 'Prata' banana under fertigation from 2010 to 2015.

analysis (Alvarez V., 1996). In correlation, different soil nutrient extractants are evaluated, and the one which is best correlated with the accumulated amount of nutrient in the plant is selected; in contrast, in calibration, critical levels and application rates of nutrients are determined. The method of nutrient recommendation based on chemical analysis of the diagnostic leaf of the banana tree was developed in a similar way, with fitting adaptations.

For sampling of the diagnostic leaf, 10 to 15 cm were collected in the inner middle portion of the lead blade, disregarding the midrib, of the third leaf from the apex, in the period of inflorescence production, as recommended for the banana crop (Martin-Prével, 1984).

Critical level of the nutrient in the soil ($_{CL}Nu_i$)

The $_{CL}Nu_i$ values for P, K, Ca, and Mg were determined based on the relationship of their contents and organic matter with the relative yield. The Boundary Line approach was applied for that purpose, with the aid of the "Boundary Fit" computer application in development at the Federal University of Viçosa.

After identifying the plots of the upper boundary line (UBL) and extracting them from the cloud of points (Figure 2), regression equations (models) were generated with the computer application Curve Expert Basic 1.4 (Hyams, 2010), in which relative yield was the dependent variable (Y-axis) as a function of the concentrations of the independent variables (X-axis), SOM (soil organic matter), P, K, Ca, and Mg.

Subsequently, UBL equations were derived by making the first derivative equal to zero, to obtain the contents (SOM, P, K, Ca, and Mg) in the soil, corresponding to the maximum point of the UBL curve. These values were replaced in the respective equations to estimate the maximum values in the Y-axis (100 % yield), whereas the Y values corresponding to 90 % yield were obtained through multiplication by 0.9. These values were used to estimate the $_{CL}Nu_i$ for SOM, P, K, Ca, and Mg.

Quadrant Diagram of the Plant-Soil Relationship (QDpsR)

After obtaining the $_{CL}Nu_i$ by the UBL approach, leaf contents of nutrients were related to their respective contents in the soil, using the method called the Quadrant Diagram of the Plant-Soil Relationship (QDpsR), according to figure 3, employed by Sousa (2016) for coffee and Deus (2016) for banana.

Leaf contents of P, K, Ca, and Mg were plotted on the dispersion graph as a function of their contents in the soil, and N and S contents were plotted as a function of SOM values. There are variability and interactions between the biotic and abiotic factors involved in the plant-soil system, and to reduce these influences, we used an approach that allowed generation of an equation (model) called the Quadrant Diagram of the Plant-Soil Relationship (QDpsR).

This method consists of stratifying a cloud of points into four quadrants (I, II, III, IV) in a Cartesian system and generating models using the points located in quadrants I and III (Figure 3) that best explain the relation between the contents of nutrients in the plant tissue and their contents in the soil. The quadrants were delimited using the mean of the leaf contents of macronutrients (dashed line perpendicular to the Y-axis), whereas the $_{CL}Nu_i$ was obtained by

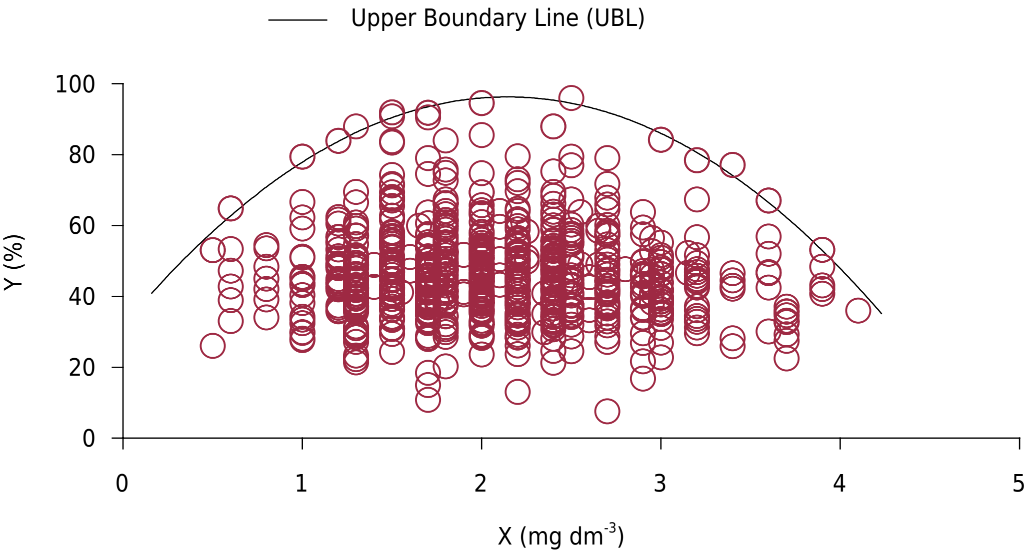

Figure 2. Example of the Upper Boundary Line of the relationship between two variables (relative yield and nutrient content in the soil).

the UBL (dashed line perpendicular to the X-axis). Then, regression equations (models) were generated with the Curve Expert Basic 1.4 computer application (Hyams, 2010).

In calculation of the application rates, it is also necessary to consider the nutrient recovery rate of the extractant specific to each nutrient. The extractants Mehlich-1 and Resin were used for P and K, whereas the extractant KCl (1 mol L^{-1}) was used for Ca and Mg (Table 1).

For P, the rate of recovery by the extractants considered the P-rem values; for situations in which P-rem is not known, one may opt for a fixed rate for K, as used for Ca and Mg.

Simulation of recommended rates for phosphorus, potassium, calcium, and magnesium

Phosphorus, K, Ca, and Mg rates were recommended using, as an example, the leaf analyses of four plots of 'Prata' banana available at the company, relative to the second half of 2015 (Table 2).

The rate of the nutrient to be applied was recommended using the value of ${}_{CL}Nu_i$ and the soil content of the nutrient estimated from the content found in the leaf analysis, as well as the recovery rate of the extractant, according to equation 1.

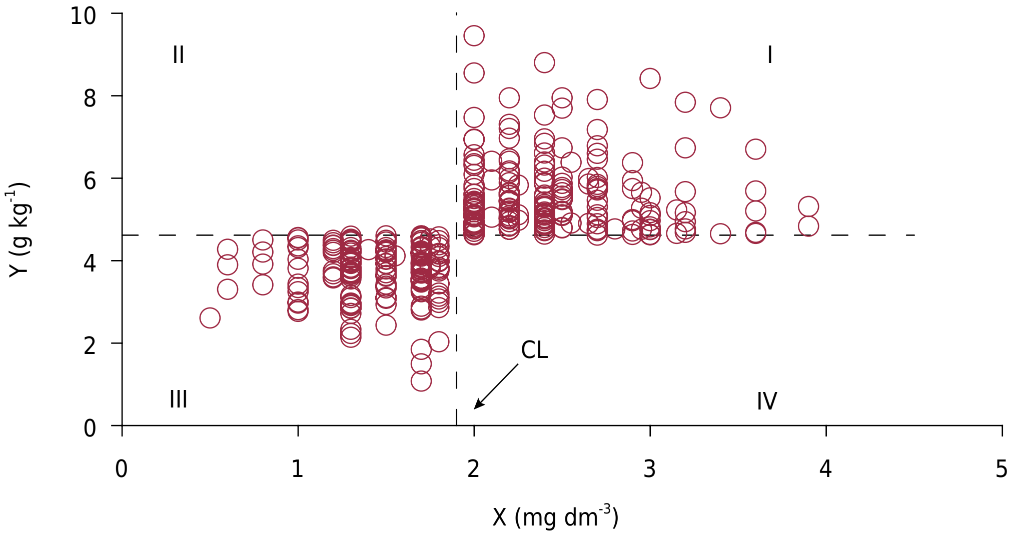

Figure 3. Example of application of the Quadrant Diagram of the Plant-Soil Relationship (QDpsR) method, obtained from the relationship between two variables (nutrient concentrations in the leaf and in the soil).

Table 1. Equations to estimate the rate of recovery by the extractant for P, K, Ca, and Mg applied to the soil through fertilizers [${}_{RR}Nu_i\_Ext$, in (mg dm^{-3})/(mg dm^{-3})], which varies, or not, with remaining P (P-rem, in mg L^{-1})

Nutrient	Extractant	Equation	R^2
P	Mehlich-1	${}^{(1,2,3,4,5)}{}_{RR}Nu_i\_Ext = 0.0672821 + 0.0121615^{**}P\text{-rem}$	0.68
P	IER	${}^{(1,2,3,4,5)}{}_{RR}Nu_i\_Ext = 0.419^{***}P\text{-rem}^{0.128099}$	0.69
K	Mehlich-1	${}^{(5)}{}_{RR}Nu_i\_Ext = 0.6555 + 0.0068^{**}\ P\text{-rem}$ ${}^{(2,3)}{}_{RR}Nu_i\_Ext = 0.8020$	0.74 -
K	IER	${}^{(5)}{}_{RR}Nu_i\_Ext = 0.6619 + 0.014355^{*}\ P\text{-rem} – 0.000293^{*}P\text{-rem}^2$ ${}^{(2,3)}{}_{RR}Nu_i\_Ext = 0.7559$	0.75 -
Ca	KCl 1 mol L^{-1}	${}^{(2,3,5)}{}_{RR}Nu_i\_Ext = 0.766102$	-
Mg	KCl 1 mol L^{-1}	${}^{(2,3,5)}{}_{RR}Nu_i\_Ext = 0.798972$	-

P-rem = remaining phosphorus: Alvarez V. et al. (2000); IER = ion exchange resin; *, **, ***: significant at 5, 1, and 0.1 % levels, respectively; Extracted from (1) Deus et al. (2015); (2) Dezordi et al. (2015); (3) Oliveira et al. (2005); (4) Santos et al. (2008); (5) Silva et al. (2009).

Table 2. Total leaf contents of N, P, K, Ca, Mg, and S of four plots relative to the second half of 2015

Plot	N	P	K	Ca	Mg	S
			g kg^{-1}			
A	20.5	1.7	34.9	7.8	3.0	1.6
B	19.4	1.6	37.4	10.1	3.0	1.6
C	23.1	1.5	32.0	6.1	2.3	1.5
D	22.3	1.5	33.2	5.7	2.1	1.4

N = sulfuric acid digestion and determination by the Kjeldahl method; P (colorimetry), S (turbidimetry), K (flame emission photometry), Ca and Mg (atomic absorption spectrophotometry) determined in acid extract with digestion in nitric acid with perchloric acid, according to Silva (2009).

$$ {}_{DR}Nu_i = [({}_{cl}Nui - {}_{EC}Nui\_Soil)/({}_{RR}Nui\_Ext)] \times 2 \quad \text{Eq. 1} $$

in which ${}_{DR}Nu_i$ = nutrient application rate recommended twice a year (kg ha^{-1}); ${}_{CL}Nu_i$ = critical level of the nutrient in the soil (mg dm^{-3}), corresponding to the nutrient content in the leaves to obtain 90 % of maximum yield; ${}_{EC}Nu_i\_Soil$ = estimated content of the nutrient in soil P, K, Ca, and Mg (mg dm^{-3}) corresponding to the nutrient content in leaf analysis; ${}_{RR}Nu_i\_Ext$ = nutrient recovery rate by the extractant [(mg dm^{-3})/(mg dm^{-3})]; and 2 = factor for conversion from mg dm^{-3} to kg ha^{-1} considering the 0.00-0.20 m surface layer and soil density of 1 g cm^{-3}.

Phosphorus and K recommendations are presented as P_2O_5 and K_2O after using the conversion factors of 2.2915 and 1.2047, respectively. For Ca and Mg, the result of subtraction of ${}_{EC}Nu_i\_Soil$ from ${}_{CL}Nu_i$, when positive, was converted to mg dm^{-3} and then divided by ${}_{RR}Nu_i\_Ext$.

Simulation of recommended rates for nitrogen and sulfur

For N and S, in which the ${}_{CL}Nu_i$ was determined based on SOM, we considered the estimated amount of the inorganic forms of N (NO_3^- + NH_4^+) and S (SO_4^-) present in the SOM to calculate the application rates. Equation 2, adapted from Stahringer (2013) for tropical soils, was used for N recommendation.

$$ N_p = 1{,}000{,}000 \times Z_{eff} \times [(\Delta SOM_{est}/1{,}000/1.724)/10)] \times 0.04 \quad \text{Eq. 2} $$

in which N_p = potentially mineralizable nitrogen (kg ha^{-1}); 1,000,000 = value relative to the area of one hectare (dm^2); Z_{eff} = root system effective depth (dm); and ΔSOM_{est} = result of subtraction of the SOM estimated in the soil from leaf N content by the critical level of SOM "${}_{CL}OM$ - ${}_{EC}OM\_Soil$" (g dm^{-3}). For SOM values expressed in dag kg^{-1}, one should use the original equation of Stahringer (2013); 1,000 = value used as factor for conversion from g to kilogram; 1.724 = value used to estimate soil organic C from SOM_{est} (considering that SOM has 58 % organic C); 10 = value used to estimate organic N (considering that SOM has C/N ratio = 10); and 0.04 = mean value of potentially mineralizable N estimated for 16 different soils (Gonçalves et al., 2001).

For S recommendation, equation 2 was adapted to obtain equation 3, and equation 4 was used to calculate S in the inorganic form, from SOM.

$$ S_{org} = 1{,}000{,}000 \times Z_{eff} \times [(\Delta SOM_{est}/1{,}000/1.724)/112)] \quad \text{Eq. 3} $$

$$ S_{inorg} = 0.0687802 \times S_{org} \quad \text{Eq. 4} $$

in which S_{org} = S in the organic form required to reach the ${}_{CL}SOM$ (kg ha^{-1}); 112 = mean value used to estimate organic S (considering that SOM has a C/S ratio = 112) for six different soils of Brazil (Silva et al., 1999); S_{inorg} = S in the inorganic form (SO_4) required to reach the ${}_{CL}SOM$ (kg ha^{-1}); and 0.0687802 = ratio between the organic and inorganic forms of S (Silva et al., 1999).

Comparison with other methods of fertilization recommendation

After simulations for the four plots, the recommended rates based on leaf analyses were compared with the P, K, Ca, and Mg rates recommended by FERTICALC®-Bananeira (Oliveira et al., 2005) and by the Recommendation Table for Banana Fertilization in the state of Ceará (Fernandes, 1993) for the same scenarios. The simulation with FERTICALC®-Bananeira considered a population of 1,667 families (mother plant + daughter plant) per hectare for bananas of the AAB group, with expected yield of 39.0 t ha^{-1} in the four plots evaluated, and the yield obtained in the previous cycle, corresponding to the second half of 2015: 21.2, 19.8, 12.4, and 22.1 t ha^{-1} for plots A, B, C, and D, respectively. These data were necessary in the simulation by FERTICALC®-Bananeira, as well as the soil chemical analyses for the 0.00-0.20 m layer for the second half of 2015 (Table 3). The simulation with the Recommendation Table for Banana Fertilization in the state of Ceará considered a population of 1,667 families ha^{-1} and soil chemical analysis (Table 3).

RESULTS AND DISCUSSION

Critical level of the nutrient in the soil (${}_{CL}Nu_i$)

The upper boundary line (UBL) was adjusted from the relationship between relative yield and the contents of P, K, Ca, Mg, and SOM (Figure 4). The UBL was selected to determine the ${}_{CL}Nu_i$ because of its technical robustness, which allows the response curve to be extracted from the cloud of points as a function of a given variable, without limitation by other factors (Chung et al., 2005).

The nutrients K, Ca, and Mg were similar regarding the model fitted for UBL ($\hat{y} = a\ b^x\ x^c$), Hoerl-type, demonstrating an initial rapid increase in yield as the contents of these elements in the soil increase. However, P and SOM fit within a second-order polynomial model ($\hat{y} = a + bx - cx^2$). These models represent the best performance of banana yield as a function of the values of SOM and nutrients in the soil. Upper boundary line allows crop yield response to be correlated with a single factor, from the data of yield influenced by multiple factors (Shatar and McBratney, 2004).

The equations in figure 4 were used to obtain the contents in the soil required to reach 90 and 100 % of yield, which were 97.5 and 159.7 mg dm^{-3} for P, 91.5 and 160.6 mg dm^{-3} for K, 2.71 and 5.33 cmol$_c$ dm^{-3} for Ca^{2+}, 0.61 and 1.16 cmol$_c$ dm^{-3} for Mg^{2+}, and 13.2 and 21.4 g dm^{-3} for SOM, respectively.

The lower limit of the sufficiency range represents the ${}_{CL}Nu_i$, i.e., the nutrient content in the soil necessary to obtain 90 % of maximum yield, if production factors and other nutrients are in adequate quantities and proportions. For plots with nutrient contents determined by soil analysis that are lower than ${}_{CL}Nu_i$, there is high probability of response

Table 3. Soil chemical properties in the 0.00-0.20 m layer for the second half of 2015, for the four plots evaluated

Plot	pH(H$_2$O)	SOM	P	K	Ca^{2+}	Mg^{2+}	CEC	V
		g dm^{-3}	——— mg dm^{-3} ———		——— cmol$_c$ dm^{-3} ———			%
A	7.6	12.0	250.0	132.9	2.9	0.9	5.25	78.8
B	7.4	18.0	68.0	62.6	3.3	0.7	5.46	76.1
C	7.1	18.0	150.0	89.9	3.5	0.8	5.73	79.0
D	7.1	20.0	130.0	101.7	2.3	0.7	47.60	68.4

pH in water at 1:2.5 ratio; SOM = soil organic matter obtained by C$_{org}$ × 1.724 (Walkley-Black, 1934); P and K, extracted by Mehlich-1; Ca^{2+} and Mg^{2+} extracted by 1 mol L^{-1} KCl; CEC = cation exchange capacity at pH 7.0; V = base saturation index.

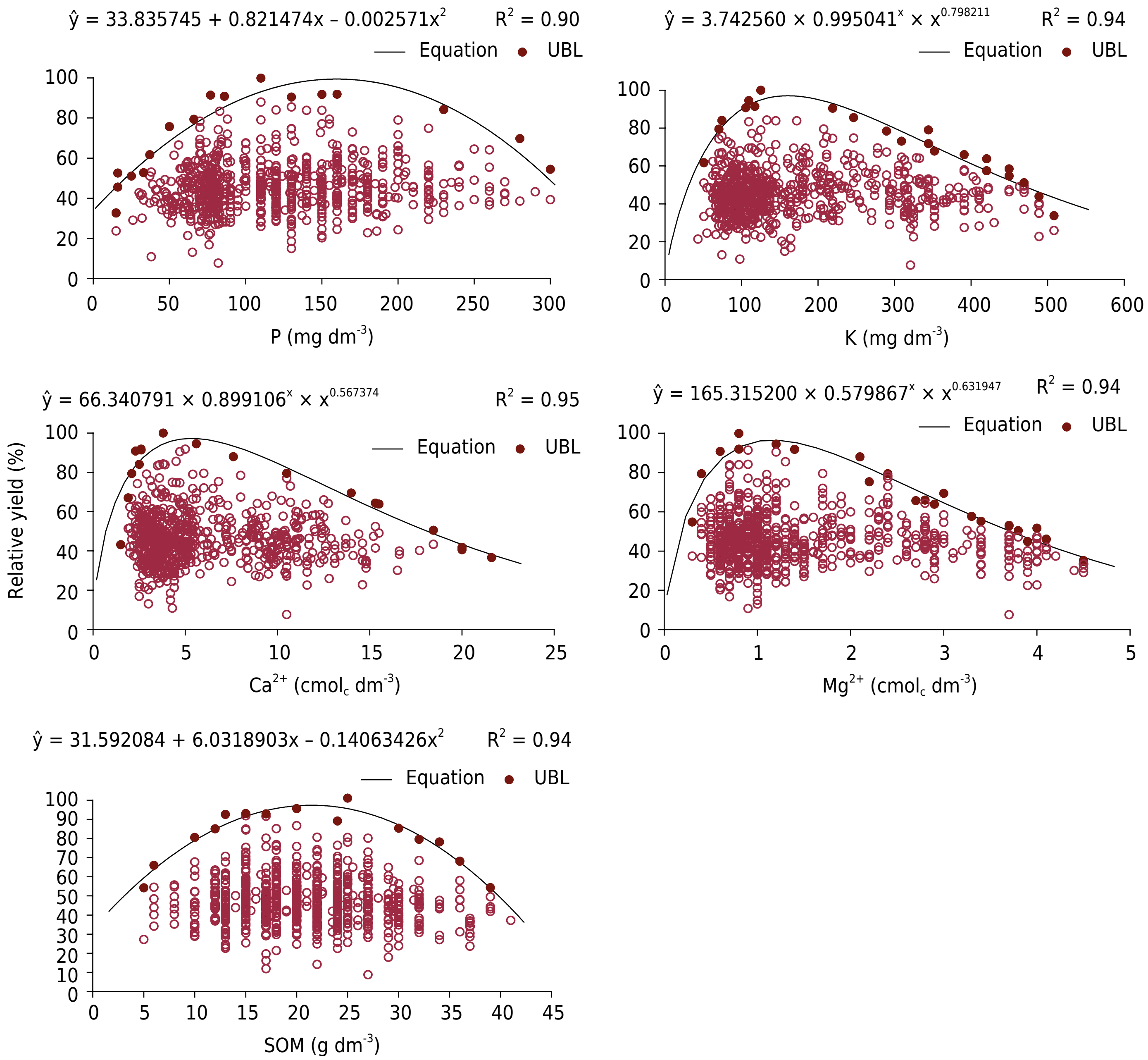

Figure 4. Upper boundary line obtained for relative yield (%) as a function of the contents of P and K (mg dm^{-3}), Ca^{2+}, and Mg^{2+} (cmol$_c$ dm^{-3}), and soil organic matter (g dm^{-3}).

from the addition of the limiting nutrient. In contrast, for plots with nutrient contents in the soil above the $_{CL}Nu_i$, application of the nutrient is considered economically unviable.

Comparing $_{CL}Nu_i$ values obtained by the UBL with the $_{CL}Nu_i$ from the Recommendation Table for Banana Fertilization currently used in the state of Ceará (Fernandes, 1993), similarity occurred only in K, in which the $_{CL}Nu_i$ is 90.0 mg dm^{-3}. For P, the $_{CL}Nu_i$ is much lower than what is necessary, at 20.0 mg dm^{-3}. The $_{CL}Nu_i$ values obtained by the UBL for Ca^{2+}, Mg^{2+}, and SOM were lower than those established by the Recommendation Table for Banana Fertilization in the state of Ceará, at 4.0 and 1.0 cmol$_c$ dm^{-3} for Ca^{2+} and Mg^{2+}, respectively, and 30.0 g dm^{-3} for SOM.

Quadrant Diagram of the Plant-Soil Relationship (QDpsR)

The QDpsR method uses principles similar to those of the method developed by Cate Júnior and Nelson (1965), which correlates the result of soil analysis with crop yield, in a way analogous to Mitscherlich's law, also known as the law of diminishing returns. The QDpsR method allows one to relate leaf contents of nutrients in the plant to the contents available in the soil through quadrants III and I (Figure 5). The models generated from this method allowed the contents of nutrients in the soil corresponding to the leaf contents to be estimated with higher predictive capacity.

The theoretical foundation of this approach is based on binary classification tests, which aim to improve the reliability of system diagnosis by eliminating possible biases (Swets, 1988). For instance, it assumes that the plots located in quadrants II and IV have two types of errors: false positive and false negative (Parent et al., 2012).

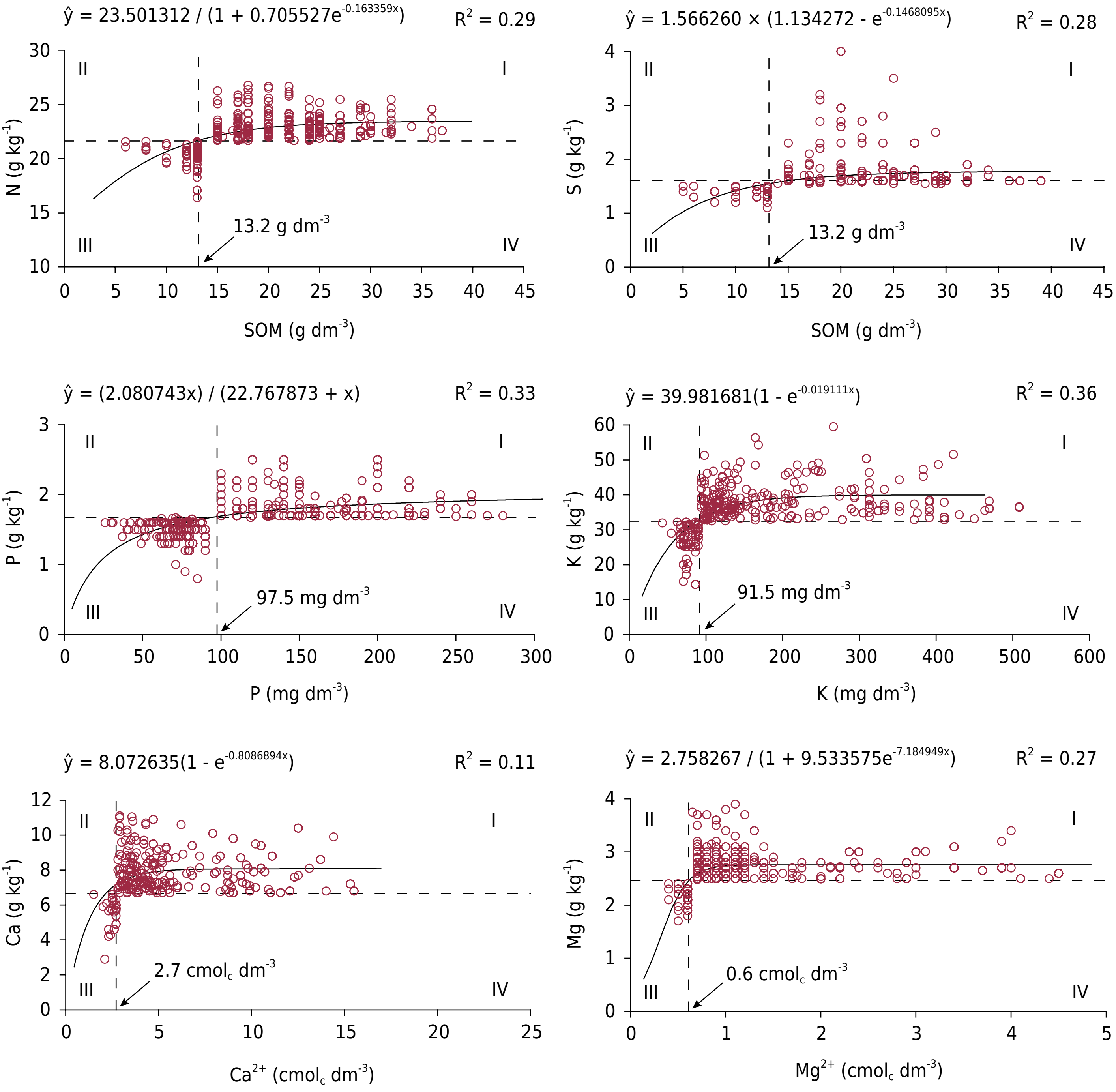

Figure 5. Contents of nutrients in the diagnostic leaf of the banana tree, as a function of the contents of organic matter and macronutrients in the soil, obtained by the Quadrant Diagram of the Plant-Soil Relationship (QDpsR) method.

In our study, the plots located in quadrant II are under the effect of the nutrient content in plant tissues because of low yield, for instance. The opposite occurs in the plots of quadrant IV, i.e., the effect of dilution, in which other factors may limit the uptake and transport of the nutrient in the plant, even in areas with soil contents of the nutrient above the $_{CL}Nu_i$ (Sousa, 2016).

Thus, the method increases the number of hits for a certain population because it minimizes the inconvenience of false positive and false negative plots with plants that do not respond to either the application or content of the nutrient in the soil.

In this context, the QDpsR method allows the plots to be stratified with nutritional (I and III) and non-nutritional (II and IV) limitations, i.e., the recommendations will only be valid if the soil and leaf chemical analyses in the evaluated plot meet the criteria established by the QDpsR for quadrants I and III (Table 4). In the specific case of quadrant I, the recommended rate is expected to be equal to zero or very close to zero, because the nutrient content in the soil is equal to or higher than the $_{CL}Nu_i$, and the contents in the leaf tissue are above average.

If a plot meets the criteria of quadrant II or IV, there is no recommendation of application rates because the concept of the method suggests that, in these cases, non-nutritional limitations are occurring; thus, the plant is not expected to respond to application of the nutrient.

Table 4. Criteria established by the Quadrant Diagram of the Plant-Soil Relationship (QDpsR) method to classify the plots

Nutrient	Criterion		Quadrant
	x	y	
N	$\forall\ 13.2 \leq x \leq 53.0$ g dm^{-3}	$\forall\ 21.6 \leq y \leq 27.0$ g kg^{-1}	I
	$\forall\ 5.0 \leq x < 53.0$ g dm^{-3}	$\forall\ 21.6 \leq y \leq 27.0$ g kg^{-1}	II
	$\forall\ 5.0 \leq x < 53.0$ g dm^{-3}	$\forall\ 15.2 \leq y < 21.6$ g kg^{-1}	III
	$\forall\ 13.2 \leq x \leq 53.0$ g dm^{-3}	$\forall\ 15.2 \leq y < 21.6$ g kg^{-1}	IV
S	$\forall\ 13.2 \leq x \leq 53.0$ g dm^{-3}	$\forall\ 1.5 \leq y \leq 13.0$ g kg^{-1}	I
	$\forall\ 5.0 \leq x < 53.0$ g dm^{-3}	$\forall\ 1.5 \leq y \leq 13.0$ g kg^{-1}	II
	$\forall\ 5.0 \leq x < 53.0$ g dm^{-3}	$\forall\ 0.7 \leq y < 1.5$ g kg^{-1}	III
	$\forall\ 13.2 \leq x \leq 53.0$ g dm^{-3}	$\forall\ 0.7 \leq y < 1.5$ g kg^{-1}	IV
P	$\forall\ 97.5 \leq x \leq 741.0$ g dm^{-3}	$\forall\ 1.7 \leq y \leq 2.9$ g kg^{-1}	I
	$\forall\ 15.0 \leq x < 97.5$ g dm^{-3}	$\forall\ 1.7 \leq y \leq 2.9$ g kg^{-1}	II
	$\forall\ 15.0 \leq x < 97.5$ g dm^{-3}	$\forall\ 0.7 \leq y < 1.7$ g kg^{-1}	III
	$\forall\ 97.5 \leq x \leq 741.0$ g dm^{-3}	$\forall\ 0.7 \leq y < 1.7$ g kg^{-1}	IV
K	$\forall\ 91.5 \leq x \leq 742.9$ g dm^{-3}	$\forall\ 32.5 \leq y \leq 59.5$ g kg^{-1}	I
	$\forall\ 43.0 \leq x < 91.5$ g dm^{-3}	$\forall\ 32.5 \leq y \leq 59.5$ g kg^{-1}	II
	$\forall\ 43.0 \leq x < 91.5$ g dm^{-3}	$\forall\ 13.8 \leq y < 32.5$ g kg^{-1}	III
	$\forall\ 91.5 \leq x \leq 742.9$ g dm^{-3}	$\forall\ 13.8 \leq y < 32.5$ g kg^{-1}	IV
Ca	$\forall\ 2.7 \leq x \leq 21.6$ cmol$_c$ dm^{-3}	$\forall\ 6.7 \leq y \leq 14.0$ g kg^{-1}	I
	$\forall\ 1.5 \leq x < 2.7$ cmol$_c$ dm^{-3}	$\forall\ 6.7 \leq y \leq 14.0$ g kg^{-1}	II
	$\forall\ 1.5 \leq x < 2.7$ cmol$_c$ dm^{-3}	$\forall\ 2.6 \leq y < 6.7$ g kg^{-1}	III
	$\forall\ 2.7 \leq x \leq 21.6$ cmol$_c$ dm^{-3}	$\forall\ 2.6 \leq y < 6.7$ g kg^{-1}	IV
Mg	$\forall\ 0.6 \leq x \leq 7.1$ cmol$_c$ dm^{-3}	$\forall\ 2.5 \leq y \leq 4.1$ g kg^{-1}	I
	$\forall\ 0.3 \leq x < 0.6$ cmol$_c$ dm^{-3}	$\forall\ 2.5 \leq y \leq 4.1$ g kg^{-1}	II
	$\forall\ 0.3 \leq x < 0.6$ cmol$_c$ dm^{-3}	$\forall\ 0.8 \leq y < 2.5$ g kg^{-1}	III
	$\forall\ 0.6 \leq x \leq 7.1$ cmol$_c$ dm^{-3}	$\forall\ 0.8 \leq y < 2.5$ g kg^{-1}	IV

x = corresponds to the values of SOM, P, K, Ca^{2+}, and Mg^{2+} contents in soil chemical analysis; y = corresponds to the values of N, S, P, K, Ca, and Mg contents in leaf chemical analysis.

Based on application of the QDpsR method for the number of plots in the first and second halves of each year, it was observed that more than 50 % of the plots are located in quadrants II and IV for most nutrients, except P, i.e., possible limitations of yield result from non-nutritional factors (Table 5). Yield is affected by approximately 52 production factors, and the nutritional aspect is only one of them (Tisdale et al., 1985).

Considering that the response to nutrient application only occurred in plots located in quadrant III, only 4, 5, 23, 11, 3, and 2 % of the plots respond to fertilization with N, S, P, K, Ca, and Mg, respectively. It is noteworthy that the P and K nutrients are the nutritional factors that most limit yield of the plots.

Simulation of recommended rates for macronutrients

Nitrogen fertilization was recommended only in plot A, at a rate of 16.6 kg ha^{-1} twice a year, because this plot, based on the criteria of the QDpsR method, is found in quadrant III (Table 6), i.e., its yield is limited by nutritional factors. In the case of plot B, the rate of 27.1 kg ha^{-1} meets the criteria of quadrant IV, i.e., a false negative, in which the estimated value of SOM was 7.37 g dm^{-3} (Table 7), different from the 18.0 g dm^{-3} determined in soil

Table 5. Percentage of plots in each quadrant according to the criteria established by the Quadrant Diagram of the Plant-Soil Relationship (QDpsR) method

Quadrant	N	S	P	K	Ca	Mg
	%					
I	45	40	30	38	38	45
II	4	3	19	10	5	4
III	4	5	23	11	3	2
IV	47	52	28	41	54	49

Percentage values refer to the 756 samples data of the first and second halves of the years from 2010 to 2015.

Table 6. Relative yield (RY) and classification of the plots per quadrant for the different nutrients, based on the criteria established by the Quadrant Diagram of the Plant-Soil Relationship (QDpsR) method

Plot	RY	N	P_2O_5	K_2O	Ca	Mg	$S\text{-}SO_4$
	%						
A	44.7	III	I	I	I	I	II
B	41.7	IV	III	II	I	I	I
C	26.1	I	IV	III	IV	IV	I
D	46.7	I	IV	IV	III	IV	IV

Table 7. Critical level of the contents of organic matter and phosphorus, potassium, calcium, and magnesium in the soil, estimated by leaf analysis, using models obtained by the Quadrant Diagram of the Plant-Soil Relationship (QDpsR) method

Plot	$OM_{(N)}$	P	K	Ca^{2+}	Mg^{2+}	$OM_{(S)}$
	g dm^{-3}	mg dm^{-3}		cmol$_c$ dm^{-3}		g dm^{-3}
A	9.63	101.66	107.93	4.19	>1.60	14.87
B	7.37	75.76	143.37	>10.00	>1.60	14.87
C	22.67	58.81	84.31	1.74	0.54	11.81
D	15.75	58.81	92.83	1.51	0.47	5.00
$_{CL}Nu_i$	13.20	97.50	91.50	2.71	0.61	1.32

$OM_{(N)}$ = corresponds to the SOM estimated by N from leaf analysis; $OM_{(S)}$ = corresponds to the SOM estimated by S from leaf analysis; $_{CL}Nu_i$ = corresponds to the critical level of the macronutrients and organic matter in the soil.

chemical analysis (Table 3) and above the $_{CL}$SOM, which is 13.2 g dm^{-3}. Therefore, the limitation of yield in this plot is probably due to a non-nutritional factor or, if nutritional, related to (an)other element(s).

The recommended rate of 16.6 kg ha^{-1} of N twice a year for plot A, apparently low, refers only to the amount of N necessary to maintain the C:N ratio of SOM close to 10:1, through the stabilization of SOM in humic substances, avoiding its depletion and, consequently, maintaining the advantages of this important soil quality index. Thus, this application rate should be added to the rates that are being used, ensuring that SOM is not a yield-limiting factor.

Arid and semi-arid regions are characterized by poorly developed soils, low rainfalls, and high temperatures, which contribute to low production of plant material (Raiesi, 2012; Oliveira et al., 2015). In addition, the soils of these regions, as in the present study, are highly susceptible to loss of fertility due to low contents of SOM (García-Orenes et al., 2010). Therefore, it is essential to adopt management practices that increase or maintain SOM values close to the critical level.

Among these management practices, we can highlight maintenance of crop residues on the soil surface, which is widely used in banana cultivation. This practice minimizes soil disturbance, reduces temperature oscillations, maintains soil moisture during hot and dry seasons, and influences soil microorganisms and their processes (Christensen, 1996; Andrade et al., 2003).

The kinetics of banana residue decomposition has been evaluated using ^{15}N by Raphael et al. (2012), who observed that 39 % of the N taken up by the daughter plant at harvest came from the residues from the previous harvest. These authors also highlighted the importance of considering the contribution of N from residues in recommendation of N fertilization rates, as used, for instance, by FERTICALC®-Bananeira (Oliveira et al., 2005). Improvements in soil quality with respect to SOM in arid and semi-arid regions can also be achieved with practices such as irrigation and fertilization, as well as intensive cultivation (Fallahzade and Hajabbasi, 2012; Oliveira et al., 2015).

Regarding P, only plot B met the criteria of quadrant III (Table 6), and fertilization was recommended at a rate of 230.6 kg ha^{-1} of P_2O_5 (Table 8). A rate of 410.3 kg ha^{-1} of P_2O_5 was recommended for plots C and D, but they met the criteria of quadrant IV, i.e., other non-nutritional factors must be involved or, if nutritional, related to (an)other element(s).

The reliability of this form of fertilization recommendation can be observed, for example, by comparing the “actual” values of nutrients present in the soil from soil analysis (Table 3) with the contents of nutrients in the soil estimated by leaf analysis (Table 7). There is similarity between “actual” P in the soil and the estimated value, 68.0 and 75.76 mg dm^{-3}, respectively. However, both are below the $_{CL}$Nu$_i$ of 97.5 mg dm^{-3} (Table 7), which is an indication that leaf analysis is a tool that can be used in quantitative adjustment of the recommended application rates, complementing the usual recommendations based on soil analysis.

Table 8. Relative yield (RY) and recommended application rates of nitrogen (N), phosphorus (P_2O_5), potassium (K_2O), calcium (Ca), magnesium (Mg), and sulfur (S-SO_4), based on leaf contents nutrient contents are relative to leaf analysis of the four plots used in the simulation (Table 2)

Plot	RY	N (OM)	P_2O_5	K_2O	Ca	Mg	S-SO_4 (OM)
	%	kg ha^{-1}					
A	44.7	16.6	-	-	-	-	-
B	41.7	27.1	230.6	-	-	-	-
C	26.1	-	410.3	21.6	506.5	21.3	1.0
D	46.7	-	410.3	-	626.5	42.6	5.8

The contents of nutrients reflect the mineral composition of plant tissues and provide basic information for diagnosis of plant nutritional status (Parent and Dafir, 1992). Particularly analyses of leaves or of other plant organs are widely used to evaluate nutrient requirements and are the tool which best provides information on the actual amounts of nutrients taken up and metabolized by the crop (Magallanes-Quintanar et al., 2006).

In plots C and D, classified as false negative, there is no agreement between the contents, and there was a dissimilarity between the "actual" values (150.0 and 130.0 mg dm^{-3}) present in the soil analysis and the contents estimated by leaf analysis (58.81 and 58.81 mg dm^{-3}). In addition to the divergence in relation to the ${}_{CL}Nu_i$ of 97.5 mg dm^{-3} (Table 7), in soil analysis, the values are above the ${}_{CL}Nu_i$, suggesting that there is no need for P application, unlike the contents estimated by leaf analysis, which are below the ${}_{CL}Nu_i$, leading to incorrect recommendation of P.

Plant nutritional status often has low correlation with the contents of nutrients in the soil (Hanson, 1987), because of the complex interactions between factors which influence the uptake and distribution of nutrients by plants (Wairegi and van Asten, 2011).

Potassium application was only recommended for plot C, with 21.6 kg ha^{-1} of K_2O (Table 8), which is considered low given the large requirement for this nutrient by the banana crop (Hoffmann et al., 2010; Ganeshamurthy et al., 2011; Silva et al., 2013; Taulya, 2013). However, considering that only 11 % of all plots respond to K fertilization and that more than 50 % of the possible limitations are non-nutritional (Table 5), it may be asserted that the K rates used by the company adequately meet crop requirements and may even be more than necessary, which may lead to either recommendation of no fertilization or recommendation of quantitatively low application rates.

As observed for P, the K contents estimated by leaf analysis, 84.31 mg dm^{-3} (Table 7), were consistent with those from soil analysis, 89.9 mg dm^{-3} (Table 3), for plot C, which met the criteria of quadrant III. Therefore, leaf analysis and the QDpsR method are tools that can be used in adjustment of fertilization recommendations.

Leaf analysis is a tool widely used and successfully employed in the diagnosis of plant nutritional status, but its direct utilization for fertilizer recommendation is very limited. It is necessary to conduct in-depth studies aiming to incorporate this tool in adjusting application rates of nutrients, taking advantage of its potential.

Values of nutrients determined by soil analysis are availability indices and not their truly available contents (Oliveira et al., 2005). Furthermore, acquisition of the nutrient from the soil by the plant is influenced by various factors (Durán et al., 2012). Consequently, a deficiency in the plant is easier to detect by leaf analysis (Hallmark and Beverly, 1991). Therefore, leaf analysis is a tool with great potential and should actively be used in fertilization programs.

For Ca, only plot D met the criteria of quadrant III (Table 6), and the rate of 625.5 kg ha^{-1} of Ca was recommended (Table 8). For this plot, the Ca content revealed by soil analysis (Table 3) and the content estimated by leaf analysis (Table 7) were closest in values, both below the ${}_{CL}Nu_i$, which is 2.71 $cmol_c$ dm^{-3} (Table 7), similar to what was observed for P and K.

For plot C, 506.5 kg ha^{-1} of Ca was recommended (Table 8), but it is a false negative because it meets the criteria of quadrant IV (Table 6). Thus, this rate should not be used, because the yield is already being limited by non-nutritional factors or, if nutritional, related to (an)other element(s).

For Mg, none of the plots met the criteria of quadrant III (Table 6). Therefore, there is no recommendation of fertilization for the plots studied. The rates of 21.3 and 42.6 kg ha^{-1} of Mg, relative to plots C and D (Table 8), respectively, constitute false positives, i.e., they are in quadrant IV; other non-nutritional factors or factors related to (an)other element(s) are influencing the yield.

In addition to interpretation of the results by individual evaluation of the nutrients which are (or are not) limiting yield, a joint evaluation is also necessary, considering the effect of the interaction among the elements on fertilization recommendation and, consequently, on yield.

Plot C, for instance, indicated the following application rates: 21.6, 506.5, and 21.3 kg ha^{-1} of K_2O, Ca, and Mg, respectively (Table 8). Nevertheless, the recommendation is only valid for K, which meets the criteria of quadrant III (Table 6). In the case of Ca and Mg, which meet the criteria of quadrant IV, these rates are not valid, and limitation may be attributed to other factors, possibly related even to ionic interactions of the nutrients in the soil.

There are many reports in the literature on the relationship between Ca, Mg, and K for the banana crop (Rufyikiri et al., 2003; Fernandes et al., 2008; Silva et al., 2008; Maia and Morais, 2015). In irrigated areas, especially in arid and semi-arid regions, one should consider the quality of the water used for irrigation, which directly influences the ionic balance of the soil solution (Jalali, 2008; Maia and Morais, 2015). An adequate amounts and proportions of K, Ca, and Mg in the soil solution are very important to maintain yield in cultivated soils (Karley and White, 2009).

For S, none of the plots met the criteria of quadrant III (Table 8); however, the rate of 1.0 kg ha^{-1} of SO_4 twice a year was recommended for plot C (Table 8), which met the criteria of quadrant I. Quadrants III and I are related to nutritional factors but, as previously mentioned, in plots located in quadrant I, the recommended rate is expected to be very close or equal to zero, as occurred for N, P, K, Ca, and Mg (Tables 6 and 8). In addition, as observed for N, this application rate is additional and does not substitute the one that is being used, because its aim is to maintain the C:S ratio of SOM close to 112:1, increasing its stability.

Comparison with other methods of fertilization recommendation

For Ca and Mg, comparisons were made only between the recommendations from leaf analysis and FERTICALC®-Bananeira, because of the absence of application rates for these nutrients in accordance with the fertility class in the Recommendation Table for Banana Fertilization in the state of Ceará.

The P rates recommended based on leaf analysis diverged from those recommended by FERTICALC®-Bananeira and the Recommendation Table (Table 9). Recommendation was only made for plot B, with a rate of 230.6 kg ha^{-1} of P_2O_5, and, no fertilization was recommended for plots C and D, because they meet the criteria of quadrant IV (Table 6).

Table 9. Comparison of the recommended rates of phosphorus (P_2O_5), potassium (K_2O), calcium (Ca), and magnesium (Mg) through leaf analysis, FERTICALC®-Bananeira, and Recommendation Table

Plot	P_2O_5			K_2O			Ca		Mg	
	Leaf	Fertic	Tab	Leaf	Fertic	Tab	Leaf	Fertic	Leaf	Fertic
	kg ha^{-1}									
A	0.0	141.3	50.0	0.0	706.1	250.1	0.0	0.0	0.0	32.4
B	230.6	145.6	50.0	-	799.3	366.7	0.0	0.0	0.0	57.4
C	-	145.3	50.0	21.6	810.9	366.7	-	0.0	-	51.2
D	-	143.6	50.0	-	734.6	250.1	626.5	0.0	-	54.9

Leaf: rates recommended based on leaf analysis for the plots that meet the criteria of quadrants III and I, and (-) for the plots that meet the criteria of quadrants IV and II; Fertic = Ferticalc: rates recommended based on nutritional balance system for banana of the AAB group, considering 1,667 families per hectare, expected yield of 39.0 t ha^{-1}, values of soil chemical analysis (Table 3), and yield obtained in the previous cycle: 21.2, 19.8, 12.4, and 22.1 t ha^{-1} for plots A, B, C, and D, respectively; Tab = Table: rates recommended for production fertilization based on the Recommendation Table for Banana Fertilization in the state of Ceará, considering 1,667 families per hectare and soil chemical analysis (Table 3).

These divergences observed in the recommendations based on leaf analysis are related to the contents in the leaves (Table 2) and in the soil (Table 3), which are used as input data in the QDpsR method (Table 4). The use of leaf analysis through this method is an advantage because it considers the nutritional status of the plant in making the decision whether to fertilize or not. Furthermore, this method is sensitive to nutritional and non-nutritional factors which affect yield, recommending application only in those cases in which limitations result from nutritional factors.

Since FERTICALC®-Bananeira does not yet have such sensitivity, it recommends rates of 145.3 and 143.6 kg ha^{-1} of P_2O_5 for plots C and D, respectively, whereas the rate of 50.0 kg ha^{-1} of P_2O_5 was recommended for all plots by the Recommendation Table (Table 9). The lower rate recommended by the Recommendation Table is partially related to the lower ${}_{CL}Nu_i$ established by it, which is 20.0 mg dm^{-3}, compared with the ${}_{CL}Nu_i$ of 97.5 mg dm^{-3} obtained by the UBL. Another important point is that the Recommendation Table does not consider that the recommended rates vary continuously with the expected yield and with the content and buffering capacity of the nutrient in the soil (Oliveira et al., 2005), especially related to P.

For K, the amounts indicated based on leaf analysis also diverged from those suggested by FERTICALC®-Bananeira and the Recommendation Table. The rates varied from 706.1 to 810.9 kg ha^{-1} of K_2O for FERTICALC®-Bananeira and from 250.1 to 366.7 kg ha^{-1} of K_2O for the Recommendation Table. When leaf analysis is considered, recommendation was only made for plot C, with rate of 21.6 kg ha^{-1} of K_2O (Table 9).

The high rates recommended from FERTICALC®-Bananeira and their discrepancy in comparison to the rates recommended by leaf analysis are related to the modules of requirement and supply of FERTICALC®-Bananeira (Oliveira et al., 2005). According to these authors, there were excessive K rates during development of the FERTICALC®-Bananeira model and simulations of recommended application rates, and one of the explanations is the low values of the biological utilization coefficient (CUB), which could be overestimating the content of K and, consequently, its requirement by the banana crop. Another explanation would be that the supply module does not consider the nonexchangeable K in the soil, which can be an important source of K to banana trees. Furthermore, according to these authors, it is important in future studies to determine the amounts and partitioning of the dry matter, K accumulation in the harvest period, and the supply of nonexchangeable K in the soil to the banana crop, in order to correct these problems in new versions of the model.

In addition, as previously mentioned, FERTICALC®-Bananeira does not yet have sensitivity to nutritional and non-nutritional factors in making a decision whether to fertilize or not. Conversely, in recommendations based on leaf analysis, in which plots B and D met the criteria of quadrants II and IV, respectively, it is evident that the limitations in yield are related to other non-nutritional factors or, if nutritional, related to (an)other element(s). Corroborating this fact, 51 % of the plots have non-nutritional limitations (quadrants II and IV) and only 11 % of the plots met the criteria of quadrant III, i.e., with high probability of response to K fertilization (Table 5). Therefore, it is unlikely that the requirement of K by the plots is at the high rates suggested by FERTICALC®-Bananeira (Table 9).

Such overestimation of K rates was also observed in FERTCALC®-Abacaxi (Silva et al., 2009), and the authors attributed it to possible luxury consumption of K and consequent overestimation of the recovery rate of the nutrient applied through fertilizer to the plant, which would be contributing to an increasing K requirement. Lack of information and the use of average values of CUB and the nutrient recovery rate by the plant, without considering the influence of soil, climatic, biological, plant, and management factors, have been highlighted by various authors (Oliveira et al., 2005; Santos et al., 2008;

Silva et al., 2009; Deus et al., 2015) as research problems to be studied to generate information that will improve and adjust future versions of the FERTICALC® model.

Regarding the application rates presented by the Recommendation Table for Banana Fertilization in the state of Ceará (Fernandes, 1993), it is necessary to highlight some limitations to their use because currently the data of yield, cultivars, spacing, management, etc. are very distant from the scenario in which this Table was developed. Another aspect to highlight is that the Tables of Recommendation usually present rates that do not vary continuously with the expected yield and the nutrient content in the soil. In addition, they do not consider soil buffering capacity, have geographic restriction, and are not very flexible regarding the cultivar, management system, and planting density (Oliveira et al., 2005; Santos et al., 2008; Silva et al., 2009; Deus et al., 2015); they do not lend themselves to adjustments and, therefore, have low future prospects. In addition, they do not contemplate all nutrients, as in the present case of Ca and Mg.

Calcium recommendations based on leaf analysis and FERTICALC®-Bananeira were similar, except for plot D, in which a rate of 626.5 kg ha^{-1} of Ca was recommended by leaf analysis (Table 9). This rate is due to the Ca contents in the soil below the $_{CL}Nu_i$ and to the leaf contents of Ca below the mean of the population, meeting the criteria of quadrant III. In general in the company plots, there are no problems related to Ca because only 3 % of the plots correspond to quadrant III, i.e., with high probability of response to Ca application.

Nevertheless, it must be noted that soil is a very complex environment and that the addition of fertilizers constantly changes the balance of soluble salts in the soil solution in intensive cultivation systems. Throughout the year, the content of salts present in the soil varies due to the rainfall regime of the region, and it is difficult to maintain the balance between solid and liquid phases in the long term. Furthermore, there is interaction between various other factors that influence the supply of nutrients in the rhizosphere, affecting the uptake of elements by the plant (Gauggel et al., 2005).

Therefore, leaf tissue analysis is a tool with great potential because it better reflects the nutritional status of the plant; if used in combination with soil analysis, it generates more adequate recommendations because it considers factors related to the soil and to the plant.

The study discussed above indicates how complex the soil-plant interface is and how understanding it can enhance nutritional management through development of new tools that improve the current forms of recommendation. It should be note that the recommendation of fertilization rates using leaf analysis is complementary and does not substitute the conventional recommendation based on soil analysis.

CONCLUSIONS

The use of leaf analysis as a tool to adjust nutrient fertilization rates proved to be a more adequate alternative for the banana crop compared to use of soil analysis alone.

The Quadrant Diagram of the Plant-Soil Relationship method allows one to more accurately relate the contents of nutrients in the diagnostic leaf of the banana to the contents of nutrients found in soil chemical analysis.

Utilization of leaf analysis along with soil chemical analysis and yield allows for more adequate fertilization recommendations for the banana crop and leads to advantages if incorporated with nutritional balance models.

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