

## Potential nutrient-response curves and sufficiency ranges for 'Prata-Anã' banana cultivated under two environmental conditions

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**ABSTRACT:** Proper plant nutrition is critical to increasing the yield of bananas. The objective was to establish the potential nutrient-response curves and sufficiency ranges using the boundary line approach (BLA) and the method proposed by Kenworthy (MK) to assess the nutritional status of 'Prata-Anã' bananas cultivated under two environmental conditions. The study was carried out using a database comprising leaf nutrient concentrations and banana yields grown at Missão Velha, Ceará, and Ponto Novo, Bahia, Brazil. The reference population consisted of high-yielding plants with yields greater than the mean yield plus 0.5 standard deviation. The database was divided into two datasets. One contained 253 leaf analysis results and a reference population with a mean yield greater than 39.81 t ha<sup>-1</sup> yr<sup>-1</sup> at Missão Velha. The other contained 147 samples and a reference population with a mean yield greater than 41.69 t ha<sup>-1</sup> yr<sup>-1</sup> at Ponto Novo. The sufficiency ranges obtained by the BLA for 'Prata-Anã' banana in Bahia and Ceará, respectively, are: a) for macronutrients (g kg<sup>-1</sup>): N (19.3-22.0) and (19.9-22.1); P (1.4-2.0) and (1.4-1.6); K (22.6-32.2) and (24.0-31.3); Ca (4.6-6.5) and (5.3-5.8); Mg (1.8-2.6) and (2.1-2.7); S (1.3-2.0) and (1.3-1.5); b) for micronutrients (mg kg<sup>-1</sup>): B (8.4-13.0) and (13.7-16.4); Cu (5.6-8.4) and (4.4-5.2); Fe (54.2-77.6) and (39.0-55.0); Mn (140.1-222.8) and (64.0-91.0); Zn (13.5-18.3) and (12.4-14.5). The sufficiency ranges obtained by the BLA are more assertive when assessing the nutritional status for 'Prata-Anã' banana.

**Keywords:** *Musa* spp., AAB, site condition, nutritional status, diagnostic methods

### Introduction

Leaf tissue analysis as a tool for assessing plant nutritional status has been widely used to improve fertilizer rate recommendations and crop management practices. Reference values are conventionally established in calibration tests in which genetic and environmental factors and the interplay between nutrients are controlled; however, the nutritional composition of plant tissues is highly influenced by several environment- and crop-related factors (Iheshiulo et al., 2019). Indiscriminate extrapolations of sufficiency ranges established in diverse environmental conditions may lead to inaccurate nutritional diagnoses; thus, determining site- and cultivar-specific sufficiency ranges is a preferable course of action.

The boundary line approach (BLA) is an alternative to calibration experiments because this method uses nutrient concentration data from commercial crop fields (Maia and Morais, 2016). The approach consists of relating nutrient concentrations to yield data, so that the optimum concentration of a given nutrient can be determined. Moreover, it permits the estimation of the highest attainable yield from observational data (Ali, 2018).

Studies found in the literature report sufficiency ranges established by BLA for several crops including forage cactus (Blanco-Macías et al., 2010), papaya (Maia and Morais, 2016), sugarcane (Mccray et al., 2010), rubber tree (Njukeng et al., 2013), haskap (Iheshiulo et al., 2019) and eucalyptus (Lima Neto et al., 2020); however, studies on bananas are in short supply.

Bananas demand large amounts of nutrients and are sensitive to nutritional imbalances. Thus, periodically, nutritional diagnoses should be adopted as a routine procedure on banana plantations (Silva, 2015) based on specific norms established using data from commercial fields (Lafond, 2013).

The objective of this study was to establish potential nutrient-response curves for determining sufficiency ranges using the BLA and the method proposed by Kenworthy to assess the nutritional status of 'Prata-Anã' bananas cultivated under two environmental conditions.

### Materials and Methods

#### Experimental conditions

The study was carried out using data from 'Prata-Anã' banana production systems under two environmental conditions. The first farm is located at Missão Velha, in the state of Ceará (CE), Brazil (7°35'90" S, 39°21'17" W, altitude of 442 m). Data were collected from plants averaging 12 years of age at the beginning of data collection and 19 by the end of it. The climate of the region is Aw – tropical savanna climate with a dry winter season and a rainy summer season (Köppen-Geiger) (Alvares et al., 2013). Mean annual rainfall and temperature are 942 mm and 25.8 °C, respectively. The soil was sandy and classified predominantly as a Red-Yellow Latosol (SiBCS) (Santos et al., 2018). On this farm, there are 57 plots averaging 3.26 ha in size of fertigated 'Prata-Anã' banana spaced at 2.8 × 2.8 m (1,275 plants ha<sup>-1</sup>).

The second farm is located at Ponto Novo, in the state of Bahia (BA), Brazil, (10°51'46" S, 40°08'01" W, and altitude of 342 m). Data collection began when bananas were eight years old and ended when they were ten. The climate is also Aw (Köppen-Geiger) (Alvares et al., 2013) with a mean annual rainfall of 697 mm and temperature 24.1 °C. The predominant soil at the site is a sandy Yellow Latosol (SiBCS) (Santos et al., 2018). On this farm, there are 100 plots averaging 4.53 ha in size of fertigated 'Prata-Anã' banana spaced at 2.8 × 2.8 m (1,275 plants ha<sup>-1</sup>).

Fertilizer rates recommended for both sites were based on their respective soil test results and followed Silva (2015) with adaptations. Table 1 and 2 show soil test results and climate data for both sites, respectively. Climate data are the year 2016, when weather stations were installed at the sites.

### Database

The results of the analysis of the leaf tissue and the yields recorded in a database belonging to the experimental area were used. Leaf tissue sampling was performed twice a year, every six months, and followed the

**Table 1** – Soil chemical test results of 'Prata-Anã' banana fields at Missão Velha, CE, and Ponto Novo, BA, Brazil, 0.0-0.2 m and 0.2-0.4 m, for the period 2014-2016.

Site	Sampling depth m	2014							
		pH	OM g dm <sup>-3</sup>	P mg dm <sup>-3</sup>	K mg dm <sup>-3</sup>	Ca mmol <sub>c</sub> dm <sup>-3</sup>	Mg mmol <sub>c</sub> dm <sup>-3</sup>	CEC mmol <sub>c</sub> dm <sup>-3</sup>	V %
Ceará	0.0-0.2	7.3	22.6	178.0	6.1	83.1	16.3	116.1	89.1
	0.2-0.4	7.7	17.0	140.0	4.7	142.2	28.0	193.3	95
Bahia	0.0-0.2	6.4	14.6	73.6	4.6	23.4	8.0	56.6	78.6
	0.2-0.4	6.4	9.0	26.1	3.0	14.5	5.8	42.1	48.6
2015									
Ceará	0.0-0.2	7.2	26.3	132.1	7.4	76.2	15.6	113.1	86.2
	0.2-0.4	7.5	21.0	115.7	8.8	109.3	22.0	152.3	92.1
Bahia	0.0-0.2	6.6	16.9	50.8	4.4	20.7	7.1	53.3	61.8
	0.2-0.4	5.6	11.0	35.2	2.5	13.3	6.0	40.0	54.7
2016									
Ceará	0.0-0.2	7.4	28.4	148.3	8.0	84.2	17.1	121.2	89.1
	0.2-0.4	7.7	27.0	130.2	8.8	136.0	24.2	181.0	93.0
Bahia	0.0-0.2	6.3	13.3	79.4	2.8	16.3	7.2	52.4	80.1
	0.2-0.4	6.2	12.0	21.0	2.1	12.5	5.0	35.0	60.3

pH in water in a 1:2.5 ratio; OM = soil organic matter content obtained by organic carbon × 1.724 (Walkley-Black); P and K = Mehlich-1 extraction; Ca and Mg = KCl 1 mol L<sup>-1</sup>; CEC = cation exchange capacity at pH 7; V = base saturation. Source: made by authors from Soil Testing Database located at Missão Velha, CE, and Ponto Novo, BA.

**Table 2** – Meteorological data recorded at Missão Velha, CE, and Ponto Novo, BA, Brazil, in 2016.

Month	Mean temperature	Max. temperature	Min. temperature	Rainfall mm	RH	VPD	Max. wind speed m s <sup>-1</sup>
	°C				%	kPa	
Missão Velha – CE							
Jan	26.91	31.96	21.86	231.10	74.22	0.76	1.60
Feb	26.95	33.17	20.73	60.90	77.61	0.67	1.60
Mar	27.79	33.38	22.21	198.50	78.13	0.68	1.54
Apr	27.05	32.84	21.26	33.50	74.05	0.78	3.09
May	27.14	33.40	20.88	30.00	66.65	1.01	3.09
June	26.23	32.64	19.82	17.60	64.00	1.05	7.72
July	26.39	33.22	19.57	0.00	50.60	1.46	5.14
Aug	27.00	34.68	19.32	0.00	45.92	1.67	5.14
Sept	28.29	35.58	21.01	3.10	45.66	1.78	4.63
Oct	29.26	36.72	21.81	0.00	44.07	1.93	3.60
Nov	29.67	36.32	23.03	0.00	43.41	1.97	3.09
Dec	29.04	35.61	22.47	69.10	52.98	1.58	3.09
Ponto Novo – BA							
Jan	25.19	29.84	22.37	190.83	82.92	0.48	5.18
Feb	25.83	31.86	21.08	20.80	74.06	0.75	5.98
Mar	26.90	32.95	21.85	0.00	69.02	0.94	6.58
Apr	26.51	32.63	21.37	14.45	64.73	1.05	5.58
May	24.48	29.58	20.45	49.25	76.05	0.64	6.21
June	23.12	27.93	19.47	31.55	78.08	0.54	5.68
July	22.60	28.29	18.16	8.85	75.48	0.60	6.11
Aug	23.33	29.25	18.57	11.75	71.71	0.72	6.50
Sept	24.48	30.63	19.66	1.80	69.65	0.82	6.75
Oct	25.99	32.57	20.86	5.95	66.99	0.98	7.10
Nov	24.53	25.23	23.82	184.00	70.79	0.74	1.34
Dec	25.2	25.98	24.42	44.20	69.49	0.80	1.32

RH = relative humidity; VPD = vapor pressure deficit. Source: made by authors from meteorological data recorded by automatic weather stations installed at Missão Velha, CE, and Ponto Novo, BA, Brazil.

recommendations of Costa et al. (2019). The mid-portion of the third leaf lamina, counting from the apex, was collected when the inflorescence had two or three open clusters of male flowers. Samples were processed and analyzed as to leaf macro- (N, P, K, Ca, Mg and S) and micronutrient (B, Cu, Fe, Mn and Zn) contents, which were determined as follows: N – Kjeldahl method; P, S, Ca, Mg, Fe, Mn, Cu, Zn, B, Al – nitric-perchloric acid digestion and determination by ICP-OES; K – nitric-perchloric digestion and determination by flame photometer as described by Deus et al. (2018a).

Yields were estimated as  $t\ ha^{-1}\ yr^{-1}$  by weighing hands of harvested bunches. Relative yield (RY) was determined based on the highest recorded yield (100 %) as recorded by Deus et al. (2018b).

The database was divided into two site-specific datasets. A dataset was from the farm located at Missão Velha, CE, and comprised annual yields and leaf analysis results relative to the years from 2010 to 2017. The initial sample containing 804 recordings, mean  $\pm$  standard deviation of  $35.91 \pm 7.8\ t\ ha^{-1}\ yr^{-1}$ , was subdivided into low- and high-yielding populations; the latter was the reference population, defined as having yields above the average plus 0.5 standard deviation, as used by Alves et al. (2019), which corresponded to  $39.81\ t\ ha^{-1}\ yr^{-1}$  (73 % maximum relative yield) ( $n = 253$ ).

The other dataset was from the farm located at Ponto Novo, BA, and contained leaf analysis results from samples collected twice a year and annual yields recorded between 2014 and 2016. The initial sample consisting of 481 recordings, mean  $\pm$  standard deviation of  $34.89 \pm 13.59\ t\ ha^{-1}\ yr^{-1}$ , was subdivided into low- and high-yielding populations. The reference population had a yield greater than average plus 0.5 standard deviation, corresponding to  $41.69\ t\ ha^{-1}\ yr^{-1}$  (57 % maximum relative yield) ( $n = 147$ ).

#### Determination of potential nutrient-response curves, reference values and sufficiency ranges by the Boundary Line Approach (BLA)

Relative yields (RY), on the y-axis, were plotted against leaf nutrient concentrations, on the x-axis, forming a scatter diagram. Data points located on the upper edge of the scatter diagram were selected by drawing a line confining all data, forming a boundary line. Each data point on the upper boundary line represents the highest yield at a corresponding nutrient concentration. A regression equation fitted to the boundary line was used to determine sufficiency ranges.

A boundary line can be determined through different approaches (Deus et al., 2018a). The line around the scatter of data points can be drawn either by hand (Maia and Morais, 2016) or by using computer applications, such as Boundary Fit, developed by the Federal University of Viçosa (UFV) (Lima Neto et al., 2020). In this study, a nonparametric boundary regression (NPBR) package in R (R Development Core

Team, 2012) was used as a routine for determining the boundary line.

Sufficiency ranges were obtained using the BLA based on the following interpretative categories: deficient ( $RY < 70\%$ ), tending to sufficient ( $70 \leq RY < 90\%$ ), sufficient ( $90 \leq RY < 100\%$ ), high ( $100 > RY \geq 90\%$ , to the right of the maximum), tending to excessive ( $90 \leq RY < 70\%$ , to the right of the maximum) and excessive ( $RY < 70\%$ , to the right of the maximum).

#### Original Method proposed by Kenworthy ( $MK_{orig}$ )

The mean and variability of leaf nutrient concentrations were obtained from the reference population of each site (Table 3). Percent of standard (P) (ratio of sample nutrient concentration to standard concentration), influence of variation (I) and coefficient of variation (CV) were calculated. The results were expressed in the form of a percentage. The following equations were used to calculate Kenworthy's balance indices (BIKW):

$$P = (100yi) / Y \quad (\text{Eq.1})$$

$$I = CV(yi - Y) / Y \quad (\text{Eq.2})$$

$$BIKW = P - I \quad (\text{Eq.3})$$

where:  $P$  is the ratio of sample nutrient concentration ( $yi$ ) to standard concentration ( $\bar{Y}$ ) (%);  $I$  is the influence of variability (%);  $CV$  is the coefficient of variation (%) of nutrient concentrations in the reference population; and  $BIKW$  is the balance index proposed by Kenworthy.

The upper limit sufficient concentration ranges obtained by  $MK_{orig}$  is the leaf nutrient concentration that corresponds to the BIKW of 100 %.

**Table 3** – Specific norms for calculating balances indices of Kenworthy for 'Prata-Anã' banana grown at Missão Velha, Ceará, and Ponto Novo, Bahia, Brazil.

Norm	Ceará			Bahia			
	$\bar{Y}$	s	CV	Norm	$\bar{Y}$	s	CV
	%			%			
N	21.9089	1.5820	7.22	N	23.0045	2.9416	12.79
P	1.6753	0.2491	14.87	P	1.6101	0.1313	8.16
K	33.9927	6.3498	18.68	K	31.3565	7.1523	22.81
Ca	6.4860	1.2523	19.31	Ca	5.6180	0.5681	10.11
Mg	2.3777	0.3690	15.52	Mg	2.7007	0.4349	16.10
S	1.5536	0.2691	17.32	S	1.4702	0.1526	10.38
B	11.0638	4.5581	41.20	B	14.7435	2.7223	18.46
Cu	6.1797	2.3583	38.16	Cu	5.2980	0.8416	15.89
Fe	67.4036	12.7856	18.97	Fe	57.3365	15.2073	26.52
Mn	179.3976	92.5274	51.58	Mn	84.6806	32.1586	37.98
Zn	16.4921	2.9857	18.10	Zn	14.8340	1.5562	10.49

Norm = reference population concentrations ( $\geq$  mean + 0.5 standard deviation), N, P, K, Ca, Mg and S concentrations are expressed as  $g\ kg^{-1}$ , and Cu, Fe, Zn, Mn and B, as  $mg\ kg^{-1}$ ;  $\bar{Y}$  = mean nutrient content in leaf sample; s = standard deviation; CV = coefficient of variation.

Sufficiency ranges were obtained based on interpretive classes originally proposed by Kenworthy (1961): deficient ( $BIKW < 50\%$ ); tending to sufficient ( $50 \leq BIKW < 83\%$ ); sufficient ( $83 \leq BIKW < 100\%$ ); high ( $100 \leq BIKW < 117\%$ ); tending to excessive ( $117 \leq BIKW < 150\%$ ); and excessive ( $BIKW \geq 150\%$ ).

### Modified Method proposed by Kenworthy ( $MK_{mod}$ )

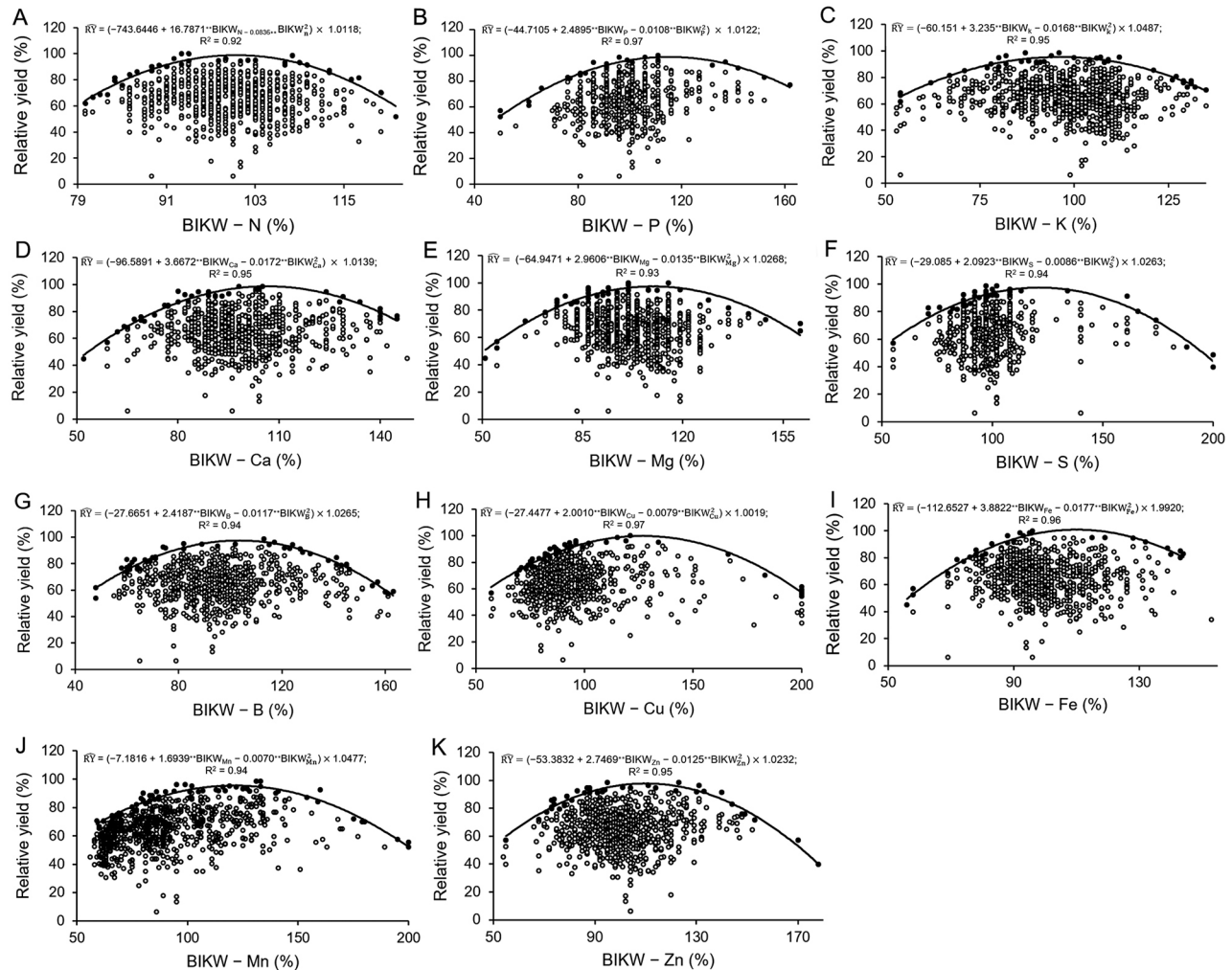
The ranges originally proposed by Kenworthy (1961) for apple trees may not be adequate because the author consistently used a mean variability of 20 % for every nutrient. This poses a problem when dealing with micronutrients because their leaf contents tend to have a variability higher than 20 %. Thus, the BLA was used to obtain nutrient-specific interpretive classes based on RY (Lima Neto et al., 2020)

After obtaining the BIKW for each nutrient studied using site-specific norms, RY was plotted against

the BIKW to form a scatter of data points. Data points located on the upper boundary of the scatter diagram were selected, and were used to determine regression equations, with which the nutrient-specific interpretive classes were determined based on the following: deficient ( $RY < 70\%$ ), tending to sufficient ( $70 \leq RY < 90\%$ ), sufficient ( $90 \leq RY < 100\%$ ), high ( $100 > RY \geq 90\%$ , to the right of the maximum), tending to excessive ( $90 \leq RY < 70\%$ , to the right of the maximum) and excessive ( $RY < 70\%$ , to the right of the maximum).

## Results and Discussion

The original methodology proposed by Kenworthy (1961),  $MK_{orig}$ , is based on the assumption that each nutrient limits crop yield equally; however, when using the BLA, the relationship between the RY and the BIKW (Figures 1A-K and 2A-K) yielded different interpretive classes (Table 4) for each nutrient, which



**Figure 1** – Boundary line fitted as a function of the relationship between relative yield (%) and indices of Kenworthy for N (A), P (B), K (C), Ca (D), Mg (E), S (F), B (G), Cu (H), Fe (I), Mn (J) and Zn (K) in 'Prata-Anã' banana, Missão Velha, CE, Brazil. \*\*Significant at  $p \leq 0.01$  by the t-test; The multipliers 1.018; 1.0122; etc. found in the equations correspond to an adjustment factor for the equation to assume the value of 100 % Relative Yield.

**Table 4** – Proposed interpretive classes for discriminating balance indices of Kenworthy (%) for 'Prata-Anã' banana grown at Missão Velha, CE, and Ponto Novo, BA, Brazil.

Nutrient	Classes (Reference value – PNRC, Potential Nutrient-Response Curve)					
	Deficient (< 70 %)	Tending to sufficient (70-90 %)	Sufficient (90-100 %)	High (100-90 %)	Tending to excessive (90-70 %)	Excessive (< 70 %)
Missão Velha, CE						
N	< 82	82-89	89-100	100-111	111-119	≥ 119
P	< 63	63-85	85-115	115-146	146-168	≥ 168
K	< 55	55-72	72-96	96-120	120-137	≥ 137
Ca	< 65	65-83	83-106	106-130	130-148	≥ 148
Mg	< 63	63-83	83-109	109-137	137-156	≥ 156
S	< 63	63-88	88-121	121-155	155-179	≥ 179
B	< 53	53-75	75-103	103-132	132-153	≥ 153
Cu	< 65	65-91	91-126	126-162	162-188	≥ 188
Fe	< 69	69-86	86-109	109-134	134-151	≥ 151
Mn	< 57	57-84	84-120	120-158	158-185	≥ 185
Zn	< 62	62-82	82-109	109-138	138-158	≥ 158
Ponto Novo, BA						
N	< 59	59-75	75-97	97-120	120-137	≥ 137
P	< 79	79-87	87-99	99-111	111-120	≥ 120
K	< 73	73-90	90-112	112-135	135-152	≥ 152
Ca	< 76	76-87	87-101	101-116	116-127	≥ 127
Mg	< 64	64-78	78-97	97-117	117-131	≥ 131
S	< 73	73-81	81-93	93-104	104-113	≥ 113
B	< 66	66-82	82-104	104-126	126-143	≥ 143
Cu	< 42	42-62	62-90	90-118	118-138	≥ 138
Fe	< 66	66-81	81-102	102-124	124-139	≥ 139
Mn	< 63	63-87	87-119	119-153	153-177	≥ 177
Zn	< 74	74-84	84-99	99-113	113-124	≥ 124

contradicts Kenworthy's approach. Differences across sufficiency ranges are mainly due to how yield-limiting the nutrient is when its concentration in plant tissues is at its lowest.

Apparently, the interpretive classes originally proposed by Kenworthy were based on a mean variability of 20 % for macro- and micronutrients alike. As micronutrient concentrations vary greatly in banana leaves, misleading interpretations are more likely to arise owing to their complex dynamics within the soil-plant system (Li et al., 2007; Rengel, 2015).

For each nutrient, regression equations were fitted to a boundary line fitted to the relationship between the RY and the BIKW of 'Prata-Anã' banana grown in CE and BA (Figures 1A-K and 2A-K) with high  $R^2$  (0.92 to 0.97). The regression equations were used to obtain nutrient-specific interpretive classes used for discriminating the BIKW (Table 4).

Lower limits of 'sufficient' interpretive classes of 'Prata-Anã' banana grown in CE and BA (Table 4) were close to that proposed by Kenworthy (1961), (83 %), with greater differences for K (72 %), Cu (91 %), and B (75 %) in CE, and for N (75 %) and Cu (%) in BA. Upper limits were also close to those proposed for  $MK_{orig}$  (100 %), except for P (115 %), S (121 %), Cu (126 %) and Mn (120 %) in CE, and for K (112 %) and Mn (119 %) in BA.

The BLA allowed for the fitting of significant quadratic regression equations with high  $R^2$  (0.91 to

0.98) to the upper boundary of the relationship between the RY and leaf nutrient concentrations in 'Prata-Anã' grown in CE (Figure 3A-K) and BA (Figure 4A-K). Sufficiency ranges were then estimated by regression equations (Table 5).

Sufficiency ranges obtained by  $MK_{mod}$  for 'Prata-Anã' grown in CE and BA are in Table 6 while sufficiency ranges obtained by  $MK_{orig}$  for CE and BA are in Table 7.

The sufficient N concentration range established by the BLA for 'Prata-Anã' grown in CE was 19.2-22.0 g kg<sup>-1</sup> (Table 5); very similar to that obtained by  $MK_{mod}$  19.3-21.9 g kg<sup>-1</sup>, (Table 6) and close to  $MK_{orig}$  17.9-21.9 g kg<sup>-1</sup> (Table 7). For BA, the sufficient N concentration range obtained by the BLA was 19.9-22.1 g kg<sup>-1</sup> (Table 5), with only the upper limit similar to that determined by  $MK_{mod}$  16.4-22.2 g kg<sup>-1</sup> (Table 6). The range was somewhat different from that proposed by  $MK_{orig}$  18.5-23.0 g kg<sup>-1</sup> (Table 7). [The sufficient N concentration ranges for Missão Velha, CE, are similar to that reported by Deus et al. (2018b) (18.0-26.8 g kg<sup>-1</sup>) for the same site and different from that reported by Silva (2015) for the same cultivar grown in northern Minas Gerais, Brazil (25.0-29.0 g kg<sup>-1</sup>). This difference was due to differences in soil organic matter levels and crop management.

Bananas grown on soils with medium-to-high organic matter content (> 16 g kg<sup>-1</sup>), such as those in this study (Table 1), are not likely to respond to N fertilization, and yields may even decrease as a result of excessive N

**Table 5** – Sufficiency ranges determined by boundary line approach for interpreting leaf nutrient concentrations in 'Prata-Anã' bananas grown at Missão Velha, CE, and Ponto Novo, BA, Brazil.

Nutrient	Classes (Reference value – PNRC, Potential Nutrient Response Curve)					
	Deficient (< 70 %)	Tending to sufficient (70-90 %)	Sufficient (90-100 %)	High (100-90 %)	Tending to excessive (90-70 %)	Excessive (< 70 %)
Missão Velha, CE						
g kg <sup>-1</sup>						
N	< 17.3	17.3-19.3	19.3-22.0	22.0-24.9	24.9-26.9	≥ 26.9
P	< 0.9	0.9-1.4	1.4-2.0	2.0-2.6	2.6-3.1	≥ 3.1
K	< 15.6	15.6-22.6	22.6-32.2	32.2-41.9	41.9-48.9	≥ 48.9
Ca	< 3.1	3.1-4.6	4.6-6.5	6.5-8.6	8.6-10.0	≥ 10.0
Mg	< 1.2	1.2-1.8	1.8-2.6	2.6-3.4	3.4-4.0	≥ 4.0
S	< 0.8	0.8-1.3	1.3-2.0	2.0-2.6	2.6-3.1	≥ 3.1
mg kg <sup>-1</sup>						
B	< 4.9	4.9-8.4	8.4-13.0	13.0-17.8	17.8-21.2	≥ 21.2
Cu	< 3.4	3.4-5.6	5.6-8.4	8.4-11.4	11.4-13.6	≥ 13.6
Fe	< 36.6	36.6-54.2	54.2-77.6	77.6-102.1	102.1-119.7	≥ 119.7
Mn	< 77.4	77.4-140.1	140.1-223.8	223.8-311.4	311.4-374.1	≥ 374.1
Zn	< 9.8	9.8-13.5	13.5-18.3	18.3-23.3	23.3-26.9	≥ 26.9
Ponto Novo, BA						
g kg <sup>-1</sup>						
N	< 18.0	18.0-19.9	19.9-22.1	22.1-24.5	24.5-26.3	≥ 26.3
P	< 1.2	1.2-1.4	1.4-1.6	1.6-1.9	1.9-2.1	≥ 2.1
K	< 18.6	18.8-24.0	24.0-31.3	31.3-38.8	38.8-44.3	≥ 44.3
Ca	< 4.9	4.9-5.3	5.3-5.8	5.8-6.3	6.3-6.7	≥ 6.7
Mg	< 1.6	1.6-2.1	2.1-2.7	2.7-3.3	3.3-3.8	≥ 3.8
S	< 1.2	1.2-1.3	1.3-1.5	1.5-1.7	1.7-1.8	≥ 1.8
mg kg <sup>-1</sup>						
B	< 11.7	11.7-13.7	13.7-16.4	16.4-19.2	19.2-21.2	≥ 21.2
Cu	< 3.9	3.9-4.4	4.4-5.2	5.2-5.9	5.9-6.4	≥ 6.4
Fe	< 27.0	27.0-39.0	39.0-55.0	55.0-71.8	71.8-83.8	≥ 83.8
Mn	< 43.8	43.8-64.0	64.0-91.0	91.0-119.2	119.2-139.4	≥ 139.4
Zn	< 10.8	10.8-12.4	12.4-14.5	14.5-16.6	16.6-18.2	≥ 18.2

applications (Silva, 2015). In addition, nutrient cycling plays a major role in replenishing the soil with N; up to 83 % of N returns to the soil after the harvest (Hoffmann et al., 2010). The increased N level in the soil resulted in a narrower sufficient N range than that reported by Silva (2015) and similar to that found by Deus et al. (2018b) in conditions akin to those of this study. This reduction in leaf N concentration was also observed by Damatto Junior et al. (2011), who reported a decrease in leaf N concentrations in 'Prata-Anã' banana subject to an increase in N supply.

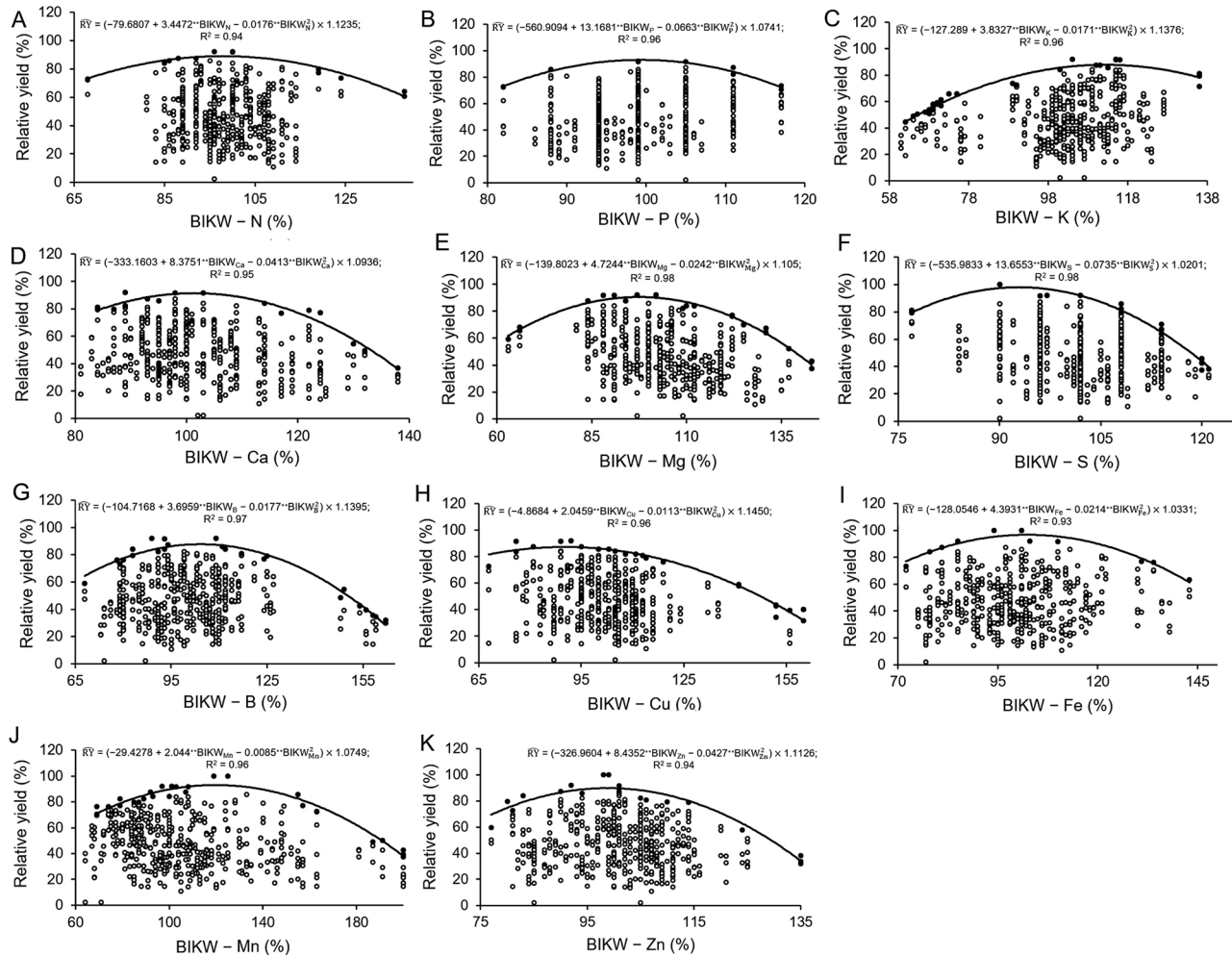
The lower sufficient N concentration ranges reported in this study, in comparison with those reported by Silva (2015), agree with previously proposed reductions in N fertilizer rates (Deus et al., 2018a). In 1999, the recommended N fertilizer rate for 'Prata-Anã' grown in northern Minas Gerais ranged from 200 to 400 kg ha<sup>-1</sup> yr<sup>-1</sup>, a rate range much greater than previous N recommendations, which ranged from 90 to 220 kg ha<sup>-1</sup> yr<sup>-1</sup> (Silva, 2015).

The sufficient P concentration range obtained by the BLA for 'Prata-Anã' grown in CE was 1.4-2.0 g kg<sup>-1</sup> (Table 5); equal to the range found by MK<sub>mod</sub> (Table 6)

and close to MK<sub>orig</sub>, 1.3-1.7 g kg<sup>-1</sup> (Table 7). For BA, the sufficient range obtained by the BLA was 1.4-1.6 g kg<sup>-1</sup> (Table 5), the same range determined by MK<sub>mod</sub> (Table 6) and very close to the range obtained by MK<sub>orig</sub>, 1.3-1.6 g kg<sup>-1</sup> (Table 7). Similarly, Deus et al. (2018b) and Silva (2015) found the ranges 1.5-1.7 g kg<sup>-1</sup> and 1.5-1.9 g kg<sup>-1</sup>, respectively; their lower variability is consistent with how banana plants respond to P (Silva, 2015).

Phosphorus is the macronutrient that accumulates the least in leaves of 'Prata-Anã' banana (Hoffmann et al., 2010). Increased leaf P concentrations may limit the yield due to imbalances in other nutrients, particularly Zn. Although soil P availability increases, leaf P concentration remains virtually unchanged (Damatto Junior et al., 2011). It has been reported that 'Prata-Anã' bananas only respond to P fertilization in the first cycle, even when grown on soils with low P levels (Silva, 2015).

The sufficient K concentration range obtained by the BLA for CE was 22.6-32.2 g kg<sup>-1</sup> (Table 5). The range limits are closer to that found by MK<sub>mod</sub>, 22.3-32.3 g kg<sup>-1</sup> (Table 6) than by MK<sub>orig</sub>, 26.9-34.0 g kg<sup>-1</sup> (Table 7). For BA, the sufficient K concentration range obtained



**Figure 2** – Boundary line fitted as a function of the relationship between relative yield (%) and indices of Kenworthy for N (A), P (B), K (C), Ca (D), Mg (E), S (F), B (G), Cu (H), Fe (I), Mn (J) and Zn (K) in 'Prata-Anã' banana, Ponto Novo, BA, Brazil. \*\* Significant at  $p \leq 0.01$  by the t-test; The multipliers 1.1235; 1.0741; etc. found in the equations correspond to an adjustment factor for the equation to assume the value of 100 % Relative Yield.

by the BLA was 24.0-31.3 g kg<sup>-1</sup> (Table 5); different from the range determined by MK<sub>mod</sub>, 27.3-36.2 g kg<sup>-1</sup> (Table 6) and similar to MK<sub>orig</sub>, 24.5-31.4 g kg<sup>-1</sup> (Table 7). The range established by Silva (2015), 27.0-35.0 g kg<sup>-1</sup>, was closer to that obtained by MK<sub>orig</sub> while Deus et al. (2018b) reported a narrower, higher range, 32.0-37.4 g kg<sup>-1</sup>, which reflects how K moves within the soil-banana system, with greater variations in tissue concentration as a result of biochemical and geochemical cycling (Silva et al., 2015).

Although bananas demand large amounts of K, up to 86 % of the K taken up by banana plants is reutilized (Hoffmann et al., 2010) when plant residues left on the soil surface after the crop harvest break down. Nevertheless, K deficiency may reduce the relative growth of 'Prata-Anã' banana by 44 % (Silva et al., 2014).

The sufficient Ca concentration range obtained by the BLA for 'Prata-Anã' grown in CE was 4.6-6.5 g kg<sup>-1</sup>; similar to the ranges determined by MK<sub>mod</sub> and

MK<sub>orig</sub>, 5.1-7.0 g kg<sup>-1</sup> (Table 6) and 5.1-6.5 g kg<sup>-1</sup> (Table 7), respectively. For BA, the sufficient range determined by the BLA was 5.3-5.8 g kg<sup>-1</sup> (Table 5), whose lower and upper limits were different, but within the ranges obtained by MK<sub>mod</sub> (4.8-5.7 g kg<sup>-1</sup>) and MK<sub>orig</sub> (4.6-5.6 g kg<sup>-1</sup>) (Table 6 and 7, respectively). Ranges determined for both sites were close to that reported by Silva (2015), 4.5-7.5 g kg<sup>-1</sup>. Compared with ranges observed in this study, the sufficient Ca range reported by Deus et al. (2018b) was broader, 5.7-10.1 g kg<sup>-1</sup>, which might be associated with greater soil Ca levels in CE, the same soil used by the authors.

The sufficient Mg concentration established by the BLA for CE was 1.8-2.6 g kg<sup>-1</sup> (Table 5); very close to MK<sub>mod</sub> and MK<sub>orig</sub>, 1.9-2.6 g kg<sup>-1</sup> (Table 6) and 1.9-2.4 g kg<sup>-1</sup> (Table 7), respectively. For BA, the sufficient Mg concentration range obtained by the BLA was 2.1-2.7 g kg<sup>-1</sup> (Table 5), which is similar to that determined by MK<sub>mod</sub> and MK<sub>orig</sub>, 2.0-2.6 g kg<sup>-1</sup> (Table 6) and 2.3-2.7

**Table 6** – Proposed sufficiency ranges determined using modified method of Kenworthy for leaf nutrient concentrations in 'Prata-Anã' bananas cultivated at Missão Velha, CE, and Ponto Novo, BA, Brazil.

Nutrient	Classes (Reference value – PNRC, Potential Nutrient-Response Curve)					
	Deficient (< 70 %)	Tending to sufficient (70-90 %)	Sufficient (90-100 %)	High (100-90 %)	Tending to excessive (90-70 %)	Excessive (< 70 %)
Missão Velha, CE						
g kg <sup>-1</sup>						
N	< 17.7	17.7-19.3	19.3-21.9	21.9-24.5	24.5-26.4	≥ 26.4
P	< 0.9	0.9-1.4	1.4-2.0	2.0-2.6	2.6-3.0	≥ 3.0
K	< 15.2	15.2-22.3	22.3-32.3	32.3-42.4	42.4-49.5	≥ 49.5
Ca	< 3.7	3.7-5.1	5.1-7.0	7.0-8.9	8.9-10.3	≥ 10.3
Mg	< 1.3	1.3-1.9	1.9-2.6	2.6-3.4	3.4-4.0	≥ 4.0
S	< 0.9	0.9-1.3	1.3-1.9	1.9-2.6	2.6-3.0	≥ 3.0
mg kg <sup>-1</sup>						
B	< 2.2	2.2-6.4	6.4-11.6	11.6-17.1	17.1-21.0	≥ 21.0
Cu	< 2.7	2.7-5.3	5.3-8.8	8.8-12.4	12.4-15.0	≥ 15.0
Fe	< 41.6	41.6-55.8	55.8-74.9	74.9-95.7	95.7-109.8	≥ 109.8
Mn	< 20.1	20.1-120.1	120.1-253.5	253.5-394.3	394.3-494.3	≥ 494.3
Zn	< 8.8	8.8-12.9	12.9-18.3	18.3-24.1	24.1-28.2	≥ 28.2
Ponto Novo, BA						
g kg <sup>-1</sup>						
N	< 12.2	12.2-16.4	16.4-22.2	22.2-28.3	28.3-32.8	≥ 32.8
P	< 1.2	1.2-1.4	1.4-1.6	1.6-1.8	1.8-2.0	≥ 2.0
K	< 20.4	20.4-27.3	27.3-36.2	36.2-45.6	45.6-52.5	≥ 52.5
Ca	< 4.1	4.1-4.8	4.8-5.7	5.7-6.6	6.6-7.3	≥ 7.3
Mg	< 1.5	1.5-2.0	2.0-2.6	2.6-3.2	3.2-3.7	≥ 3.7
S	< 1.0	1.0-1.2	1.2-1.4	1.4-1.5	1.5-1.7	≥ 1.7
mg kg <sup>-1</sup>						
B	< 8.6	8.6-11.5	11.5-15.5	15.5-19.4	19.4-22.5	≥ 22.5
Cu	< 1.6	1.6-2.9	2.9-4.7	4.7-6.4	6.4-7.7	≥ 7.7
Fe	< 30.8	30.8-42.5	42.5-58.9	58.9-76.1	76.1-87.8	≥ 87.8
Mn	< 34.2	34.2-66.9	66.9-110.6	110.6-157.0	157.0-189.8	≥ 189.8
Zn	< 10.5	10.5-12.2	12.2-14.7	14.7-17.0	17.0-18.8	≥ 18.8

g kg<sup>-1</sup> (Table 7), respectively. The sufficient Mg range determined by Silva (2015) was 2.4-4.0 g kg<sup>-1</sup>, whose lower limit is close to the upper limit of the sufficient Mg concentration ranges found in this study. Narrower ranges for Mg might be associated with the high K supply via fertigation to a soil containing high K levels (8.4 mmol<sub>c</sub> dm<sup>-3</sup>). Thus, the K/Mg ratio increased, which limited Mg uptake (Silva, 2015; Deus et al., 2018b).

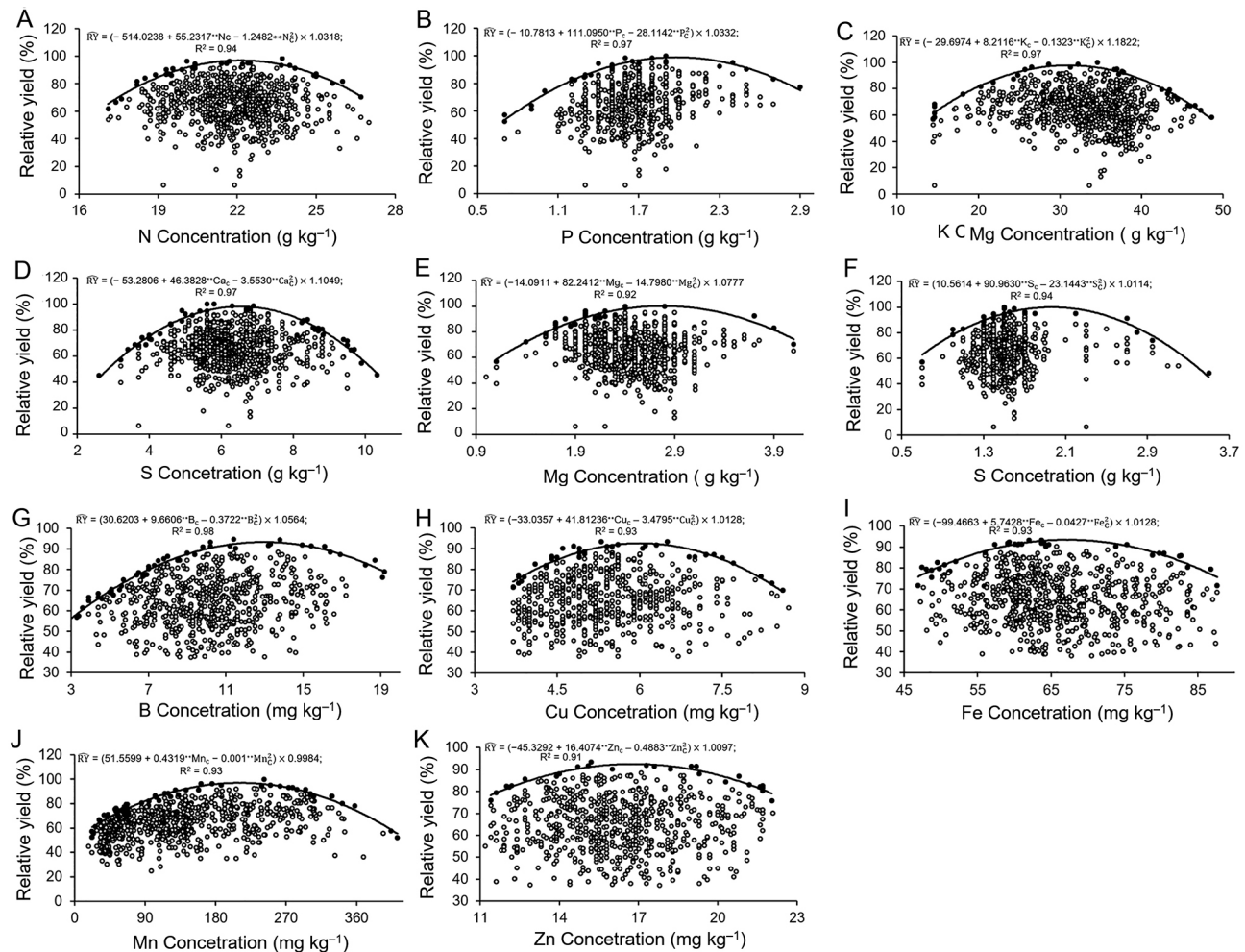
Banana is a monocot and thus has low root cation exchange capacity, which means the plant can take up more monovalent cations to the detriment of divalent cations. Similarly, high soil Ca levels, particularly in CE, contribute to decreases in Mg uptake by competitive inhibition. In a pot experiment withholding Mg, 'Prata-Anã' reduced growth by 67 % (Silva et al., 2014); therefore, one should be careful when supplying Mg to banana plants grown on soils containing high K levels, especially when the plants are under stress because Mg and K play an important role in alleviating plant stress (Marschner, 2012).

The sufficient S concentration range determined the BLA for 'Prata-Anã' grown in CE was 1.3-2.0 g kg<sup>-1</sup> (Table 5), whose limits are close to those established by MK<sub>mod</sub>

and MK<sub>orig'</sub>, 1.2-1.6 g kg<sup>-1</sup> (Table 6) and 1.3-1.9 g kg<sup>-1</sup> (Table 7), respectively. For BA, the sufficient S concentrations by the BLA was 1.3-1.5 g kg<sup>-1</sup> (Table 5), whose limits are close to those determined by MK<sub>mod</sub> and MK<sub>orig'</sub>, 1.2-1.4 g kg<sup>-1</sup> (Table 6) and 1.2-1.5 g kg<sup>-1</sup> (Table 7), respectively. Silva (2015) established a sufficient S range of 1.7-2.0 g kg<sup>-1</sup>, similar to the ranges proposed herein, but narrower. The sulfur concentration range reported by Deus et al. (2018b) was even narrower, 1.4-1.6 g kg<sup>-1</sup>.

The sufficient B concentration range established by the BLA for 'Prata-Anã' cultivated in CE was 8.4-13.0 mg kg<sup>-1</sup> (Table 5), while by MK<sub>mod</sub> and MK<sub>orig'</sub>, the ranges were 6.4-11.6 mg kg<sup>-1</sup> (Table 6) and 7.9-11.1 mg kg<sup>-1</sup> (Table 7), respectively. For BA, the sufficient B concentration range obtained by the BLA was 13.7 to 16.4 mg kg<sup>-1</sup> (Table 5). The range differs from those determined by MK<sub>mod</sub> and MK<sub>orig'</sub>, 11.5-15.5 mg kg<sup>-1</sup> (Table 6) and 11.7-14.7 mg kg<sup>-1</sup>, respectively. The sufficient B concentration range established for CE is lower than those proposed by Silva (2015), 12.0-25.0 mg kg<sup>-1</sup>, whose lower limit has the same value as the corresponding upper limit reported herein. The sufficient range established for BA was different, but within the range proposed by Silva (2015).





**Figure 3** – Boundary line fitted as a function of the relationship between relative yield (%) and leaf concentrations of N (A), P (B), K (C), Ca (D), Mg (E), S (F), B (G), Cu (H), Fe (I), Mn (J) and Zn (K) in 'Prata-Anã' banana, Missão Velha, CE, Brazil. \*\*Significant at  $p \leq 0.01$  by the t-test; The multipliers 1.0318; 1.0332; etc. found in the equations correspond to an adjustment factor for the equation to assume the value of 100 % Relative Yield.

The sufficient Cu concentrations obtained by the BLA for 'Prata-Anã' grown in CE ranged from 5.6 to 8.4  $\text{mg kg}^{-1}$  (Table 5), which is similar to the range determined by  $\text{MK}_{\text{mod}}$  5.3-8.8  $\text{mg kg}^{-1}$  (Table 6), but different from that obtained by  $\text{MK}_{\text{orig}}$  4.5-6.2  $\text{mg kg}^{-1}$  (Table 7). The sufficient Cu concentration range determined by the BLA for BA was 4.4-6.2  $\text{mg kg}^{-1}$  (Table 5), whose limits are different from those determined by  $\text{MK}_{\text{mod}}$  2.9-4.7  $\text{mg kg}^{-1}$  (Table 6), and equal to the  $\text{MK}_{\text{orig}}$  4.2-5.3  $\text{mg kg}^{-1}$  (Table 7). Silva (2015) reported a sufficiency range of 2.6-8.8  $\text{mg kg}^{-1}$ , whose lower limit is different from those determined in CE by the BLA and  $\text{MK}_{\text{mod}}$  and altogether different from limits obtained by  $\text{MK}_{\text{orig}}$ . For BA, all sufficient Cu ranges except the one obtained by  $\text{MK}_{\text{mod}}$  were different from the range proposed by Silva (2015).

For CE, the sufficient Fe concentration range established by the BLA was 54.2-77.6  $\text{mg kg}^{-1}$  (Table 5), by  $\text{MK}_{\text{mod}}$  55.8-74.9  $\text{mg kg}^{-1}$  (Table 6), and by  $\text{MK}_{\text{orig}}$  53.3-67.4  $\text{mg kg}^{-1}$  (Table 7). The sufficient Fe concentration range obtained by the BLA for 'Prata-Anã' grown in BA was 39.0

to 55.0  $\text{mg kg}^{-1}$  (Table 5), whose lower limits differ from those established by  $\text{MK}_{\text{mod}}$  42.5-58.9  $\text{mg kg}^{-1}$  (Table 6) and by  $\text{MK}_{\text{orig}}$  44.1-57.3  $\text{mg kg}^{-1}$  (Table 7). All sufficient Fe concentration ranges reported herein were lower than that reported by Silva (2015), 72.0-157.0  $\text{mg kg}^{-1}$ .

The sufficient Mn concentration range established by the BLA for CE was 140.1-223.8  $\text{mg kg}^{-1}$  (Table 5), different from ranges determined by  $\text{MK}_{\text{mod}}$  120.1-253.5  $\text{mg kg}^{-1}$  (Table 6) and by  $\text{MK}_{\text{orig}}$  116.4-179.4  $\text{mg kg}^{-1}$  (Table 7). The sufficient Mn concentration range obtained by the BLA was 64.0-91.0  $\text{mg kg}^{-1}$  (Table 5), whose upper limit is different from that obtained by  $\text{MK}_{\text{mod}}$  66.9-110.6  $\text{mg kg}^{-1}$  (Table 6), and similar to that obtained by  $\text{MK}_{\text{orig}}$  61.5-84.7  $\text{mg kg}^{-1}$  (Table 7). These ranges were lower and narrower than that reported by Silva (2015), 173.0-630.0  $\text{mg kg}^{-1}$ .

Manganese is the most variable element in both CE (CV = 51.8 %) and BA (CV = 38.0 %). If leaf nutrient concentrations in a population have a CV higher than 30 %, the sufficiency ranges obtained by  $\text{MK}_{\text{orig}}$  are less

**Table 7** – Leaf nutrient concentration ranges proposed by the original method of Kenworthy (1961) for 'Prata-Anã' bananas cultivated at Missão Velha, CE, and Ponto Novo, BA, Brazil.

Categories (Reference value BIKW)						
Nutrient	Deficient (< 50 %)	Tending to sufficient (50-83 %)	Sufficient (83-100 %)	High (100-117 %)	Tending to excessive (117-150 %)	Excessive (≥ 150 %)
Missão Velha, CE						
g kg <sup>-1</sup>						
N	< 10.1	10.1-17.9	17.9-21.9	21.9-25.9	25.9-33.7	≥ 33.7
P	< 0.7	0.7-1.3	1.3-1.7	1.7-2.0	2.0-2.7	≥ 2.7
K	< 13.1	13.1-26.9	26.9-34.0	34.0-41.1	41.1-54.9	≥ 54.9
Ca	< 2.5	2.5-5.1	5.1-6.5	6.5-7.9	7.9-10.5	≥ 10.5
Mg	< 1.0	1.0-1.9	1.9-2.4	2.4-2.9	2.9-3.8	≥ 3.8
S	< 0.6	0.6-1.2	1.2-1.6	1.6-1.9	1.9-2.5	≥ 2.5
mg kg <sup>-1</sup>						
B	< 1.7	1.7-7.9	7.9-11.1	11.1-14.3	14.3-20.5	≥ 20.5
Cu	< 1.2	1.2-4.5	4.5-6.2	6.2-7.9	7.9-11.2	≥ 11.2
Fe	< 25.8	25.8-53.3	53.3-67.4	67.4-81.5	81.5-109.0	≥ 109.0
Mn		116.4 <sup>1</sup>	116.4-179.4	179.4-242.4	242.4-364.6	≥ 364.6
Zn	< 6.4	6.4-13.1	13.1-16.5	16.5-19.9	19.9-26.6	≥ 26.6
Ponto Novo, BA						
g kg <sup>-1</sup>						
N	< 9.8	9.8-18.5	18.5-23.0	23.0-27.5	27.5-36.2	≥ 36.2
P	< 0.7	0.7-1.3	1.3-1.6	1.6-1.9	1.9-2.5	≥ 2.5
K	< 11.1	11.1-24.5	24.5-31.4	31.4-38.3	38.3-51.7	≥ 51.7
Ca	< 2.5	2.5-4.6	4.6-5.6	5.6-6.7	6.7-8.7	≥ 8.7
Mg	< 1.1	1.1-2.2	2.2-2.7	2.7-3.3	3.3-4.3	≥ 4.3
S	< 0.7	0.7-1.2	1.2-1.5	1.5-1.8	1.8-2.3	≥ 2.3
mg kg <sup>-1</sup>						
B	< 5.7	5.7-11.7	11.7-14.7	14.7-17.8	17.8-23.8	≥ 23.8
Cu	< 2.1	2.1-4.2	4.2-5.3	5.3-6.4	6.4-8.4	≥ 8.4
Fe	< 18.3	18.3-44.1	44.1-57.3	57.3-70.6	70.6-96.4	≥ 96.4
Mn	< 16.4	16.4-61.5	61.5-84.7	84.7-107.9	107.9-152.9	≥ 152.9
Zn	< 6.5	6.5-12.0	12.0-14.8	14.8-17.7	17.7-23.1	≥ 23.1

<sup>1</sup>As for Mn, it corresponds to both deficient and tending to sufficient ranges.

precise in detecting nutrient deficiencies. Moreover, Silva (2015) found a wider sufficient Mn range because the author did not use a correction factor (k) that is needed to narrow the range down (Alves et al., 2019) in the event of highly fluctuating tissue nutrient levels, mostly micronutrients with a CV higher than 20 %.

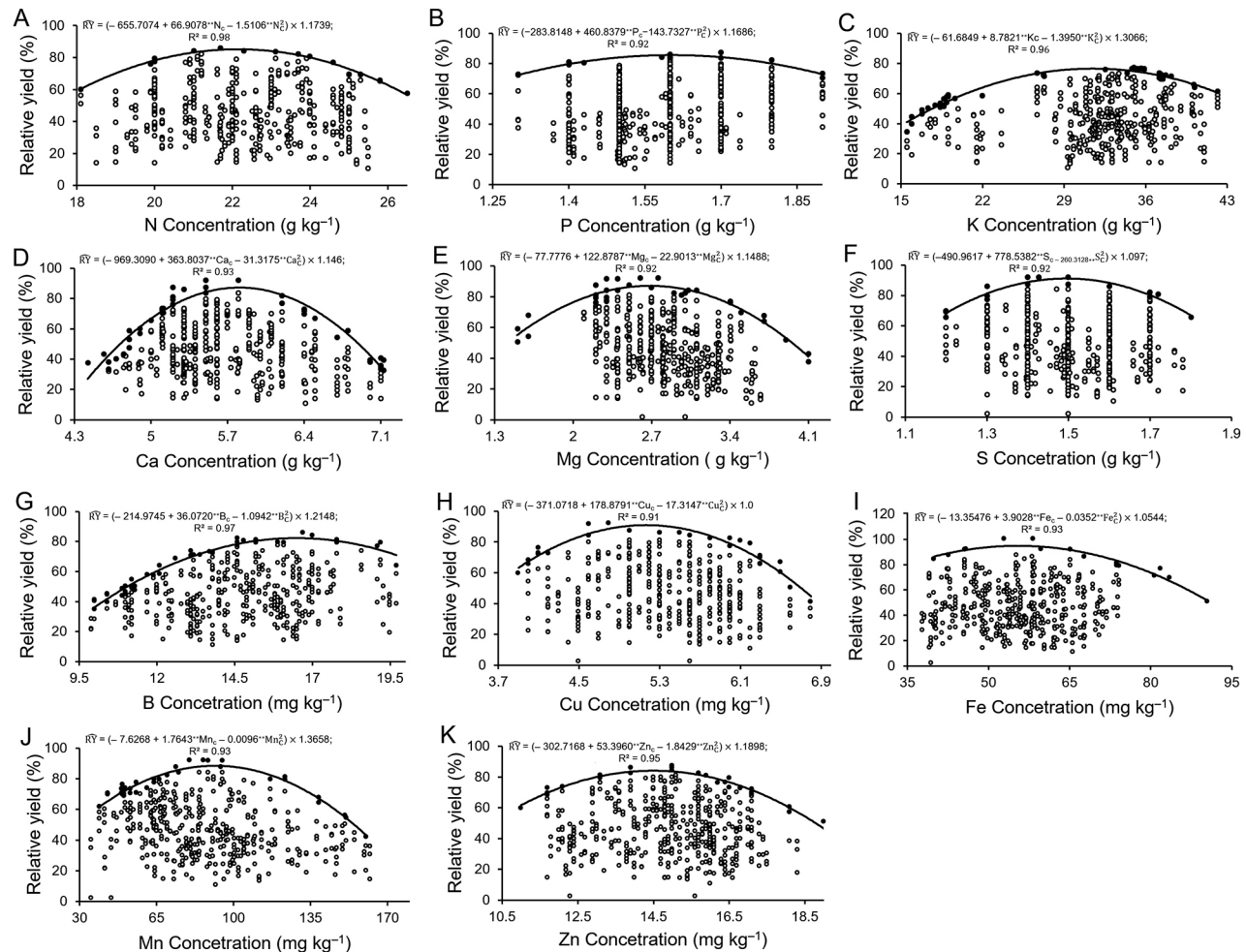
The sufficient Zn concentration range obtained by the BLA for CE was 13.5-18.3 mg kg<sup>-1</sup> (Table 5), similar to the range determined by MK<sub>mod</sub> and MK<sub>orig</sub>, 12.9-18.3 mg kg<sup>-1</sup> (Table 6) and 13.1-16.5 mg kg<sup>-1</sup> (Table 7), respectively. For 'Prata-Anã' grown in BA, the sufficient Zn concentration range obtained by the BLA was 12.4-14.5 mg kg<sup>-1</sup> (Table 5), similar to ranges obtained by MK<sub>mod</sub> and MK<sub>orig</sub>, 12.2-14.7 mg kg<sup>-1</sup> (Table 6) and 12.0-14.8 mg kg<sup>-1</sup> (Table 7), respectively. Proposed ranges for CE are close to that established by Silva (2015), 14.0-25.0 mg kg<sup>-1</sup>, despite the latter's higher upper limit. As for BA, the upper limits were identical to the lower limits proposed by Silva (2015).

The sufficient ranges for micronutrients are less consistent with the literature than for macronutrients. Micronutrient concentrations in leaves are associated

with their dynamic within the soil-plant system. Their availability in the soil is governed by pH, organic matter content, clay content, soil source rock, and, specifically for Fe and Mn, by the reduction potential (Li et al., 2007; Rengel, 2015). These factors can interfere with element uptake, thereby affecting leaf micronutrient concentrations.

For example, in CE, soil pH averaged 7.3, at which metal cations, such as Cu, Fe, Zn and Mn, as well as B, are considerably less available. In general, soil pH has a major impact on Mn availability in the soil (Marschner, 2012). Therefore, sufficient ranges established for 'Prata-Anã' were higher for Cu, Fe, Mn and Zn in CE compared with BA, but lower for B, which is associated with the higher fertility of soils in CE. However, a higher soil availability of Fe and Mn may cause temporary toxicity in plants in the case of heavy rain and may precipitate a rise in reducing conditions, especially in soils containing high Mn levels.

Sufficient concentration ranges obtained by the BLA for N, P, K, Mg, and S are highly consistent regardless of the site; however, the sufficient Ca concentration range



**Figure 4** – Boundary line fitted as a function of the relationship between relative yield (%) and leaf concentrations of N (A), P (B), K (C), Ca (D), Mg (E), S (F), B (G), Cu (H), Fe (I), Mn (J) and Zn (K) in 'Prata-Anã' banana, Ponto Novo, BA, Brazil. \* Significant at  $p \leq 0.01$  by the t-test; The multipliers 1.1739; 1.1686; etc. found in the equations correspond to an adjustment factor for the equation to assume the value of 100 % Relative Yield.

proposed for CE (4.6-6.5 g kg<sup>-1</sup>) is broader than that determined for BA (5.3-5.8 g kg<sup>-1</sup>) due to higher Ca levels in soils in CE, 79.7 mmol<sub>c</sub> dm<sup>-3</sup> compared to that in BA at 28.0 mmol<sub>c</sub> dm<sup>-3</sup> (Table 1). Consecutive calcitic lime applications to soils in CE over the years are the reason for this discrepancy. Furthermore, in CE, the Ca/Mg ratio of 4.4:1 tends to result in a slight imbalance in the soil due to excessive Ca. The ideal soil Ca/Mg ratio for 'Prata-Anã' ranges from 1.5:1 to 3:1 (Silva, 2015). In BA, the Ca/Mg ratio is 2.5:1, thereby contributing to a higher Mg uptake.

The sufficient ranges established by MK<sub>mod</sub> were consistent for nearly all nutrients, and, in a number of cases, different from the sufficient range established by MK<sub>orig</sub>. The sufficient concentration ranges obtained by the BLA were more accurate (Table 5) owing to their lower estimated values, especially for N and K, the most accumulated nutrients in bananas (Hoffman et al., 2010; Deus et al., 2018a). This is consistent with decreases in the N and K fertilizer rates recommended for 'Prata-Anã' banana (Silva, 2015; Deus et al., 2018b).

The results highlight the importance of this study. The advantages of using the BLA to obtain sufficiency ranges include taking into account the site specificities, climate, soil, cultivar, and management, which increase the degree of precision in assessing the nutritional status of 'Prata-Anã' bananas by preventing miscalculated extrapolations.

Potential response curves and sufficiency ranges for leaf macro- and micronutrient concentrations and BIKW were established. They allow for an improved assessment of the nutritional status of fertigated 'Prata-Anã' bananas under different environmental conditions, which is a refinement to be incorporated into production systems.

## Conclusions

The sufficiency ranges obtained by the BLA for 'Prata-Anã' banana in BA and CE, respectively, are: a) for macronutrients (g kg<sup>-1</sup>): N (19.3-22.0) and (19.9-22.1); P (1.4-2.0) and (1.4-1.6); K (22.6-32.2) and (24.0-31.3); Ca

(4.6-6.5) and (5.3-5.8); Mg (1.8-2.6) and (2.1-2.7); S (1.3-2.0) and (1.3-1.5); b) for micronutrients (mg kg<sup>-1</sup>): B (8.4-13.0) and (13.7-16.4); Cu (5.6-8.4) and (4.4-5.2); Fe (54.2-77.6) and (39.0-55.0); Mn (140.1-222.8) and (64.0-91.0); Zn (13.5-18.3) and (12.4-14.5). The sufficiency ranges obtained by the BLA are more assertive when assessing the nutritional status for 'Prata-Anã' banana.

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## Authors' Contributions

Conceptualization: Rodrigues Filho, V.A.; Neves, J.C.L.; Donato, S.L.R.; Guimarães, B.V.C. Data acquisition: Rodrigues Filho, V.A.; Neves, J.C.L.; Donato, S.L.R. **Data analysis:** Rodrigues Filho, V.A.; Neves, J.C.L.; Donato, S.L.R.; Guimarães, B.V.C. **Design of methodology:** Rodrigues Filho, V.A.; Neves, J.C.L.; Donato, S.L.R.; Guimarães, B.V.C. **Software development:** Rodrigues Filho, V.A.; Neves, J.C.L.; Donato, S.L.R. **Writing and editing:** Rodrigues Filho, V.A.; Neves, J.C.L.; Donato, S.L.R.; Guimarães, B.V.C.

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