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Nutritional reference values using the DRIS method and sample size for peach palm production

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ABSTRACT: One of the challenges in the peach palm production system is the interpretation of leaf analyses and the adaptation of fertilization recommendations. Tools that enhance fertilizer use efficiency are therefore needed. This study aimed to establish norms for evaluating the nutrient status of peach palms using the Diagnosis and Recommendation Integrated System (DRIS) and to determine the adequate number of palm heart samples necessary for a more accurate assessment of productivity. Production, leaf nutrient content, and soil fertility data were collected from 102 commercial stands of peach palm in the Ribeira Valley, state of São Paulo, Brazil, between 2015 and 2020. Adequate number of individual samples (palm hearts) to be collected per stand for productivity assessment was estimated. DRIS norms were established by dividing the database into high-yield (reference population) and low-yield subpopulations, using average productivity as a criterion. By assuming an acceptable error of 5 to 10 % for the assessment of peach palm productivity, taking into account total palm heart weight and/or the weight of cylinders, respectively, 16 plants per stand should be sampled. DRIS was not sensitive enough to diagnose differences in the probability of positive response to fertilization; however, the P, K, Ca, Mg, S, B, Fe, Cu, Mn and Zn contents were positively correlated with the respective nutrient indices.

Keywords: *Bactris gasipaes*, nutritional diagnosis, fertilization.

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INTRODUCTION

Brazil is the largest producer and consumer of peach palm, accounting for approximately 95 % of its whole production worldwide (Spacki et al., 2022). Brazilian market is estimated to generate around US$ 350 million annually from peach palm production, whereas global market is estimated to reach US$ 500 million (Spacki et al., 2022; Kramer et al., 2023). According to IBGE (2021), the state of São Paulo is the largest producer, with a production of 38,853 Mg in an area of 11,168 ha and an average yield of 3,479 kg per hectare in 2022, mainly concentrated in the Ribeira Valley region.

Peach palm (*Bactris gasipaes* Kunth) demonstrates great potential for the expansion of production areas, having characteristics such as precociousness, with harvest starting after 18 months and tillering, producing, on average, for twenty years, generating around 1.5 palm hearts per year (Spacki et al., 2021). However, research is still needed to understand the management of this crop better, how to estimate productivity, adjust fertilizer doses, and interpretation of leaf nutrient levels (Kramer et al., 2023).

Productivity determination in peach palm production areas is only carried out at the time of harvest; however, the advanced estimation of production allows adjustments to decision-making, especially for fertilization management (Schmildt et al., 2019). Sampling an area is the process of selecting a subset of units that represents the desired parameter estimation with a minimum number of sample units while ensuring an acceptable error level (Valliant et al., 2013).

Diagnosing the nutritional status of plants is vital to achieving success in modern and competitive agriculture, allowing rationalization in the application of inputs, leading to the search for efficient techniques to detect nutritional imbalances and assist in the fertilizer recommendation process and reducing false diagnoses of lack or excess of nutrients. Diagnosis and Recommendation Integrated System (DRIS), devised by Beaufils (1973), uses bivariate relationships of nutrients with the mean ratios that correspond to the norms established from a reference population. DRIS analysis identifies the deficient nutrient, ranks the nutrients from most deficient to most excessive, and shows the specific nutrient's contribution to yield reduction, evaluating nutrient status in plants better than using critical values or ranges (Prado and Rozane, 2020; Manzoor et al., 2022).

DRIS has already been employed to establish the nutrient status of some crops of the *Arecaceae* family, such as açaí palm (Ribeiro et al., 2020), coconut palm (Saldanha et al., 2017), oil palm (Matos et al., 2017), and peach palm in the southwestern Amazon region, where the authors considered phytotechnical evaluations as parameters to indicate the reference population (Azevedo et al., 2016). However, there are no DRIS norms for peach palm grown in the Ribeira Valley under edaphoclimatic and management conditions. This valley, located in the state of São Paulo, Brazil, has the largest production of peach palm in Brazil (IBGE, 2021).

The aim of this study was to establish norms for assessing the nutrient status of peach palm in the Ribeira Valley, using DRIS, and to determine the adequate number of palm heart samples necessary for more accurate sampling of peach palm productivity.

MATERIALS AND METHODS

This study was based on productivity and leaf nutrient contents data collected from 102 commercial stands of peach palm (*Bactris gasipaes* H. B. K.) between 2015 and 2020 at different times of the year in the following towns in the Ribeira Valley: Registro, Sete Barras, Jacupiranga, Eldorado, Iguape, and Juquiá (Figure 1). According to Köeppen-Geiger classification system, the region has a tropical Cfa climate, characterized by hot

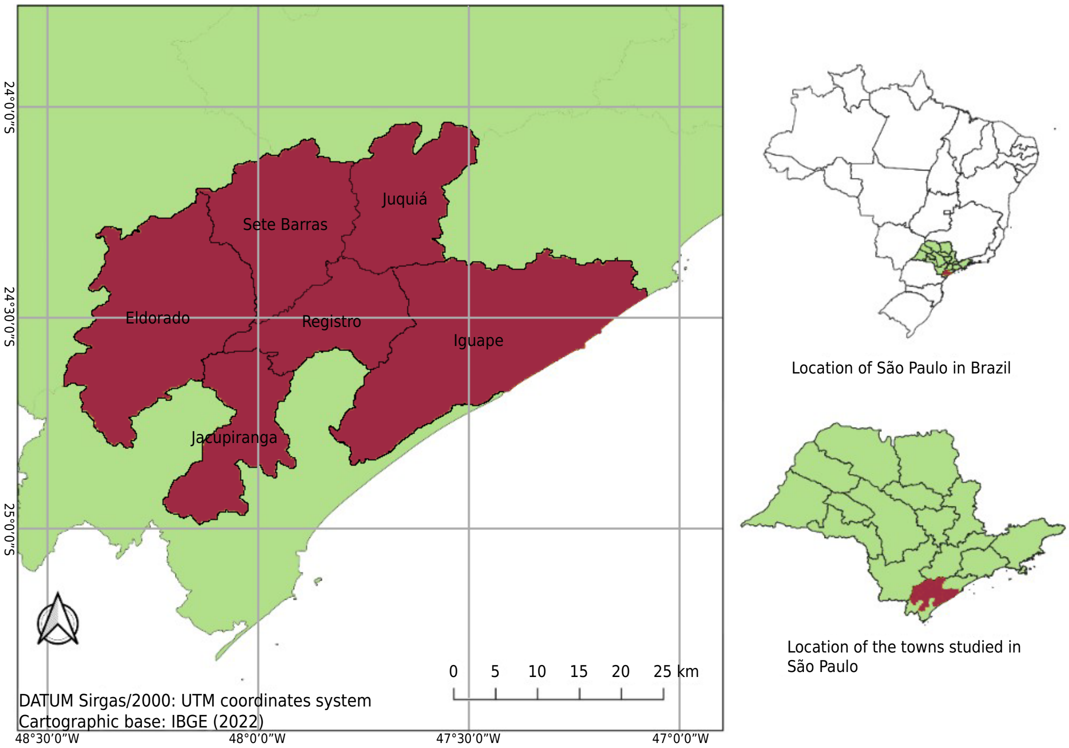

Figure 1. Location of study areas.

summers and no dry winter season. Predominant soils in the region are classified as *Cambissolos Háplicos eutróficos* (Inceptisols - Soil Taxonomy; Cambisols - WRB/FAO) and *Argissolos eutróficos* (Oxisols - Soil Taxonomy; Acrisols - WRB/FAO).

To assess the nutrient status of peach palm (*Bactris gasipaes* H. B. K.), leaf samples were collected from adult plants 6 ± 2 years old, with some areas showing the limits of 3 and 17 years, with 2 × 1 m row spacing, from non-irrigated areas and grown in monoculture. Liming was carried out to maintain base saturation at 55 ± 5 % and fertilization according to soil analysis as indicated by van Raij and Cantarella (1997). To obtain a composite sample, 20 plants per stand with a height of approximately 1.6 ± 0.15 m (from the ground to the insertion point of the newest leaf) were sampled. Middle portion of the leaflets was removed from the central part of the second newest leaf that consisted of a broad expanded blade (van Raij and Cantarella, 1997).

Leaf samples were washed in three stages: 1) under running water, deionized water, and neutral detergent solution (0.1 %); 2) deionized water solution and hydrochloric acid (0.3 %); and 3) deionized water. Subsequently, the leaves were dried in a forced-air oven at 60 ± 3 °C at a constant mass, ground in a Willey mill (Tecnal TE-650/1) with a mesh opening size of 0.841 mm (20 mesh). Nutrient content was determined according to the method proposed by Bataglia et al. (1983). Nitrogen (N) was carried out by digestion in sulfuric acid, and its determination carried out in a Kjeldahl steam distiller. Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) contents were measured after nitro-perchloric digestion and the concentrations of Ca, Mg, Cu, Zn, Fe and Mn were determined in an atomic absorption spectrophotometer; P was determined by colorimetry, based on the methodology described by Murphy and Riley (1962), in a spectrophotometer; and K in a flame photometer. Boron (B) was burned in the muffle furnace and determined using a spectrophotometer.

A total of 82 soil samples were collected in the 0.00-0.20 m soil layer as described by van Raij and Cantarella (1997), and usually used by producers, being pH in calcium chloride in the soil/solution volumetric ratio of 1:2.5; organic matter and carbon in Walkley Black; P, K, Ca and Mg in resin; H+Al in SMP buffer; Al to potassium chloride; S-SO_4 in calcium phosphate; boron in hot water and Cu, Fe, Mn and Zn with DTPA.

Adequate number of individual samples (palm hearts) to be collected per stand for productivity assessment was estimated by the equation proposed by Thompson (1992), in which an infinite population is estimated at a desired accuracy rate, based on the standard error of the mean (Equation 1).

$$n = \frac{t^2 s^2}{d^2 m^2} \quad \text{Eq. 1}$$

in which: *n* is the estimated sample size; *t* is Student's *t* distribution at 5 % of probability; s^2 is the variance; *d* is the mean estimation error (%); and *m* is the sample mean.

Database used for establishing DRIS norms for each stand consisted of productivity and leaf nutrient contents. Two standards were established: i) DRIS for productivity (DRIS for whole palm heart) – in which productivity was determined by the average weight (g) of 16 palm hearts processed for each assessed stand (after removing the peel and considering the total weight of edible parts: base, cylinder, and free top); ii) DRIS for quality (DRIS for cylinders) – in which productivity is determined by the average weight (g) of 16 cylinders per stand, focusing on quality, given that this edible part is the one with the highest economic value.

DRIS norms were established by dividing the database into high-yield (reference population) and low-yield subpopulations, using average productivity of the 102 plots as the criterion for the division, as described by Santos and Rozane (2017), having a normal distribution by the Kolmogorov-Smirnov test.

Mean and standard deviation (DRIS norms) for the dual logarithmic relationships of the reference population were calculated, as proposed by Beverly (1987). Subsequently, the nutrient ratio functions were estimated according to Jones (1981) (Equation 2).

$$f\left(\frac{X}{Y}\right) = \left[\left(\frac{X}{Y_a}\right) - \left(\frac{X}{y_r}\right)\right] \times \left(\frac{c}{S}\right) \quad \text{Eq. 2}$$

in which: $(\frac{X}{Y_a})$ is the dual relationship among the nutrients in the sample; $(\frac{x}{y_r})$ is mean for dual relationship among the nutrients in the reference population; *S* is standard deviation for dual relationships among the nutrients in the reference population; *c* is the sensitivity coefficient (equal to 1).

DRIS indices were calculated using the formula proposed by Beaufils (1973) (Equation 3).

$$I_x = \frac{\sum f\left[\frac{X}{Y}\right] - \sum f\left[\frac{Y}{X}\right]}{n+m} \quad \text{Eq. 3}$$

in which: I_x is DRIS index of the nutrient *x*; $f\left[\frac{X}{Y}\right]$ is the directly proportional function between two nutrients; $f\left[\frac{Y}{X}\right]$ is the inversely proportional function between two nutrients; *n* is the number of direct relationships assessed; and *m* is the number of inverse relationships assessed.

Mean nutrient balance index (mNBI) was obtained by the quotient of the sum, in module, of DRIS indices for each nutrient and the total number of nutrients assessed (n) (Equation 4).

$$mNBI = \frac{|IN| + |IP| + |IK| + |ICa| + \cdots + |IZn|}{n} \quad \text{Eq. 4}$$

Obtained DRIS indices were classified in terms of potential response to fertilization into the following response classes: positive (p), positive or null (pz), null (z), negative or null (nz), and negative (n). Positive (p) and positive or null (pz) classes were grouped as deficient, and negative or null (nz) and negative (n) classes were categorized as excessive, and the null (z) class into non-limiting (NL), as described by Silva et al. (2005).

Expected frequency (EF) and observed frequency (OF), and the chi-square (χ^2) at 5 % of probability were also calculated for limitation cases to assess whether the frequency at which each nutrient occurred as the primary limiting factor due to deficiency was random, as proposed by Urano et al. (2006), obtained by Diagnosis and Recommendation Integrated System (DRIS (Equations 5 and 6).

$$EF(\%) = \left(\frac{\text{total number of assessed stands}}{\dfrac{\text{total number of assessed nutrients}}{\text{total number of assessed stands}}} \right) \times 100 \quad \text{Eq. 5}$$

$$OF(\%) = \left(\frac{\text{number of nutrients in which the nutrient was } (p)}{\text{number of assessed stands}} \right) \times 100 \quad \text{Eq. 6}$$

Statistical models were fitted between leaf nutrient concentration and the corresponding nutrient balance index to establish critical level of each nutrient. The lower and upper limits of the normal range for nutrient concentration were obtained by equating the statistical model of each nutrient to zero and ± $^2/_3$ of the standard deviation (Serra et al., 2012; Souza et al., 2015; Rozane et al., 2020; Lima Neto et al., 2022).

RESULTS

Estimated number of plants (individual samples) to be included in the sample for assessment of peach palm production per commercial stand was 16, considering a mean estimation error of 5 to 10 % (Table 1). This error is acceptable for productivity assessment (Tonini, 2013; Krause et al., 2013), as well as for total palm heart weight and cylinder weight, indicating the sampling is within acceptable limits for the estimation of the mean of the remunerated production sections, recalling that the cylinder represents on average 60 % of the value paid to the producer for the palm heart (Rozane et al., 2017), accounting for 26.6 % of total palm heart weight in the present study, whereas the heart and free top accounted for 66.8 and 6.6 %, respectively.

Both subpopulations presented average levels of K^+, P, B and Cu and high levels of Ca^{2+}, Mg^{2+}, S and Fe (Table 2). For Mn and Zn, the high-yield subpopulation presented high levels and the low-yield subpopulation presented medium levels (van Raij and Cantarella, 1997).

Table 1. Descriptive statistic and estimate of the number of peach palms necessary for productivity assessment as a function of the mean estimation error

Mean estimation error "f"	Parts			Total
	Heart	Cylinder	Free top	
1 %	380	1.597	10.527	406
3 %	42	177	1.170	45
5 %	15	64	421	16
10 %	4	16	105	4
$\hat{m}$ (g palm heart^{-1})	428	209	24	662
s^2	1.602	1.605	142	4.090
CV	9.3	19.2	49.2	9.7

$\hat{m}$ is the estimate for the sample mean; s^2 is variance; CV is the coefficient of variation.

Table 2. Minimum, maximum, mean, and confidence interval (IC) of the results of soil analysis obtained from high- and low-yield stands of peach palms in the Ribeira Valley, state of São Paulo, Brazil

High-yield subpopulation (n = 37)									
Variable	**P**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**Na^+**	**H+Al**	**Al^{3+}**	**SB**	**CTC**
	mg dm^{-3}					$mmol_c$ dm^{-3}			
Minimum	5.0	0.5	2.0	1.2	0.2	11.0	0.0	4.9	30.4
Maximum	79.4	4.7	67.7	43.0	1.1	124.0	26.8	96.7	164.3
Mean	21.9	1.8	22.2	11.6	0.5	62.7	9.4	35.8	98.5
IC (95 %)	16.1-27.7	1.5-2.1	17.4-27.0	9.0-14.2	0.3-0.7	53.4-72.0	7.1-11.7	28.7-42.9	87.3-109.7
	pH	**MO**	**V**	**S**	**B**	**Cu**	**Fe**	**Mn**	**Zn**
	$CaCl_2$	g dm^{-3}	%				mg dm^{-3}		
Minimum	3.7	8.2	7.8	7.0	0.3	0.2	36.0	0.6	0.2
Maximum	5.5	46.0	78.2	92.5	1.4	2.7	405.0	38.5	14.4
Mean	4.4	24.4	36.0	29.5	0.5	0.7	157.5	6.7	2.9
IC (95 %)	4.2-4.6	21.8-27.0	29.9-42.1	22.8-36.2	0.4-0.6	0.5-0.9	127.3-187.7	3.1-10.3	1.7-4.1
Low-yield subpopulation (n = 45)									
	P	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**Na^+**	**H+Al**	**Al^{3+}**	**SB**	**CTC**
	mg dm^{-3}					$mmol_c$ dm^{-3}			
Minimum	5.0	0.7	1.2	2.0	0.2	27.1	0.0	5.0	37.1
Maximum	95.0	3.8	76.0	24.0	1.6	248.0	36.0	93.8	264.9
Mean	17.1	1.9	20.5	9.5	0.5	77.3	10.0	32.3	109.6
IC (95 %)	12.4-21.8	1.7-2.1	16.2-24.8	7.8-10.2	0.4-0.6	61.2-93.4	7.4-12.6	26.6-38.0	94.9-124.3
	pH	**MO**	**V**	**S**	**B**	**Cu**	**Fe**	**Mn**	**Zn**
	$CaCl_2$	g dm^{-3}	%				mg dm^{-3}		
Minimum	3.6	9.2	5.6	7.0	0.2	0.2	34.0	0.6	0.2
Maximum	6.4	65.0	77.6	89.0	1.0	2.2	346.8	26.0	3.9
Mean	4.4	27.9	33.4	28.1	0.5	0.6	116.2	4.5	1.0
IC (95 %)	4.2-4.6	24.7-31.1	27.3-39.5	22.8-33.4	0.4-0.6	0.5-0.7	97.0-135.4	2.8-6.2	0.7-1.3

The high-yield subpopulation presented a higher mean of SB and V, and Zn in the soil compared to the low-yield subpopulation. Although the soils of the low-yield subpopulation have a higher CTC, they are soils with a high aluminum content.

Descriptive statistics of leaf nutrient concentration assessed in high- and low-yield subpopulations, with the assessment of the whole palm heart (Table 3). The CVs obtained for mean leaf nutrient concentration in the low-yield population followed an increasing order: Mn>Fe>Ca>B>Mg>Cu>S>Zn>P>K>N (Table 3). Note that Mn was the nutrient with the highest variability in both the high-yield subpopulation (CV = 57.4 %) and the low-yield subpopulation (CV = 57.9 %).

After the population division, the mean and standard deviation (DRIS norms) of dual logarithmic relationships were calculated for nutrient content in the leaf tissue of high-yield plants (Table 4).

Regression equations of the relationships among nutrient content in peach palm leaves and the respective DRIS indices show a good fit, with high coefficients of determination (R^2). Except for N (R^2 = 0.60), the other index provided mathematical models with coefficients of determination equal to or greater than 70 % (R^2 ≥0.70), and greater than 90 % for P, Ca, B, Fe, Cu, and Mn (Table 5).

Relationship between productivity and the mean nutrient balance index ($_m$NBI) of commercial stands was not significant, with R^2 = 0.0247 (Figure 2), which indicates variation in productivity was not associated solely with the nutrient concentration of

Table 3. Minimum, maximum, mean, standard deviation, and coefficient of variation (CV) of leaf nutrient concentration and of productivity obtained from high- and low-yield stands of peach palms in the Ribeira Valley, state of São Paulo, Brazil

High-yield subpopulation (n = 41)						
Variable	**N**	**P**	**K**	**Ca**	**Mg**	**S**
	g kg^{-1}					
Minimum	21.7	1.7	6.5	1.8	1.8	2.1
Maximum	38.8	4.2	16.5	4.9	3.4	4.2
Mean	30.0	2.5	11.6	3.1	2.5	2.7
Standard dev.	3.4	0.9	2.6	0.7	0.4	0.5
CV (%)	11.3	36.7	22.2	24.2	17.1	18.5
Variable	**B**	**Cu**	**Fe**	**Mn**	**Zn**	**Prod.**
	mg kg^{-1}					g palm heart^{-1}
Minimum	7.2	1.7	23.0	11.0	17.0	724.1
Maximum	21.4	8.0	234.0	146.0	40.0	1226.9
Mean	13.3	5.1	90.7	43.5	25.7	867.4
Standard dev.	2.9	2.2	39.1	25.0	4.27	122.6
CV (%)	22.0	42.7	43.1	57.4	16.61	14.1
Low-yield subpopulation (n = 61)						
Variable	**N**	**P**	**K**	**Ca**	**Mg**	**S**
	g kg^{-1}					
Minimum	20.2	1.4	6.1	1.6	1.9	1.9
Maximum	37.9	3.7	16.4	5.7	4.0	3.8
Mean	28.8	1.9	13.0	3.2	2.5	2.5
Standard dev.	3.9	0.3	2.0	1.0	0.5	0.5
CV (%)	13.6	15.9	15.6	30.0	20.1	19.1
Variable	**B**	**Cu**	**Fe**	**Mn**	**Zn**	**Prod.**
	mg kg^{-1}					g palm heart^{-1}
Minimum	4.6	1.8	51.0	8.1	18.0	416.5
Maximum	30.1	9.0	216.0	142.0	42.0	718.4
Mean	14.2	6.4	96.5	49.5	27.7	625.8
Standard dev.	4.0	1.2	32.6	28.6	5.1	68.5
CV (%)	28.5	19.1	33.8	57.9	18.6	10.9

peach palms and that productivity was affected by non-nutritional factors. Low R^2 values were also observed when productivity was associated with mNBI in atemoya (Santos and Rozane, 2017), banana (Villaseñor et al., 2020), and mango (Tullio and Rozane, 2022).

By comparing the sufficiency ranges proposed herein with those suggested by Modolo et al. (2022), Azevedo et al. (2016), and Rozane and Natale (2017), there was, in general, a reduction in the amplitude of the adequate ranges and an increase in the lower limit (Table 6).

Given that most of the production payment is related to the cylinder, DRIS nutrient norms were also established, taking into account only the cylinder weight (reference population ≥192 g per cylinder), using the same estimation procedures for establishing the norms, considering the whole palm heart (reference population ≥722.9 g palm per heart) (Table 6). By comparing the nutrient indices of high-yield populations used to establish the nutrient reference values (Table 7), one perceives that they do not differ between themselves for any nutrient, which can be explained by the 84.1 % coincidence between the samples in the two databases, i.e., there is a strong correlation between palm hearts production and cylinders.

Table 4. Mean and standard deviation (DRIS norms) of the relationships between the leaf content of two nutrients in the high-yield subpopulation of peach palms

N/	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
Mean	1.11	0.42	1.00	1.09	1.06	0.36	0.82	-0.45	-0.10	0.07
SD	0.16	0.11	0.11	0.09	0.09	0.12	0.23	0.16	0.22	0.08
P/	N	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
Mean	-1.11	-0.68	-0.11	-0.02	-0.05	-0.74	-0.28	-1.55	-1.21	-1.04
SD	0.16	0.22	0.19	0.14	0.17	0.14	0.38	0.28	0.32	0.16
K/	N	P	Ca	Mg	S	B	Cu	Fe	Mn	Zn
Mean	-0.42	0.68	0.58	0.66	0.63	-0.06	0.40	-0.87	-0.53	-0.35
SD	0.11	0.22	0.12	0.14	0.13	0.16	0.20	0.15	0.25	0.11
Ca/	N	P	K	Mg	S	B	Cu	Fe	Mn	Zn
Mean	-1.00	0.11	-0.58	0.09	0.06	-0.64	-0.18	-1.45	-1.10	-0.93
SD	0.11	0.19	0.12	0.11	0.12	0.15	0.22	0.17	0.27	0.10
Mg/	N	P	K	Ca	S	B	Cu	Fe	Mn	Zn
Mean	-1.09	0.02	-0.66	-0.09	-0.03	-0.72	-0.26	-1.53	-1.19	-1.02
SD	0.09	0.14	0.14	0.11	0.09	0.11	0.27	0.20	0.23	0.08
S/	N	P	K	Ca	Mg	B	Cu	Fe	Mn	Zn
Mean	-1.06	0.05	-0.63	-0.06	0.03	-0.69	-0.23	-1.50	-1.16	-0.99
SD	0.09	0.17	0.13	0.12	0.09	0.14	0.24	0.17	0.23	0.09
B/	N	P	K	Ca	Mg	S	Cu	Fe	Mn	Zn
Mean	-0.36	0.74	0.06	0.64	0.72	0.69	0.46	-0.81	-0.47	-0.29
SD	0.12	0.14	0.16	0.15	0.11	0.14	0.29	0.23	0.27	0.11
Cu/	N	P	K	Ca	Mg	S	B	Fe	Mn	Zn
Mean	-0.82	0.28	-0.40	0.18	0.26	0.23	-0.46	-1.27	-0.93	-0.75
SD	0.23	0.38	0.20	0.22	0.27	0.24	0.29	0.19	0.30	0.25
Fe/	N	P	K	Ca	Mg	S	B	Cu	Mn	Zn
Mean	0.45	1.55	0.87	1.45	1.53	1.50	0.81	1.27	0.34	0.52
SD	0.16	0.28	0.15	0.17	0.20	0.17	0.23	0.19	0.30	0.18
Mn/	N	P	K	Ca	Mg	S	B	Cu	Fe	Zn
Mean	0.10	1.21	0.53	1.10	1.19	1.16	0.47	0.93	-0.34	0.17
SD	0.22	0.32	0.25	0.27	0.23	0.23	0.27	0.30	0.30	0.22
Zn/	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn
Mean	-0.07	1.04	0.35	0.93	1.02	0.99	0.29	0.75	-0.52	-0.17
SD	0.08	0.16	0.11	0.10	0.08	0.09	0.11	0.25	0.18	0.22

DRIS indices were interpreted by the potential response to fertilization, according to Wadt (2005), regardless of environmental conditions. Additionally, the use of DRIS could reduce the costs for farm planning. This study evaluated the relationship between the soil class and nutritional status of coffee plants (Coffea canephora Pierre (Table 8). The decreasing order of nutrients with the higher frequency of limitation due to deficiency for the high-yield subpopulation was N>Zn>B>K=Fe>Mn>P>Ca=Mg=S=Cu. Nutrients with a higher frequency of limitation due to excess, in decreasing order, were as follows: Zn>N>Ca>Mg=S>Fe>P=K=B>Mn>Cu. For the low-yield subpopulation, the frequency with higher limitation due to deficiency, in decreasing order, was: N>Cu=Fe>Zn>Ca>K>S=B>Mg=Mn, and for higher frequency of limitation due to excess, in decreasing order, was: Mn>N>P>S>K=B>Cu=Zn>Ca=Fe. However, there should be no more than 20 % of expected frequencies less than 5 or equal to zero (Gomes, 1985) for application of the chi-square test (χ^2). Thus, it is necessary to group only the high-yield subpopulation in that it does not meet this criterion.

Table 5. Statistical models of relationships among nutrient concentration and the respective DRIS indices in sampled peach palm leaves

Nutrient	Equation	R^2	Critical level
N ($g\ kg^{-1}$)	$I_N = -0.0035\ N^2 + 0.32\ N - 6.479$	0.60^{**}	30.3
P ($g\ kg^{-1}$)	$I_P = -0.1169\ P^2 + 1.6419\ P - 3.2772$	0.92^{**}	2.4
K ($g\ kg^{-1}$)	$I_K = 0.2301\ K - 2.6991$	0.78^{**}	11.7
Ca ($g\ kg^{-1}$)	$I_{Ca} = -0.1015\ Ca^2 + 1.5052\ Ca - 3.6715$	0.91^{**}	3.1
Mg ($g\ kg^{-1}$)	$I_{Mg} = 1.1882\ Mg - 3.0133$	0.78^{**}	2.5
S ($g\ kg^{-1}$)	$I_S = -0.3666\ S^2 + 3.1095\ S - 5.6774$	0.75^{**}	2.7
B ($mg\ kg^{-1}$)	$I_B= 3.0076\ln (B) - 7.7451$	0.90^{**}	13.1
Cu ($mg\ kg^{-1}$)	$I_{Cu} =1.5943\ln (Cu) - 2.3903$	0.95^{**}	4.5
Fe ($mg\ kg^{-1}$)	$I_{Fe} = 1.9589\ln (Fe) - 8.7152$	0.93^{**}	85.5
Mn ($mg\ kg^{-1}$)	$I_{Mn} = 1.7047\ln (Mn) - 6.239$	0.97^{**}	38.9
Zn ($mg\ kg^{-1}$)	$I_{Zn} = 2.7874\ln (Zn) - 9.0323$	0.75^{**}	25.5
Productivity	$I_{Prod} = -8E^{-06}\ Prod^2 + 0.0127\ Prod + 0.6216$	0.03^{ns}	

$^{(ns)}$, $^{(**)}$: nonsignificant and significant according to F test at 1 % of probability, respectively.

The chi-square test was not significant for either subpopulation, indicating that the method was not sensitive enough to diagnose differences in the probability of positive response to fertilization; therefore, the potential response to fertilization cannot be recommended for any nutrient and/or class of response (Table 8), in line with the findings of Santos and Rozane (2017), and Tullio and Rozane (2022).

DISCUSSION

The largest sampling errors were detected when a smaller number of plants were sampled, reducing the error by increasing the number of sampled plants, in line with Rozane et al. (2011), who claim the higher the CV, the larger the sample size as a function of the estimation error (Table 1). Representativeness of individuals (plants) required to determine the number of individual samples necessary for a composite sample for assessment of the productivity of commercial stands is related to the spatial heterogeneity of natural soil properties as a result of pedogenetic processes observed in horizontal and vertical

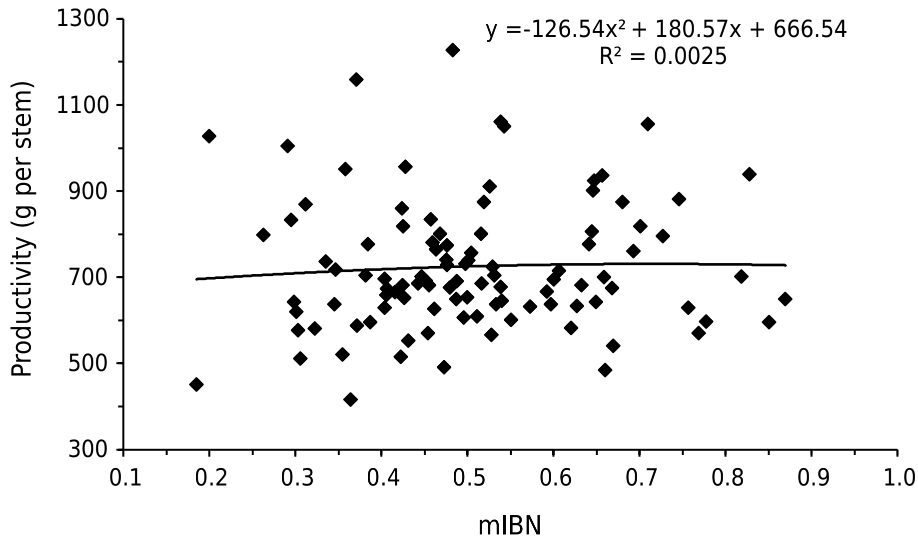

Figure 2. Relationship between mNBI and peach palm production.

Table 6. Range of appropriate leaf nutrient concentration in peach palms, using DRIS and the literature for comparison of reference values[1]

Nutrients	Methods	Appropriate range	Appropriate content
N ($g kg^{-1}$)	DRIS (whole palm heart)	27.8 – 32.8	30.3
	DRIS (cylinder)	28.5 – 33.5	31.0
	Modolo et al. (2022)	25 – 35	-
	Rozane and Natale (2017)	25 – 32	-
	Azevedo et al. (2016)	21.5 – 34.6	26.7
P ($g kg^{-1}$)	DRIS (whole palm heart)	1.9 – 2.8	2.4
	DRIS (cylinder)	1.9 – 2.8	2.4
	Modolo et al. (2022)	2.0 – 3.0	-
	Rozane and Natale (2017)	1.7 – 2.0	-
	Azevedo et al. (2016)	1.4 – 1.9	1.7
K ($g kg^{-1}$)	DRIS (whole palm heart)	10.2 – 13.3	11.7
	DRIS (cylinder)	10.1 – 13.3	11.7
	Modolo et al. (2022)	9 – 15	-
	Rozane and Natale (2017)	11 – 15	-
	Azevedo et al. (2016)	10.3 – 18.8	14.2
Ca ($g kg^{-1}$)	DRIS (whole palm heart)	2.5 – 3.7	3.1
	DRIS (cylinder)	2.5 – 3.6	3.0
	Modolo et al. (2022)	2.5 – 4.0	-
	Rozane and Natale (2017)	2 – 4	-
	Azevedo et al. (2016)	1.7 – 3.6	2.6
Mg ($g kg^{-1}$)	DRIS (whole palm heart)	2.2 – 2.8	2.5
	DRIS (cylinder)	2.2 – 2.8	2.5
	Modolo et al. (2022)	2.0 – 4.5	-
	Rozane and Natale (2017)	1.9 – 2.9	-
	Azevedo et al. (2016)	1.6 – 2.7	2.1
S ($g kg^{-1}$)	DRIS (whole palm heart)	2.3 – 3.0	2.7
	DRIS (cylinder)	2.3 – 2.9	2.6
	Modolo et al. (2022)	2.0 – 3.0	-
	Rozane and Natale (2017)	2.0 – 2.9	-
	Azevedo et al. (2016)	-	-
B ($mg kg^{-1}$)	DRIS (whole palm heart)	10.7 – 15.6	13.1
	DRIS (cylinder)	11.0 – 15.9	13.4
	Modolo et al. (2022)	12 – 30	-
	Rozane and Natale (2017)	11 – 18	-
	Azevedo et al. (2016)	6 – 21	11.0
Cu ($mg kg^{-1}$)	DRIS (whole palm heart)	3.3 – 5.7	4.5
	DRIS (cylinder)	3.6 – 5.9	4.7
	Modolo et al. (2022)	5 – 10	-
	Rozane and Natale (2017)	5 – 8	-
	Azevedo et al. (2016)	4 – 7	6.0
Fe ($mg kg^{-1}$)	DRIS (whole palm heart)	62.0 – 109.1	85.5
	DRIS (cylinder)	62.6 – 109.7	86.1
	Modolo et al. (2022)	50 – 200	-
	Rozane and Natale (2017)	70 – 110	-
	Azevedo et al. (2016)	34 – 105	48.0

Continue

Continuation

Nutrients	Methods	Appropriate range	Appropriate content
Mn (mg kg^{-1})	DRIS (whole palm heart)	20.7 – 57.0	38.9
	DRIS (cylinder)	21.6 – 57.9	39.8
	Modolo et al. (2022)	40 – 150	-
	Rozane and Natale (2017)	20 – 80	-
	Azevedo et al. (2016)	45 – 117	71.0
Zn (mg kg^{-1})	DRIS (whole palm heart)	22.3 – 28.8	25.5
	DRIS (cylinder)	22.2 – 28.8	25.5
	Modolo et al. (2022)	15 – 40	-
	Rozane and Natale (2017)	22 – 33	-
	Azevedo et al. (2016)	17 – 68	25.0

(1) Optimal range estimated based on lower and upper limits, setting the equations for the relationship between nutrient content and DRIS indices to zero and to ± 2/3 of the standard deviation.

directions of the soil, which anthropic activities can alter through the management and cultural practices needed for economically sustainable production (Siqueira et al., 2010).

Soils of the low-productivity subpopulation have greater potential acidity, reducing soil base saturation (V) (Table 2). In acidic mineral soils, aluminum toxicity is one of the main factors that limit plant growth and productivity, and may have contributed to the reduction in productivity, since it can affect the absorption of nutrients by plant roots and harm their development (Marschner, 2012). Appropriate leaf nutrient contents of both subpopulations were within the appropriate range as described by van Raij and Cantarella (1997), confirming that the plants adequately absorbed the nutrients available in the soil. By and large, the leaf micronutrient contents showed higher variability than those observed for macronutrients, corroborating the findings obtained for other species of perennial plants (Rozane et al., 2020; Lima Neto et al., 2022). Except for P, K, Ca, and Cu, the leaf nutrient content in the high-yield subpopulation demonstrates lower variability when compared with nutrient content in the low-yield subpopulation. The high variation of Mn^{2+} is partially influenced by soil acidity in areas that directly change the availability of this nutrient by reducing pH which, coupled with oxygen availability, increases the form that can be absorbed by the plant (Mn^{2+}) (Marschner, 2012) and the high range of soil pH in the studied areas favored high variability in Mn availability.

Table 7. Standard deviation and significance (*p*) between the nutrient content of high-yield populations, considering the whole palm heart (heart + cylinder + free top) for the high-yield population and only the cylinder for DRIS norms

Nutrients	Palm heart (n = 41)	Cylinder (n = 44)	F	*p*
N	0.44	0.43	1.06	0.85
P	0.89	0.88	1.03	0.92
K	0.65	0.65	1.00	0.99
Ca	0.65	0.65	1.01	0.99
Mg	0.58	0.59	1.04	0.91
S	0.59	0.60	1.03	0.93
B	0.75	0.72	1.08	0.81
Cu	0.91	0.89	1.04	0.90
Fe	0.82	0.83	1.04	0.91
Mn	0.91	0.93	1.04	0.90
Zn	0.50	0.52	1.10	0.76

Table 8. Chi-square (χ²), frequency (%) of potential response to fertilization of nutrients in peach palm leaf samples in the high- and low-yield subpopulations

Nutrients	High-yield				Low-yield					
	LE	NL	LD	χ^2	n	nz	z	Pz	p	χ^2
N	6.6	38.8	8.0	53.3 ns	5.5	6.8	16.1	2.6	7.5	38.6 ns
P	0.6	0.1	1.1	1.8 *	3.7	16.6	0.7	14.2	1.1	36.3 ns
K	0.6	8.6	3.2	12.4 ns	2.2	0.0	9.2	8.1	2.3	21.8 ns
Ca	5.3	14.7	1.0	21.0 ns	0.0	3.5	5.3	2.6	3.6	15.0 ns
Mg	2.3	8.6	1.0	12.0 ns	0.1	9.6	12.4	0.2	0.0	22.3 ns
S	2.3	8.6	1.0	12.0 ns	2.3	11.2	12.4	0.0	1.1	26.9 ns
B	0.6	10.5	4.2	15.2 ns	2.2	2.6	10.7	9.6	1.1	26.2 ns
Cu	0.0	1.3	1.0	2.3 *	0.4	10.7	2.4	14.7	5.5	33.8 ns
Fe	1.6	12.5	3.2	17.3 ns	0.0	5.6	22.5	1.3	5.5	35.0 ns
Mn	0.2	4.2	1.6	6.0 ns	7.5	3.5	5.3	4.5	0.0	20.8 ns
Zn	9.5	38.8	5.3	53.6 ns	0.4	2.6	30.1	5.6	3.7	42.4 ns
χ^2	29.67 ns	146.62 ns	30.74 ns	207.03ns	24.30ns	72.86ns	127.08ns	63.44ns	31.51ns	319.18 ns

(ns), (*): nonsignificant and significant at 5 % of probability, respectively; n: negative, with high probability; nz: negative, with low probability; z: null; pz: positive, with low probability; p: positive, with high probability, according to Wadt (2005). LE (n + nz): limiting due to excess; NL (z): non-limiting; LD (pz + p): limiting due to deficiency.

There are around 1,200 peach palm producers in the Ribeira Valley, who produce an average 3.1 to 4.2 thousand palm hearts ha^{-1} yr^{-1} with an average weight of 650 to 750 g (Silva, 2017), which is consistent with the mean productivity found in this study (722.9 g palm $heart^{-1}$) for a population of 5,000 plants ha^{-1}, corresponding to 3.6 Mg ha^{-1}, 121 kg more than the average for the state of São Paulo. However, among the 102 stands assessed, 41 (40.2 %) were classified as high-yield (reference population ≥722.9 g palm $heart^{-1}$), and 61 (59.8 %) were classified as low-yield (<722.9 g palm $heart^{-1}$), considering that the reference population produces 3.6 to 6.1 Mg ha^{-1}.

The variability in production across cultivation areas is mainly related to the effect of fertilization, water supply, and peach palm harvesting palm heart, in addition to non-uniform genetic material with respect to vigor and production (Kalil Filho et al., 2021) since they are non-irrigated areas and mostly have irregular topography. Azevedo et al. (2016) derived sufficiency ranges for peach palms in the Amazon region for different management palm hearts, and they noted that, despite some similarities to the ranges proposed in the present study, the amplitude was higher, with the appropriate concentration being lower, except for K, Cu, and Mn, underscoring the importance of establishing and using norms and specific values for each region according to the cultivar, technological level, management, and edaphoclimatic conditions (Lima Neto et al., 2022), improving the accuracy of the interpretations of leaf analysis results and minimizing the likelihood of misinterpretations regarding deficiency, sufficiency, or excess of nutrient (Yamane et al., 2022).

Nitrogen was the nutrient with the highest frequency of limitation due to deficiency and the second with the highest frequency of limitation due to excess in both populations, probably because it is the nutrient required in greater amounts by the peach palm. Deenik et al. (2000) and Bovi et al. (2002) indicate that N positively affects the growth of the main palm heart diameter, which is directly related to the production of heart and/or fruit. Nitrogen fertilizer is overapplied to prevent yield losses, given its importance to the crop.

Manganese was the nutrient with the highest frequency of limitation due to excess in the low-yield population, and this is related to average low base saturation

(V = 33.4 %) and high acidity of low-yield stands, with low soil pH, with consequent solubilization of Mn oxides, releasing Mn^{2+} into the soil solution.

CONCLUSIONS

Considering an acceptable sampling error of 5 to 10 % for assessing peach palm productivity (total palm heart weight and/or cylinder weight), 16 plants were enough for the analyses. The varying productivity of peach palm in the Ribeira Valley is not related to the assessment of nutrient content by the DRIS method. However, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn contents showed a positive correlation with their respective nutrient indices. No differences were found between DRIS norms for the whole palm heart and the cylinder, which can be explained by the strong relationship between the production of palm hearts and cylinders (84.1 %). Sufficiency ranges of nutrients in the present study can be used by peach palm producers in the Ribeira Valley, providing higher accuracy in the nutritional diagnosis of this crop under the current production conditions and higher fertilizer use efficiency.

AUTHOR CONTRIBUTIONS

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