__Original Research Article__

CANONICAL CORRELATION BETWEEN SOIL ATTRIBUTES AND FOLIAR NUTRIENTS OF CONILON COFFEE TREES

ABSTRACT

The nutritional status of the coffee tree is influenced by the concentration of nutrients in the soil of the growing area. The objective of this work was to evaluate, using canonical correlation, the linear relationships between chemical attributes of soil and nutrients of leaf tissues in seminal coffee. The work was developed in a commercial crop located in the municipality of Cachoeiro de Itapemirim, the southern region of the state of Espírito Santo. In the crop, an irregular sampling mesh was constructed, totalizing 80 georeferenced points. The canonical correlation analysis was performed considering the original data observed in two consecutive conilon coffee harvests, 2015/16 and 2016/17, to verify the associations between a (dependent) group formed by foliar nutrients (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn) and an independent group formed by soil chemical attributes (pH, Ca, Al, K, S, P, Cu, Fe, Mn and Zn). Even if nutrients are available, that is, available in a satisfactory amount in the soil, it can happen that it does not reach the leaf tissue, resulting in a deficiency for some nutrients. There was a direct relationship between the concentration of K in the leaf tissue and K in the soil in the two harvests. Other soil attributes, such as Organic Matter, Fe, Mn, and S, also influenced this relationship, showing that the soil attributes in the independent group interact together on the nutrients in the leaf tissue. There is an inverse relationship between the concentrations of K in the leaf tissue and the Mn in the soil in the two harvests, showing that the excess of Mn in the soil is influencing the K deficiency in the leaf tissue.

Keywords: Coffea canephora; Multivariate analysis; Nutritional status; canonical analysis.

INTRODUCTION

The Coffee conilon (*Coffea canephora*) is a prominent crop in the state of Espírito Santo and of great importance in the economy of Brazil, which is the largest coffee producing and exporting country. The cultive of coffee is responsible for generating jobs in the field and is extremely relevant in the economic income of several municipalities, and it is of great importance to carry out studies that may contribute to improving understanding of the culture and management adopted.

The study of nutritional status is of extreme importance to understand the behavior of the coffee crop and to know which nutrients to be supplied and those that are in excess. The coffee tree has as a characteristic a great export of nutrients from the soil, necessitating the adequate application of correctives and fertilizers to achieve high productivity [1]. For author [2], fertilization and liming must supply the nutrients in sufficient quantity without forgetting the appropriate balance between them, aiming at their better use, and the excess of some is detrimental, both by the greater investment required and by the imbalances and antagonisms. Already the deficiency affects the development and the production of coffee, reducing productivity and quality of the coffee harvested.

Studies have confirmed that the analyzes of coffee fertilization systems should involve joint information on the soil and the nutritional status of the plants [3,4]. Thus, it is of extreme importance to study the relationship between nutrients in leaf tissue and soil attributes, such as the study by authors [5], who found a relationship between the variability of Prem in soil and P in the plant.

One tool to study the interaction between groups of variables is the canonical correlation, a multivariate statistical method. This correlation predicts multiple dependent variables from multiple independent variables simultaneously [6]. The canonical function is formed by a pair of statistical variables, being a dependent one and independent one [6,7].

Canonical correlation is one of the methods of multivariate analysis, in which the maximum number of canonical functions is equal to the number of variables of the smallest group under study. The first canonical function is obtained in order to present the highest correlation possible with the groups of variables [8]. Other functions may be meaningful, containing information that has not been explained in the first function. The authors [9] found 3 significant functions studying the canonical correlation in the analysis of the yield of bean grains and their components. Other good results in previous research involving canonical correlations were obtained for castor bean [10], melon [11] and sugarcane [12].

The existence of interactions between soil chemical attributes and foliar tissue nutrients helps in the decision of soil fertilization and allows to understand coffee development and interaction with productivity. In this context, the objective of this work was to use the canonical correlation to determine the relationship between soil chemical attributes and foliar nutrients of the coffee conilon seed propagation.

MATERIAL AND METHODS

The work was carried out in a commercial plantation of coffee seedlings, located in the municipality of Cachoeiro de Itapemirim (20º37'31 '' S latitude and 41º05'22 '' W longitude) and an average altitude of 520.0 m. According to the climatic classification [13], the region has Cwa categorization. The soil of the area was classified as Cambisol, of clay-sandy texture with 460 g kg-1 of clay; 90 g kg-1 of silt; and 450 g kg-1 of total sand.

The plant species used was Coffea canephora Pierre, of seminal propagation, adopting the spacing of 1,5m x 1,5m (4,444 plants ha^{-1}). The application of correctives and chemical fertilizers was carried out according to the chemical analysis of the soil [14] and the cultural and phytosanitary treatments according to authors [15].

The precipitation values were estimated by Inverted Weighted Distance (IDP) interpolation method, with exponent grade three, using data from 17 automatic climatic stations of the National Institute of Meteorology (INMET), according to author [16]. Temperature data were obtained according to author [17]. The maximum and minimum temperatures in the 2015/16(¹) crop were 33.23 ° C and 15.8 ° C, respectively, with an annual rainfall of 820 mm. In the 2016/17(²) harvest, the maximum temperature was 32.71 °C and minimum 14.72 °C, with cumulative precipitation of 1167 mm.

In the experimental area were used 80 sampling points that constituted the irregular grid, identified with metal markers, being the topographic survey carried out by means of a total station, with each sampling point having an area of 6.75 m^2.

The foliar analysis was used to characterize the nutritional status of each sampling point, and to obtain these data, two pairs of lateral branches were removed from the middle third of each plant (3rd and 4th pairs counting from the tip to the basis of the plagiotropic), in the four cardinal points [18] in February 2016 and 2017.

The collected leaves were conditioned in a paper envelope and identified, dried in an oven at 65 ° C until constant mass in the Laboratory of Hydraulics, Water Resource of the Federal University of Espírito Santo, Center of Agrarian Sciences and Engineering - LHRG / UFES-CCAE. (N), Phosphorus (P), Potassium (K), Calcium, Magnesium (Mg) and Nitrogen (N) were analyzed.), Sulfur (S), Boron (B), Manganese (Mn), Iron (Fe), Zinc (Zn) and Copper

(Cu). The analyses were performed according to the Manual of Methods of Analysis presented by Embrapa [19].
At each georeferenced point, a soil sample was collected in the month of February 2016 and 2017, in the layer of 0-0.20 m depth, with stainless steel, in the projection of the coffee canopy. The values of active acidity in water (pH), potential acidity (H + Al), calcium (Ca), magnesium (Mg), potassium (K), aluminum (Al) Mehlich (P+), remaining phosphorus (Prem), Zn (Zn), Iron (Fe), Manganese (Mn), Copper (Cu), Boron (B), organic matter (OM), cation exchange (t), cation exchange capacity at pH 7 (T), base saturation (V%).
The obtained data were analyzed through the position measurements (mean and median); dispersion measurements (maximum and minimum values, standard deviation and coefficient of variation); and the multivariate normality was evaluated by the Quantil-Quantil graph (Q-Q Plot).
Preliminary to the canonical correlation analysis, the simple linear correlations between the variables were estimated by the Pearson correlation ($p \leq 0.05$) to verify if there is multicollinearity. In case of high correlation between the variables, the canonical analysis was performed without one of the variables, to verify the influence of this correlation in the canonical analysis, if the withdrawal of the variable had little effect on the correlation, the group of original variables was maintained.
The analysis of canonical correlation was carried out considering the original data to verify the associations between the soil chemical attributes (^{s}) group (pH, Ca, Al, K, S, P, Prem, MO, B, Cu, Fe, Mn, and Zn) with a second group formed by leaf nutrients (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn). The first group represents the independent variables (X) and the second dependent ones (Y). In this way, 11 canonical functions were determined, according to the smallest group.
After defining the groups, the canonical functions were generated, and the significance of the functions was tested by the chi-square test ($p \leq 0.01$).
The canonical charges were estimated, which are the correlations between the original variables and their respective canonical functions and the crossed canonical charges that represent the correlation between an original variable of a given group and the canonical function of the other group.
The amount of shared variance explained between the observed dependent and independent variables, and their respective canonical statistical variables were determined by raising the canonical loads squarely. The same was done for the crossed canonical charges in order to estimate the shared variance explained between the dependent variable or independent observed with the opposite canonical statistical variable.
The procedures used for the statistical analyses were based on the work of several authors [7,6,8, 20].

RESULTS AND DISCUSSION

Considering the average nutrient values of leaf tissues (Table 1), among the macronutrients, only K^1 and K^2 are deficient below the appropriate range. The macronutrients that are in high concentration are P^1 and Ca^2, according to the range proposed by authors [21].
Raising K concentration in the plant is fundamental because of its importance in productivity. The K appears with greater concentration in the fruits, in particular in the pulp of the coffee, but without participating in organic molecules [22]. Still, according to these authors, the quantities of K in the vegetative parts are sufficient to show that this nutrient plays an important role in the nutrition of this crop. In general, high levels of K are associated with high yields [23]. The presence of potassium in the coffee straw is high, and its return to the crop is important, aiming to reduce its export from the soil reservoir [24]. In addition, raising the K content in the applied formulation is another way of making this nutrient available to the plant.

Table 1 - Descriptive statistics of leaf nutrient contents for conilon coffee

Nutrient	Average	Md	S	Values		CV (%)	Test
				Mín	Máx		KS
N^1 (dag kg^{-1})	2.95	2.87	0.22	2.59	3.50	7.45	ns
N^2 (dag kg^{-1})	2.90	2.87	0.27	2.31	3.57	9.44	ns
P^1 (dag kg^{-1})	0.17	0.17	0.02	0.13	0.22	11.76	ns
P^2 (dag kg^{-1})	0.15	0.15	0.02	0.09	0.19	14.29	ns
K^1 (dag kg^{-1})	1.64	1.67	0.16	1.40	2.00	10.36	ns
K^2 (dag kg^{-1})	1.65	1.63	0.26	1.20	2.54	15.95	ns
Ca^1 (dag kg^{-1})	1.35	1.35	0.18	1.00	1.67	13.33	ns
Ca^2 (dag kg^{-1})	1.54	1.53	0.32	0.91	2.23	20.74	ns
Mg^1 (dag kg^{-1})	0.37	0.37	0.03	0.30	0.43	8.11	ns
Mg^2 (dag kg^{-1})	0.38	0.39	0.04	0.26	0.47	12.35	ns
S^1 (dag kg^{-1})	0.22	0.22	0.03	0.17	0.30	13.63	ns
S^2 (dag kg^{-1})	0.21	0.21	0.02	0.17	0.28	11.82	ns
Fe^1 (mg kg^{-1})	108.33	108.92	19.07	65.60	149.05	17.61	ns
Fe^2 (mg kg^{-1})	149.56	142.5	28.99	110.00	245.00	19.38	ns
Zn^1 (mg kg^{-1})	7.79	7.52	1.45	5.10	11.35	18.58	ns
Zn^2 (mg kg^{-1})	14.13	12.53	9.57	8.95	92.50	67.75	ns
Mn^1 (mg kg^{-1})	90.17	90.00	32.38	28.20	165.00	35.92	ns
Mn^2 (mg kg^{-1})	106.43	100.00	45.61	45.00	325.00	42.86	ns
B^1 (mg kg^{-1})	39.51	39.23	6.15	26.59	54.75	15.56	ns
B^2 (mg kg^{-1})	67.58	66.76	9.74	37.01	99.23	14.41	ns
Cu^1 (mg kg^{-1})	18.67	17.22	6.40	7.15	35.50	34.26	ns
Cu^2 (mg kg^{-1})	13.35	11.35	10.00	7.05	95.60	74.90	ns

[1]crop of 2015/16; [2]crop of 2016/17; Md – Average; S – standard~~t~~ deviation; CV – coefficient~~iciente~~ of variation; ns – normal distribu~~ubui~~tion by the Kolmogorov-Smirnov test (KS) in 1% of probability.

For micronutrients (Table 1), it is verified that Fe^1, Zn^1 and B^1 have average levels below that recommended for conilon coffee trees. Mn^{12} (crops 1 and 2) and B^2 present concentrations higher than or equal to those recommended.

The micro-nutrient deficiency in a crop can cause an imbalance in the plant metabolism, making the plants more susceptible to pests and diseases, causing an increase in the expenses with pesticides and costing the crop [25]. In the coffee crop, the lack of micronutrients can cause a decrease in plant growth and a decrease in production [26]. In view of this, the correction of micronutrients in deficiency is fundamental for the good development of the crop.

The results of the descriptive analysis of soil attributes of coffee conilon in the harvests of 2015/16 (^{1}) and 2016/17 (^{2}) are in Table 2. According to the classification proposed by authors [14] and according to the analysis, the soil presents medium acidity, with low concentrations of Cu^s and P^s (^{s} = soil) and high concentrations of Fe^s, Mn^s and S^s. For the Zn^s the concentration was average in crop 1 and high in crop 2. All other attributes presented average concentration in both crops.

As emphasized by authors [27] when the nutrient content is low, the dose should be adjusted to recompose the export by the crop and achieve or maintain the optimum soil content. Thus, there is an immediate need to provide Cu and P in the soil.

Table 2. Descriptive statistics of soil attributes of coffee crop.

Nutrient	Average	Md	S	Values		CV (%)	Test
				Mín	Máx		KS
pH^1 (em H_2O)	5.26	5.30	0.42	4.40	6.40	8.05	ns
pH^2 (em H_2O)	5.38	5.40	0.18	5.00	5.90	3.37	ns
Al^1 (cmol$_c$ dm^{-3})	0.42	0.35	0.21	0.10	1.10	50.77	ns

Al[2] (cmol$_c$ dm^{-3})	0.30	0.26	0.16	0.10	0.84	55.40	ns
B[1] (mg dm^{-3})	0.42	0.40	0.10	0.30	0.70	24.08	ns
B[2] (mg dm^{-3})	0.54	0.50	0.29	0.11	1.28	54.16	ns
Ca[1] (cmol$_c$ dm^{-3})	2.41	2.30	0.95	0.80	5.10	39.69	ns
Ca[2] cmol$_c$ dm^{-3})	1.84	2.00	0.35	1.00	2.50	19.21	ns
Cu[1] (mg dm^{-3})	0.60	0.60	0.16	0.40	1.00	26.20	ns
Cu[2] (mg dm^{-3})	0.62	0.60	0.33	0.10	1.80	53.08	ns
Fe[1] (mg dm^{-3})	93.19	94.00	25.85	35.00	150.00	27.74	ns
Fe[2] (mg dm^{-3})	155.43	152.50	45.95	73.00	252.00	29.56	ns
K[1] (mg dm^{-3})	136.20	118.50	54.89	52.00	287.00	40.30	ns
K[2] (mg dm^{-3})	115.41	111.50	42.35	42.00	224.00	36.70	ns
Mn[1] (mg dm^{-3})	28.16	27.55	14.43	6.60	71.80	51.23	ns
Mn[2] (mg dm^{-3})	39.59	35.90	19.05	11.60	107.90	48.12	ns
OM[1] (dag dm^{-3})	2.52	2.50	0.39	1.50	3.40	15.69	ns
OM[2] (dag dm^{-3})	1.65	1.70	0.17	1.20	2.00	10.48	ns
P[1] (mg dm^{-3})	7.40	6.55	4.07	1.70	20.10	54.95	ns
P[2] (mg dm^{-3})	9.47	8.65	3.51	4.20	21.00	37.06	ns
Prem[1] (mg L^{-1})	21.36	22.15	4.21	10.90	31.00	19.71	ns
Prem[2] (mg L^{-1})	25.79	25.95	2.82	19.30	33.30	10.93	ns
S[1] (mg dm^{-3})	39.74	37.50	17.96	12.00	70.00	45.21	ns
S[2] (mg dm^{-3})	25.99	26.00	5.16	15.00	38.00	19.86	ns
Zn[1] (mg dm^{-3})	1.51	1.40	0.63	0.00	3.00	41.53	ns
Zn[2] (mg dm^{-3})	2.30	2.20	0.69	0.90	4.10	30.04	ns

[1]crop of 2015/16; [2]crop of 2016/17; Md – Average; s – S – standard~~t~~ deviation; CV – coefficient~~iciente~~ of variation; ns – normal distribu~~ubui~~tion by the Kolmogorov-Smirnov test (KS) in 1% of probability

Pearson's correlation coefficients ($p \leq 0.05$) for soil and plant variables are presented in Tables 3 and 4. In relation to the magnitude of the significant correlations among all evaluated variables, they ranged from 0.22 to 0.94 in the first crop and between 0.22 to 0.95 in the second crop.
The Ca^s (0.94^1; 0.95^2) and Al^s (-0.93^1; -0.81^2) maintained a high correlation, according to Callegari-Jaques classification (2003), in the two harvests with soil pH, values in parentheses being the correlation in crop 1 and 2, respectively. Despite the high correlation of Ca^{2+} and Al^{3+} with pH, the removal of the pH variable did not influence enough to be removed from the analysis. The number of significant functions was maintained, and the nutrient weights did not have major modifications, so we opted to maintain the pH in the analysis.
The first canonical function in crop 1 and the first two canonical functions in crop 2 (Table 5) were significant at the 1% probability level ($p \leq 0.01$), by the chi-~~-~~square test. C~~, c~~onsequently, these will be the canonical functions interest of the study. The significance of these functions indicates that when these are removed, there is no significance for the rest of the set of roots.
The canonical R or canonical correlation in crop 1 is significant and equal to 0.85 for the first and most important canonical function. This value shows the intensity of the relationship between the dependent and independent canonical statistical variable. In the second crop, they have two significant functions with canonical R of 0.77 and 0.74, respectively.

Table 3. Pearson correlation (p≤0.05) between soil attributes and nutrients in leaf tissue for crop 1.

	pH^s	Ca^s	Al^s	K^s	S^s	P^s	$Prem^s$	OM^s	B^s	Zn^s	Cu^s	Fe^s	Mn^s	N^t	P^t	K^t	Ca^t	Mg^t	S^t	B^t	Cu^t	Fe^t	Mn^t	Zn^t
pH^s	1.00	0.94	-0.93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca^s		1.00	-0.79	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Al^s			1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
K^s				1.00	0.49	0.44	-	-	-0.24	0.22	-	0.33	-	-	-	-0.31	-0.23	-	-0.32	-	-	-0.29	-	-
S^s					1.00	0.61	-0.23		-0.24	0.39	-	0.32	-	-	-	-	-0.40	-	-	-	-	-	-	-
P^s						1.00	-	-	-	-	0.26	-	-	-	-	-	-	-	-	-	-	-	-	-
$Prem^s$							1.00		0.26	-0.29	-	-0.33	-	-	-	-	0.23	-	-	-	-	-	-	-
OM^s								1.00		-	-	0.31	-	-	-	-	-	-	-	-	-	-0.25	-0.24	-
B^s									1.00	-0.37	-	-0.28	-	-	-	-	-	-	-	-	-	-	-	-
Zn^s										1.00	0.63	0.33	-	-0.29	-	-	-0.26	-	-	-	-	-	-	-
Cu^s											1.00		0.22	-	-	-	-	-	-	-	-	-	0.35	-
Fe^s												1.00	-	-	-	-	-	-	-0.23	-	-	-0.35	-0.25	-0.30
Mn^s													1.00	-	-0.30	-	-	0.23	0.32	0.29	-0.39	0.37	0.58	-
N^t														1.00	0.26	-	-	-	-	-	-	-	-	-
P^t															1.00	-	-	-	-	-	0.34	-0.23	-	-
K^t																1.00	-	-	-	-	-	-	-	-
Ca^t																	1.00	-	-	0.28	-	-	-	0.22
Mg^t																		1.00	-	-	-	-	-	-
S^t																			1.00	0.15	-0.31	0.37	-	-
B^t																				1.00	-0.28	0.35	0.36	0.26
Cu^t																					1.00	-	-0.34	-
F^t																						1.00	0.48	0.27
Mn^t																							1.00	0.32
Zn^t																								1.00

^{s}: soil atribute; ^{t}: nutrient in foliar tissue.

Table 4. Pearson correlation (p≤0.05) between soil attributes and nutrients in leaf tissue for crop 2.

	pH^s	Ca^s	Al^s	K^s	S^s	P^s	Prem^s	OM^s	B^s	Zn^s	Cu^s	Fe^s	Mn^s	N^t	P^t	K^t	Ca^t	Mg^t	S^t	B^t	Cu^t	Fe^t	Mn^t	Zn^t
pH^s	1.00	0.95	-0.81	0.28	-0.25	-	-0.28	-	-	0.36	-	-	-	-	-	0.24	-	-	-	-	-	-	-	-
Ca^s		1.00	-0.77	0.33	-0.23	-	0.25	-	-	0.37	-	-	-	-	-	-	-	-	0.24	-	-	-	-	-
Al^s			1.00	-	-	-	-	-	-	-0.24	-	-	-	-	-0.24	-	-	-	-	-	-	-	-	-
K^s				1.00	-	-	-	0.28	-	0.38	-	0.24	-	-0.25	-	-	0.29	-0.30	-	-	-	-	-	-
S^s					1.00	-	-0.45	-	-	-	-	-0.25	-	-	-	-	-0.25	-	-	-	-	-0.34	-	-
P^s						1.00	-	-	-	-	0.23	-	-	-	0.29	-	-	-	-	-	-	-	-0.22	-
Prem^s							1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OM^s								1.00	-	-	-	-	-	-	-	-	-	-0.24	-	-	-	-	-	-
B^s									1.00	-	-	0.33	-	-	-	-	-	-	-	-	-	-	-	-
Zn^s										1.00	0.41	0.24	-	-	-	-	-	-	0.34	-	0.34	-	-0.37	-
Cu^s											1.00	0.28	-	-	-	-	-	-	0.34	-	0.29	-	-0.33	-
Fe^s												1.00	-	-	-	-	0.41	-	-	-	-	0.24	-0.33	-
Mn^s													1.00	-	-	-0.38	-	-	-	-	-0.39	-	0.42	-
N^t														1.00	0.25	0.31	-	-	-	-	-	-	-	0.22
P^t															1.00	0.24	-	-	-	-	0.25	-	-	-
K^t																1.00	-	-	-	-	-	-0.33	-	-
Ca^t																	1.00	0.27	-	0.32	-	0.47	-0.29	-
Mg^t																		1.00	-	-	-	-	-	0.31
S^t																			1.00	-	0.32	-	-0.23	-
B^t																				1.00	-	-	-	-
Cu^t																					1.00	-	-0.50	-
F^t																						1.00	-	0.25
Mn^t																							1.00	-
Zn^t																								1.00

^{s}: soil atribute; ^{t}: nutrient in foliar tissue.

Table 5. Canonical correlation and significance test for canonical functions.

Canonical Function	Canonical Correlation	R^2 canonical	Chi Square	GL	P
Crop 1					
1	**0.85**	**0.72**	**242.62**	**143.00**	**0.000***
2	0.70	0.49	156.82	120.00	0.014
3	0.62	0.39	111.65	99.00	0.182
4	0.56	0.31	79.15	80.00	0.506
5	0.49	0.24	54.37	63.00	0.772
6	0.44	0.19	36.38	48.00	0.890
7	0.37	0.14	22.14	35.00	0.955
8	0.28	0.08	12.09	24.00	0.979
9	0.23	0.05	6.69	15.00	0.966
10	0.16	0.03	2.99	8.00	0.935
11	0.13	0.02	1.18	3.00	0.758
Crop 2					
1	**0.77**	**0.59**	**240.49**	**143.00**	**0.000***
2	**0.74**	**0.55**	**180.39**	**120.00**	**0.000***
3	0.64	0.41	127.71	99.00	0.028
4	0.59	0.35	92.42	80.00	0.162
5	0.53	0.28	64.24	63.00	0.433
6	0.46	0.21	42.16	48.00	0.710
7	0.39	0.15	26.46	35.00	0.850
8	0.34	0.12	15.78	24.00	0.896
9	0.26	0.07	7.41	15.00	0.945
10	0.15	0.02	2.57	8.00	0.958
11	0.12	0.01	0.96	3.00	0.811

In bold, significant by Chi Square test.

The results show R^2 values of 0.72 for the first function in crop 1 and 0.59 and 0.55 for the two functions of crop 2. A high canonical R^2 indicates that the amount of variance explained among the canonical statistical variables independently and function dependent was significant for the groups of characteristics analyzed [12]. This high R^2 value is indicative of the influence of soil attributes on the nutrients present in the plant tissue of the coffee tree.
The canonical functions represent the weighted sum of the variables in each set;~~,~~ that is, each variable has different weight, as shown in Table 6. For the author [28], the analysis and interpretation of canonical weights involve~~s~~ examining the signal and its magnitude, so that the variables with relatively larger canon weights contribute more to the statistical variables and vice versa.
The nutrients in leaf tissue of crop 1 with higher weights are K^t, S^t, and Mn^t, which have absolute weights greater than 0.30. For soil attributes, they have Ca^{2+s}, OM^s and Mn^s with higher weights. In crop 2, o Ca^t, Mg^t, S^t, Fe^t are Mn^t are the nutrients in leaf tissue that contribute most to function 1 and P^t, K^t, Ca^t and Fe^t for function 2. The soil attributes that contribute most to function 1 are Ca^s, Al^s, Prem and Mn^s. For function 2 are pH, K^s, S^s, OM, B^s, Fe^s and Mn^s.

Table 6. Weights, canonical charges and canonical cross loads for the canonical functions in the two harvests.

	Canonical Weigh	Canonical charges	Cross canonical charges	Canonical Weigh		Canonical charges		Cross canonical charges	
	Crop 1			Crop 2					
	Functions								
	1	1	1	1	2	1	2	1	2
N^t	0.05	0.00	0.00	-0.06	0.00	-0.13	-0.08	-0.10	-0.06
P^t	-0.18	-0.36	-0.31	0.17	0.30	0.30	0.15	0.23	0.11
K^t	-0.34	-0.25	-0.21	-0.01	-0.85	0.17	-0.56	0.13	-0.43
Ca^t	0.10	0.10	0.08	0.32	-0.40	0.11	-0.54	0.08	-0.42
Mg^t	0.05	0.17	0.15	-0.41	-0.10	-0.37	-0.17	-0.28	-0.13
S^t	0.30	0.51	0.43	0.47	-0.01	0.47	0.02	0.36	0.02
B^t	0.02	0.41	0.35	0.06	0.17	0.05	-0.16	0.04	-0.12
Cu^t	-0.24	-0.57	-0.49	0.13	0.09	0.60	0.00	0.46	0.00
Fe^t	0.17	0.62	0.52	-0.51	-0.51	-0.30	-0.42	-0.23	-0.32
Mn^t	0.58	0.80	0.68	-0.45	0.14	-0.65	0.32	-0.50	0.25
Zn^t	-0.16	0.17	0.15	-0.06	0.29	-0.20	0.04	-0.16	0.03
pH^s	-0.02	0.04	0.03	-0.01	-0.34	0.50	-0.19	0.39	-0.14
Ca^s	-0.33	0.01	0.01	0.82	0.21	0.60	-0.17	0.46	-0.13
Al^s	-0.22	-0.07	-0.06	0.30	-0.22	-0.32	-0.05	-0.25	-0.04
K^s	-0.23	-0.41	-0.35	0.08	-0.43	0.35	-0.37	0.27	-0.28
S^s	0.25	-0.10	-0.09	0.00	0.33	0.05	0.52	0.04	0.40
P^s	-0.15	-0.06	-0.05	0.29	0.05	0.39	0.03	0.30	0.02
Prem	0.03	0.14	0.12	-0.50	-0.13	-0.31	-0.32	-0.24	-0.24
OM	-0.38	-0.31	-0.26	0.22	0.45	0.30	0.42	0.23	0.33
B^s	0.03	0.09	0.08	0.23	0.34	0.29	0.18	0.22	0.14
Zn^s	-0.25	0.03	0.03	-0.03	0.04	0.57	-0.10	0.44	-0.08
Cu^s	0.22	0.31	0.26	0.25	0.19	0.34	0.01	0.26	0.01
Fe^s	-0.04	-0.35	-0.30	-0.05	-0.39	0.24	-0.39	0.18	-0.30
Mn^s	0.87	0.82	0.70	-0.32	0.44	-0.41	0.44	-0.32	0.34

The authors [29] studying broccoli plant characters that determined head production, found a weight of 0.64 in the variable that most contributes to the correlation. In this study, the highest weight was 0.87 for Mn^s in crop 1, followed by Mn^t in crop 1 (0.58), Mn^t in crop 2 in the first and second functions (0.51). For the first and second canonical function in crop 2, the soil attributes that presented the highest weight were $Prem^s$ (-0.50) and Fe^s (-0.39).

Table 6 also shows canonical charges and cross-canonical charges. The greater the canonical charge of a variable within a group, the greater the correlation of this variable with the other variables of the group. When using canonical correlation, direct relationships that were not found in the Pearson correlation were observed, such as the relationship of Mn^t with St and Pt. The results found in crop 1 show that Mn^t has a direct relationship with S^t, B^t and Fe^t,, and inverse with P^t and Cu^t. This shows that although Mn^t is in excess, it has not yet reached the point of reducing Fe^t level, showing that Fe^t deficiency in crop 1 did not occur due to excess Mn. Another relation that is evidenced in this crop by the canonical correlation is the antagonism between Fe^t and Cu^t. Thus, Cu^t excess may be contributing to Fe^t deficiency.

When analyzing the soil attributes, it sees a direct relation between MO, K^{+s} and Fe^s. Cu^s has an inverse relationship with it. The inverse relation between OM and Cu^s is expected since the quality and quantity of organic matter in the soil can affect the availability and mobility of metals such as Cu [30]. According to authors [31], there are interactions between Cu and humic acids forming AH-Cu complexes. As well as the interaction with OM, canonical analysis also demonstrated the antagonism between Fe^s and Cu^s, showing that Cu excess can cause Fe deficiency and that this relationship occurs in both soil and leaf tissue. The Mn^s had an inverse relationship with Fe^s.

In the evaluation of crop 2, there was a direct relation of Mn^t with Mg^t and inverse with S^t and Cu^t. The inverse relationship between Mn^s and Cu^s was also observed. The authors [32] observed a tendency of decrease in Cu concentration in black pepper as the concentration of Mn increases. Fe^t and Mn^t, as well as in crop 1, have a direct relationship.

The interactions between o pH, Ca^s and Al^s can be seen in the first canonical function in crop 2, a direct relationship of pH with Ca^s and inverse with Al^s. This correlation is important to explain the need for liming in soils with low pH, showing that it must be carried out constantly to prevent the soil from reaching a state that could damage the crop. The inverse relationship between pH and Al was studied by authors [33], who showed that as the pH increases to a pH around 6.0, the concentration of Al in the soil is reduced linearly. Correction of soil acidity, if performed correctly, can correct the negative effects of Al, raising the agricultural potential of the soil and, consequently, increasing the productivity of the crops. According to authors [34] under acidic conditions, some of the essential nutrients, such as P, Ca and Mg, are made unavailable in the soil solution for plant absorption due to the abundance of elements such as Al and Mn. The canonical correlation confirms this assertion through the direct relationship between the Al^s and Mn^s and the inverse of the two with the Ca^s and P^s.

The second canonical function shows the direct relationship between K^t, Ca^t and Fe^t and their inverse relationship with Mn^t. In the soil there is a direct relationship K^{+s}, Prem and Fe^s, and these are inversely related to S^s, OM and Mn^s. Thus, Mn and K^+ have an inverse relationship in soil and leaf tissue. The authors [35] observed that K, Ca and Mg play an important role in the uptake of Mn by plants. The cations promote absorption when Mn is present in small amounts or effectively decreases the absorption of Mn when it is present in high amounts and may be toxic. The Mn is in excess in both leaf tissue and soil, so K is acting as an antagonistic nutrient, to avoid that the absorption of Mn can harm the plant.

The authors [36] reported that the addition of Mn in the soil was attributed to the reduction of Fe concentration. The authors [37] reported that the absorption of S by alfalfa, wheat, rice and red clover decreased levels of Fe in the growth medium. Similarly, alfalfa, red clover and wheat, the Mn uptake decreases in high Fe concentrations. Although they are different crops, in the coffee crop the canonical analysis showed similar results, showing this inverse relationship between S^s e F^s and between Mn^s e Fe^s.

Evaluating the crossed canonical load, the K^+ in the leaf tissue had relation with the independent statistical variable in the two harvests. The soil attributes that most influenced the concentration of K in the leaf tissue in the two harvests were Mn s, K, OM and Fe. The authors [38] found that K^+ fertilization significantly increased K concentrations in leaf tissue at the expense of Mg^{+2} and Ca^{2+} concentrations in three fresh season grasses. The direct relations of K in leaf tissue with K^s and Ca^s confirm the relationship between these two nutrients for the coffee crop. The authors [39] studied the interactions of Ca with other nutrients and reported that Ca stimulated the absorption of K at certain concentrations of ions.

The P^t was influenced by the independent statistical variable, being P^s, K^s, Ca^s, Zn^s, pH, MO, Fe^s e Mn^s the soil attributes that contributed to~~in~~ this interaction. The Mn^s was the soil attribute that most influenced the Pt, having an inverse relationship between the two. For the authors [4], insufficient levels of P in plant tissue affect the absorption of other essential elements that are important protectors during the phases of growth and development of the crop. According to authors [40], interactions between P and other elements in the plant can occur during absorption and radial transport over long distances, and in the metabolism of the element within the metabolic chains of coffee.

The linear correlation between the independent and dependent variable was strongly influenced by K^t and Mn^s. The analysis of canonical correlation showed an inverse relationship between the concentrations of K^t and Mn^s in the two harvests, showing that the excess of Mn^s is influencing the K deficiency in leaf tissue.

The concentrations of Cu^t, Fe^t was~~ere~~ directly related to the concentration of these attributes in the soil (Cu^s and Fe^s) in the two harvests. The advantage of interpreting the relationship between soil attributes and foliar nutrients by canonical correlation is to have a dimension of which soil elements are influencing the absorption of the others. For example, although Fe is in high concentration in the soil, it is deficient in foliar tissue, this is because it is being affected by the excess of S^s and Mn^s, as can be seen in the canonical cross load of function 2.

During the analysis of the data found synergism, antagonism and the neutral relationship between nutrients, however, these relationships are complex and should be carefully evaluated. In all analyzes, it was possible to observe that a nutrient interacts simultaneously with more than one attribute, as reported by the author [41].

The result found shows the importance of evaluating the interaction of nutrients for decision making in crop management. Cu is deficient in soil, and one of the inorganic sources of this nutrient is copper sulphate ($CuSO_4$), but it is possible to see in the canonical load of the second function of crop 2 that the soil S content was one of the attributes of the group of independent variables that affected K content in leaf tissue, thus recommending cupric oxide is the best option. This same evaluation can be used as a choice of formulas of silicate oxides ("frits") that present different micronutrient contents.

The amount of shared variance explained by the dependent canonical statistical variable in crop 1 was, on average, 18.45% (Table 7). It is observed that Mn^t presented the highest percentage of variance explained in the dependent canonical statistical variable (64%). Thus, Mn^t can be considered the most relevant nutrient in the dependent canonical statistical variable. Mn^s was also the most relevant attribute in the independent statistical variable, with 67% of variance explained. The mean variance shared by the independent canonical statistical variable was 4.42%.

In crop 2, the mean of the shared variance was 12.91% canonical dependent variable and 14.58% independent in the first function. Mn^t and Ca^s were the most relevant in their groups, with 42% and 36% of variance explained, respectively. In the second canonical function, we obtained a mean of shared variance explained from 8.82% for the dependent canonical statistical variable and 12.91 for the independent variable. Since K^t (31%) and S^s (27%) are the most relevant for the shared variance explained.

Evaluating the redundancy index in crop 1, it is observed that 13.27% of the nutrient variance in the leaf tissue was explained by the soil attributes~~,~~ and that 46% of the Mn^t variance can be explained by the soil attributes. This result reinforces the need to control the concentration of Mn in the soil. 3.17% of the variance of the independent canonical statistical variable was explained by the dependent variable.

In the second harvest, we have 7.64% and 5.09% of the nutrient variance explained by the soil attributes in the first and second canonical functions, respectively. The dependent variables explained 12.91% and 7.64% of the independent variables. The redundancy index is similar to the R^2 of ~~a~~ multiple regression, but the canonical analysis works with a group of dependent variables, thus the redundancy index.

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Table 7. Explained shared variance and redundancy index for the canonical functions in the two harvests.

	1		1		1		2		1		2	
	CC²	VCE	CCC²	IR	CC²	VCE	CC²	VCE	CCC²	IR	CCC²	IR
N^t	0.00		0.00		0.02		0.01		0.01		0.00	
P^t	0.13		0.10		0.09		0.02		0.05		0.01	
K^t	0.06		0.04		0.03		0.31		0.02		0.18	
Ca^t	0.01		0.01		0.01		0.29		0.01		0.18	
Mg^t	0.03	18.45	0.02	13.27	0.14	12.91	0.03	8.82	0.08	7.64	0.02	5.09
S^t	0.26		0.18		0.22		0.00		0.13		0.00	
B^t	0.17		0.12		0.00		0.03		0.00		0.01	
Cu^t	0.32		0.24		0.36		0.00		0.21		0.00	
Fe^t	0.38		0.27		0.09		0.18		0.05		0.10	
Mn^t	0.64		0.46		0.42		0.10		0.25		0.06	
Zn^t	0.03		0.02		0.04		0.00		0.03		0.00	
pH	0.00		0.00		0.25		0.04		0.15		0.02	
Ca^s	0.00		0.00		0.36		0.03		0.21		0.02	
Al^s	0.00		0.00		0.10		0.00		0.06		0.00	
K^s	0.17		0.12		0.12		0.14		0.07		0.08	
S^s	0.01		0.01		0.00		0.27		0.00		0.16	
P^s	0.00	4.42	0.00	3.17	0.15	14.58	0.00	12.91	0.09	12.91	0.00	7.64
Prem	0.02		0.01		0.10		0.10		0.06		0.06	
MO	0.10		0.07		0.09		0.18		0.05		0.11	
B^s	0.01		0.01		0.08		0.03		0.05		0.02	
Zn^s	0.00		0.00		0.32		0.01		0.19		0.01	
Cu^s	0.10		0.07		0.12		0.00		0.07		0.00	
Fe^s	0.12		0.09		0.06		0.15		0.03		0.09	
Mn^s	0.67		0.49		0.17		0.19		0.10		0.12	

CC² : Square caonical charge VCE:shared variance explained; CCC²: Square cross canonical charge;

According to authors [6], no generalized orientation was established on the minimum acceptable redundancy index, and in the evaluation of canonical functions, the researcher must judge its theoretical and practical significance in relation to the research carried out. Authors [8] found redundancy rates of 8.68% for the group of dependent variables using the canonical correlation analysis between wood and charcoal characteristics of Eucalyptus. Authors [28] found values of 50% and 26% in two canonical functions when using the canonical correlation to evaluate charcoal characteristics of Qualea parviflora Mart.

In this study, the percentage of variance explained did not present high values, but this is expected due to a~~the~~ large number of variables in each group. However, the interaction between nutrients was evidenced with a theoretical basis to explain the relationship between nutrients.

CONCLUSION

There was a direct relationship between the potassium concentration in the leaf tissue and the potassium in the soil in the two harvests. Other soil attributes such as organic matter, iron, manganese and sulfur also influenced this relationship, showing that soil attributes in the independent group interacted together on nutrients in leaf tissue.

In crop 1 the Mn^t can be considered the most relevant nutrient in the dependent canonical statistical variable. Mn^s was also the most relevant attribute in the independent statistical variable, with 67% of variance explained. In crop 2, in the first canonical function, Mn^t and Ca^s were the most relevant in their groups, with 42% and 36% of variance explained,

respectively. In the second canonical function, the K^t (31%) and the S^s (27%) are the most relevant for the shared variance explained.
The results obtained demonstrate the possibility of using this technique of multivariate analysis to make inferences about the interaction between nutrients in the leaf tissue and soil attributes in Coffea canephora.

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