Australian Journal of Crop Science AJCS
AJCS 9(12):1214-1220 (2015) ISSN:1835-2707

Nutritional components of growth of Arabica coffee genotypes cultivated under different levels of phosphorus fertilization studied by path analysis

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Abstract

The high nutritional exigency of new cultivars of coffee led this study to estimate correlations between nutrient contents and to estimate their direct and indirect effects, by path analysis, over the early growth of eight genotypes of *Coffea arabica* L, cultivated in environments with different levels of phosphorus supply. The experiment was conducted under controlled environment, following an 8×5 factorial scheme, in a completely randomized design, with four replications. The factors studied were eight genotypes of *Coffea arabica* L. and five conditions of availability of phosphorus in the soil: 0.00, 0.18, 0.36, 0.72, and 1.44 grams of P_2O_5 per kilogram of soil. The growth analyses were based on dry matter, leaf area, and chlorophyll content accumulated in 150 days of cultivation. The leaf content of P, K, Ca, Mg, Zn, Cu, Fe, and Mn were used as nutritional components. The correlations were estimated and unfolded between direct and indirect effects through path analysis. Significant correlations were observed between nutritional components, and these correlations are modulated by environmental factors, such as soil type and water supply. Different levels of phosphorus fertilization promotes interactions between P×Mg, K×Ca, Ca×Mg, Ca×Mn, Ca×Zn; Mg×Mn, Cu×Fe, Cu×Mn, and Mg×Zn. Some nutritional components cause strong positive effects over the early growth of genotypes of *Coffea arabic*a L.; highlighting the content of K for accumulation of biomass and development of leaf area, and Fe for chlorophyll synthesis; being possible to be explored in the indirect selection aiming to improve the early growth simultaneously to improvement of nutritional parameters.

Keywords: *Coffea Arabica*; mineral nutrition; chlorophyll; synergy; biomass.
Abbreviations: r_p_Phenotypic correlation; r_g_Genetic correlation.

Introduction

Coffee is one of the most valuable commodities traded worldwide, and its cultivation is greatly important for the social and economic development in Brazil, which is the largest producer and exporter of this product. With a total export of more than 28 million bags from February 2013 to January 2014 (Ico, 2015). Among the species of coffee, Arabica coffee (*Coffea arabica* L.) is the most widely cultivated and contributes to the major proportion of the coffee produced in Brazil (Conab, 2015). The availability of different cultivars provides new options for farmers, being possible to choose highly productive cultivars that also present resistance to different adversities and lower production costs. The genetic variability that is found among genotypes of *Coffea arabica* L. from different breeding programs allows the identification of genotypes that are more suitable for cultivation in different cultivation systems and regions (Rodrigues et al., 2014). The study of correlations between different agronomic traits can be used to determine the viability of simultaneous or indirect selections, allowing the breeding program to evade evaluations that take too long or are too expensive (Fonseca, 1999).

The phenotypic correlation is result of the combination between genetic and environmental factors; therefore, it is important to study the magnitude of genetic correlations, to be able to identify the contribution of genotypic effects to the association between traits. Since coffee is cultivated in a wide range of different agricultural systems and the correlations can be modulated by environmental conditions, it is necessary to study the expression of characteristics in different cultivation systems to better understand the association between useful agronomic traits. The cultivation of coffee in Brazil covers a considerable area and, along its expansion, it started covering new regions that, in many cases, presented low natural soil fertility. This scenario created a dependency of utilizing fertilization to enable the cultivation in tropical soils, where phosphorus (P) constantly limits the growth and production. The source material that originated these soils create a system in which the soil particles have strong interactions with this nutrient, often making it unavailable for the plant absorption (Novais et al., 2007; Oladiran et al., 2012; Martins et al., 2013).

This fact makes phosphorus became a very important target for studies involving nutritional characteristics of coffee genotypes, since the recent cultivars are highly productive but also highly exigent to fertilization with this nutrient.

Studies of correlation between two variables alone normally do not allow inferring about the cause-effect relationship of the association between the evaluated traits. The path analysis can be considered an expansion of the multiple regression analysis, for cases in which multiple and complex interrelationships between variables are involved. This analysis permits to split the correlation coefficient in direct and indirect effects aiming to a better understanding of the association between important traits (Furtado et al., 2002; Cruz and Carneiro, 2003; Amorim et al., 2008). The objective of this study was to estimate phenotypic and genetic correlations between nutrient contents and estimate their direct and indirect effects, by path analysis, over the early growth of eight genotypes of *Coffea arabica* L, cultivated in environments with different levels of phosphorus supply.

Results and Discussion

Correlations between nutrient contents

Significant effects of the sources of variation were observed for all the nutrient contents and growth variables, indicating the existence of variability for the nutritional components and for the growth of the genotypes interacting with the effect of the environments with modified phosphorus supply.

The magnitude of genotypic correlations surpassed the estimated values of phenotypic correlations for P×Ca, P×Mg, P×Zn, P×Cu, P×Fe, P×Mn, K×Ca, K×Mg, K×Zn, Ca×Mg, Ca×Cu, Ca×Fe, Ca×Mn, Mg×Zn, Mg×Fe, Mg×Mn, Zn×Fe, Zn×Mn, Cu×Mn and Fe×Mn in the environment with low phosphorus supply (0.00 g kg^{-1} of P_2O_5). Also for P×K, P×Ca, P×Zn, P×Cu, P×Fe, P×Mn, K×Ca, K×Mg, K×Zn, K×Cu, K×Fe, K×Mn, Ca×Zn, Ca×Cu, Ca×Fe, Ca×Mn, Mg×Zn, Mg×Cu, Mg×Fe, Zn×Fe, Zn×Mn, Cu×Fe, Cu×Mn and Fe×Mn for the environment with addition of 0.18 g kg^{-1} P_2O_5. And for P×K, P×Ca, P×Mg, P×Zn, P×Cu, P×Fe, P×Mn, K×Ca, K×Mg, K×Zn, K×Fe, Ca×Mg, Ca×Zn, Ca×Cu, Ca×Fe, Ca×Mn, Mg×Fe, Mg×Mn, Zn×Cu, Zn×Mn, Cu×Fe, Cu×Mn and Fe×Mn for the environment with fertilization at level of 0.36 g kg^{-1} P_2O_5. The same fact occurred for P×Ca, P×Mg, P×Zn, P×Cu, P×Mn, K×Mg, K×Cu, K×Fe, Ca×Mg, Ca×Zn, Ca×Cu, Ca×Fe, Ca×Mn, Mg×Zn, Mg×Cu, Mg×Fe, Mg×Mn, Zn×Cu, Zn×Fe, Zn×Mn, Cu×Fe, Cu×Mn and Fe×Mn in the environment with addition of 0.72 g kg^{-1} P_2O_5. And for P×K, P×Mg, P×Fe, P×Mn, K×Ca, K×Mg, Ca×Mg, Ca×Zn, Ca×Cu, Ca×Fe, Mg×Zn, Mg×Cu, Mg×Fe, Mg×Mn, Zn×Cu, Zn×Fe, Zn×Mn, Cu×Fe, Cu×Mn and Fe×Mn in the environment with supply of phosphorus at level of 1.44 g kg^{-1} P_2O_5 (Fig. 2). This fact indicates a greater influence of genetic factors for most nutritional components over environmental factors, considering the five distinct environments of this study. Among the correlations considered significant by the t-test, all values were equal to or greater than |0.72|, which indicates the occurrence of strong correlations between these nutritional components (Carvalho et al., 2004). Overall, the nutrient content that showed the highest number of significant correlations with other contents was Ca, correlated with other nutrients (Mg, Mn, and Zn) in nine cases (Fig. 2). The existence of strong positive correlations between nutritional components indicate the possibility of obtaining gains through selection in more than one component simultaneously if breeding programs decide to explore traits such as the nutritional efficiency. The strong correlations also allow the selection based on a smaller set of components, for simpler and less costly evaluations, without compromising the proper representation of these genotypes. Negative correlations became more commonly observed between the content of P and all the others nutrients in environment with higher levels of fertilization with P_2O_5. The fertilization with P often cause antagonist effect to the leaf content of Ca, Fe, Mn, and Zn (Lana et al., 2010). This fact was observed in all environments where the phosphorus fertilization was performed, being noticeable for Ca; and happened in most environments for Fe and Mn; for Zn, for which this behavior was noticed in all environments submitted to fertilizing over 0.36 g kg^{-1} of P_2O_5. Strong and positive correlations were observed between the contents of Ca and Mg for the environments with 0.00 g kg^{-1} of P_2O_5 (r_p=0.90), 0.72 g kg^{-1} of P_2O_5 (r_p=0.87) and 1.44 g kg^{-1} of P_2O_5 (r_p=0.89). Supplying phosphorus in levels higher or lower than the recommendation caused changes in the contents of Ca and Mg, and both conditions (higher or lower supply) modulated the correlation, causing it to become stronger between those nutrients. This is also confirmed by the significance of the coefficients, which only wasn't statistically significant in the environment with supply of 0.36 g kg^{-1} of P_2O_5 (r_p=0.39). Martinez et al. (2001) described significant correlations between these nutrients in leaf tissues of Arabica coffee plants. The positive correlation is associated to the normal levels of supply of both nutrients in the environments of this experiment, as these nutrients present antagonist effect in conditions of high content of Ca, which normally reduce the absorption of Mg (Fränzle, 2010). The content of Ca also correlated to the content of Mn in the environments with low supply of phosphorus (r_p=0.78 with 0.00 g kg^{-1} of P_2O_5 and r_p=0.78 with 0.18 g kg^{-1} of P_2O_5). There is synergy between these nutrients; and the limitation of the absorption of both occurs simultaneously, especially under conditions of high concentration of K; and significant and positive correlations between these nutrients have been reported (Clarkson, 1988; Fränzle, 2010; Lana et al., 2010; Moore, 1972).

The contents of Ca and Zn were positively correlated in the environments with higher levels of fertilization with phosphorus, reaching phenotypic correlations of 0.89, 0.87 and 0.91 with the addition of 0.36, 0.72 and 1.44 g kg^{-1} of P_2O_5, respectively. This fact supports the results described by Martinez et al. (2001) and Lana et al. (2010), who also described significant correlations between these nutrients. The nutritional combination of Ca and Zn, in optimal levels, is benefic to the absorption of others nutrients like P and K (Ranade-Malvi, 2011), this effect may had been favored in the environments with higher fertilization. The nutrients K and Ca presented a negative significant correlation (r_p=-0.73) with the phosphorus fertilization at level of 0.36 g kg^{-1} of P_2O_5. Affecting the functional stability of cell membranes, Ca can promote the accumulation of others nutrients on the plant tissues, which can be noticed by the positive correlation between the content of Ca and others nutrients. However, Ca is also responsible for a competitive inhibition of others nutrients, as observed for P, K, Cu, and Fe in environments

Table 1. Estimative of direct and indirect effects of eight nutritional components in leaves of eight genotypes of Arabica coffee, after 150 days of cultivation with different levels of phosphorus fertilization, over the production of dry matter, development of leaf area and chlorophyll content, obtained by patch analysis, with diagnosis of multicollinearity.

Secondary component	Association	Primary component		
		Dry matter[(1)]	Leaf area[(2)]	Chlorophyll[(3)]
P	Direct effect	0.2180	-0.0451	-0.3025
	Indirect effect through K	0.1950	0.1864	-0.1030
	Indirect effect through Ca	0.0293	0.0357	0.0201
	Indirect effect through Mg	-0.0129	-0.0423	0.0497
	Indirect effect through Zn	-0.0232	-0.0559	-0.0683
	Indirect effect through Cu	-0.1111	-0.1696	0.1262
	Indirect effect through Fe	-0.0131	-0.0125	0.0344
	Indirect effect through Mn	0.0288	0.0587	0.0163
	r_g[(4)]	0.9469	-0.2117	-0.8413
K	Direct effect	0.6166	0.5894	-0.3257
	Indirect effect through P	0.0689	-0.0142	-0.0956
	Indirect effect through Ca	0.1137	0.1385	0.0781
	Indirect effect through Mg	-0.0322	-0.1053	0.1236
	Indirect effect through Zn	-0.0462	-0.1114	-0.1360
	Indirect effect through Cu	0.0564	0.0861	-0.0641
	Indirect effect through Fe	-0.0500	-0.0476	0.1307
	Indirect effect through Mn	-0.0611	-0.1248	-0.0346
	r_g[(4)]	0.9215	0.7891	-0.4526
Ca	Direct effect	-0.1204	-0.1467	-0.0827
	Indirect effect through P	-0.0531	0.0110	0.0737
	Indirect effect through K	-0.5824	-0.5567	0.3076
	Indirect effect through Mg	0.0353	0.1155	-0.1356
	Indirect effect through Zn	0.0506	0.1220	0.1490
	Indirect effect through Cu	-0.0148	-0.0226	0.0168
	Indirect effect through Fe	0.0481	0.0458	-0.1257
	Indirect effect through Mn	0.0647	0.1321	0.0367
	r_g[(4)]	-0.7946	-0.3991	0.4300
Mg	Direct effect	0.0446	0.1459	-0.1712
	Indirect effect through P	-0.0633	0.0131	0.0878
	Indirect effect through K	-0.4450	-0.4254	0.2350
	Indirect effect through Ca	-0.0954	-0.1162	-0.0655
	Indirect effect through Zn	0.0252	0.0608	0.0742
	Indirect effect through Cu	0.0731	0.1116	-0.0831
	Indirect effect through Fe	-0.0142	-0.0136	0.0373
	Indirect effect through Mn	0.0711	0.1451	0.0403
	r_g[(4)]	-0.4773	0.0013	0.3608
Zn	Direct effect	0.0640	0.1542	0.1883
	Indirect effect through P	-0.0790	0.0163	0.1097
	Indirect effect through K	-0.4456	-0.4259	0.2353
	Indirect effect through Ca	-0.0953	-0.1161	-0.0655
	Indirect effect through Mg	0.0176	0.0575	-0.0675
	Indirect effect through Cu	0.0534	0.0816	-0.0607
	Indirect effect through Fe	0.0135	0.0129	-0.0354
	Indirect effect through Mn	0.0184	0.0377	0.0104
	r_g[(4)]	-0.6140	-0.2262	0.5130
Cu	Direct effect	0.3448	0.5265	-0.3919
	Indirect effect through P	-0.0702	0.0145	0.0974
	Indirect effect through K	0.1008	0.0964	-0.0532
	Indirect effect through Ca	0.0051	0.0063	0.0035
	Indirect effect through Mg	0.0094	0.0309	-0.0363
	Indirect effect through Zn	0.0099	0.0239	0.0292
	Indirect effect through Fe	-0.1735	-0.1653	0.4535
	Indirect effect through Mn	-0.0426	-0.0871	-0.0242
	r_g[(4)]	0.3431	0.6779	-0.0585
Fe	Direct effect	0.2519	0.2399	0.6584
	Indirect effect through P	-0.0114	0.0023	-0.0158
	Indirect effect through K	-0.1224	-0.1170	-0.0646
	Indirect effect through Ca	-0.0230	-0.0280	0.0158
	Indirect effect through Mg	-0.0025	-0.0082	-0.0097
	Indirect effect through Zn	0.0034	0.0083	-0.0101
	Indirect effect through Cu	-0.2375	-0.3626	-0.2700
	Indirect effect through Mn	0.0305	0.0624	-0.0173
	r_g[(4)]	0.1961	-0.0820	0.8102
Mn	Direct effect	0.1041	0.2125	0.0590
	Indirect effect through P	0.0602	-0.0124	-0.0836
	Indirect effect through K	-0.3622	-0.3462	0.1913
	Indirect effect through Ca	-0.0748	-0.0912	-0.0514
	Indirect effect through Mg	0.0304	0.0996	-0.1169
	Indirect effect through Zn	0.0113	0.0273	0.0334
	Indirect effect through Cu	-0.1414	-0.2158	0.1607
	Indirect effect through Fe	0.0739	0.0704	-0.1933
	r_g[(4)]	-0.4473	-0.3727	0.1439

[(1)]Total dry matter accumulated by the plant at 150 days of cultivation; [(2)]Total leaf area of the plant at 150 days of cultivation; [(3)]Total chlorophyll content (*a*+*b*) in mature leaves; [(4)]Genetic correlation considering the conjunct analyses.

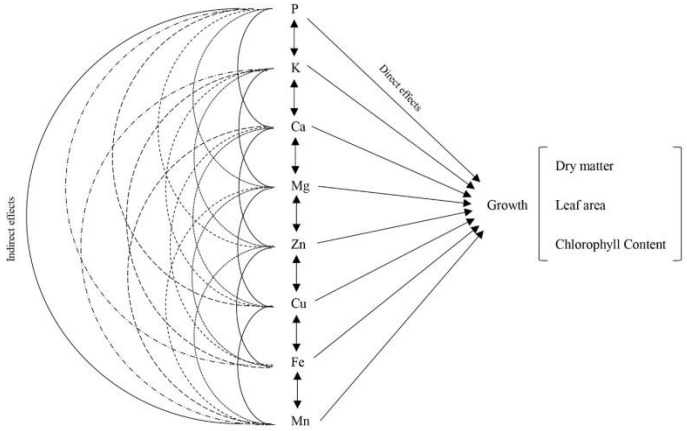

Fig 1. Chain diagram for the interrelationship of the direct and indirect effects for the explicative variables (nutrient contents) and the basic growth variables (dry matter, leaf area and chlorophyll content).

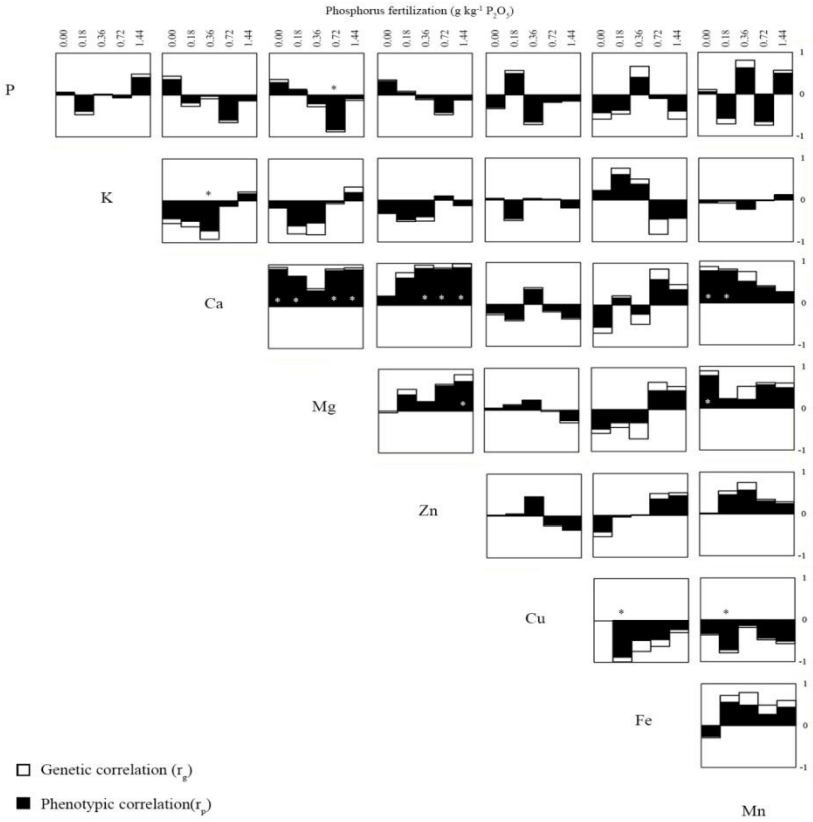

Fig 2. Correlogram of phenotypic (r_p) and genetic (r_g) correlations between eight nutritional components in leaves of eight genotypes of Arabica coffee, after 150 days of cultivation with different levels of phosphorus fertilization (*Significant at 5% of probability by the t-test).

studied in this experiment (Malavolta et al., 1997; Lana et al., 2010). In the environment without supply of phosphorus by fertilization, the correlation between Mg and Mn was positive (r_p=0.79). The presence of Mg have a synergic effect over the absorption of Mn, therefore, depending on the intensity of the interactions between nutrients present in the environment, correlations between the content of these nutrients may occur (Fränzle, 2010). In the environment with 0.18 g kg^{-1} of P_2O_5, the correlations between Cu with Fe and Mn were negative (r_p=-0.89 and r_p=-0.73, respectively). Martinez et al. (2001) also reported negative correlations between those nutrients, but not as strong as noticed here. With the fertilization near the recommended level, this correlation became weaker. In environments with high level of phosphorus, there was positive correlation between Mg and Zn (r_p=0.72 at 1.44 g kg^{-1} of P_2O_5) and negative correlation between P and Mg (r_p=-0.84 at 0.72 g kg^{-1} of P_2O_5). The characteristics of these correlations support the results of Martinez et al. (2001), which can be explained by the synergist and antagonist interactions, respectively, between those nutrients (Fränzle, 2010). The possible effects of increasing levels of fertilization with P_2O_5 include a series of factors. The modulation of growth and nutritional contents can be caused by the interaction of phosphorus with others nutrients in the soil, which can cause competition for absorption sites. A limitation of the translocation rate of nutrients from roots to

the aerial part can also be a result of a higher fertilization. The imbalance between nutrient levels can also change the plant metabolism. In addition, it is possible that the higher growth, promoted by the phosphorus fertilization, causes dilution of the other nutrients in the plant mass (Olsen, 1972).

Direct and indirect effects over growth

The corrections of the distortions were done with the coefficient *k* being equal to 0.25 to obtain the multicollinearity diagnostic. The growth of genotypes of *Coffea arabica* L. can be influenced by several factors and is result of a series of interactions, but the nutritional components were able to explain at least 68% of the accumulation of biomass, development of leaf area and chlorophyll content (lowest value of coefficient of determination obtained in the patch analysis for chlorophyll content). The magnitude of the direct effects of the nutritional components over the growth followed the decreasing order |K|>|Cu|>|Fe|>|P|>|Ca|>|Mn|>|Zn|>|Mg| for accumulation of biomass,|K|>|Cu|>|Fe|>|Mn|>|Zn|>|Ca|>|Mg|>|P| for development of leaf area, and |Fe|>|Cu|>|P| >|K|>|Zn|>|Mg|>|Ca|>|Mn| for chlorophyll content (Table 1).

The content of K caused the highest direct effects over the accumulation of biomass (0.61) and development of leaf area (0.58). Potassium has a role in the activation of starch synthetase, the enzyme responsible for the synthesis of starch. Therefore, the high direct effect of K over the plant growth can be explained by the regulation of this process, as a low level of starch synthesis restricts in its mobility from source to sink, causing accumulation of soluble carbohydrates and nitrogen-based compounds in the sources. Excessive amounts of soluble carbohydrates in leaves cause losses in the leaf resistance, having negative effects over the functionality of the organ (Ranade-Malvi, 2011). In addition, this nutrient also presented the highest indirect effects through P (0.19), Ca (-0.58), Mg (-0.44), Zn (-0.44), and Mn (-0.36) for both growth regarding dry matter and leaf area. The content of K regulates the transport of water and nutrients in the xylem transport system, being responsible to keep the water content in the vacuoles in order to sustain the osmotic concentration required for the transportation of nitrates, phosphates, calcium, magnesium, and amino acids (Taiz and Zeiger, 2013). Potassium is also essential to keep the efficiency of the transport of specific enzymes and plant growth hormones (Ranade-Malvi, 2011). This nutrient also presented highest indirect effect through Ca (0.30), Mg (0.23), Zn (0.23), and Mn (0.19) for the chlorophyll content. The content of Fe presented the highest direct effect (0.65) over the chlorophyll content and the highest indirect effect through Cu (0.45) over this variable. Iron presents an important role in the synthesis of photosynthetic pigments; plants with low Fe uptake normally present a rapid reduction in the content of chlorophylls. Furthermore, this nutrient is responsible to constitute and activate enzymes involved in the carbon fixation, being also a constituent of ferredoxins that are involved in energy transference in several metabolic processes, such as the transport of electrons in the photosynthesis (Malavolta et al., 1997; Epstein and Bloom, 2006; Hänsch and Mendel, 2009). These results indicates that is possible to infer about and explore an indirect selection to improve the growth parameters of genotypes of *Coffea arabica* L. based on nutritional components, allowing breeding programs to seek improvement of nutritional efficiency of the species, simultaneously obtaining gains in the early production of biomass, growth of leaf area and chlorophyll content.

Materials and Methods

Experimental setup

The experiment was conducted in greenhouse, under controlled environment, installed in the municipality of Alegre, Espírito Santo State, located in the southeast region of Brazil (20º45`S, 41º30`W, 136 m of elevation). The average temperature along the experimental period was 24 °C, measured daily inside the greenhouse.

The experiment followed an 8x5 factorial scheme, in a completely randomized design, with four replications. The factors studied were eight genotypes of *Coffea arabica* L. (recommended for cultivation in Brazil) and five environments with modified conditions of availability of phosphorus in the soil (0.00, 0.18, 0.36, 0.72, and 1.44 g kg^{-1} of P_2O_5).

Selection of genotypes

The genotypes of *Coffea arabica* L. used in the experiment were: Catuaí Amarelo IAC 86, Catuaí Vermelho IAC 44, Catuaí Vermelho IAC 81, Catucaí Amarelo 2SL, Catucaí Amarelo 24/137, Catucaí Amarelo F5 Multilínea, Obatã IAC 1669-20, and Topázio MG 1190; originated from breeding programs of different institutions that are world references in the development of cultivars of Arabica coffee.

Soil, fertilization and water management

The soil used as substrate, a dystrophic oxisol of clayey texture (Embrapa, 2006), was collected at a depth of 40 cm, discarding the first 10 cm, in order to reduce the effect of organic matter present in the superficial layer. Chemical and physical analysis of the soil was performed in order to establish the nutrients availability. The analysis determined that the soil presents 552.4 g kg^{-1} of sand, 43.6 g kg^{-1} of silt, 404.0 g kg^{-1} of clay, 1.2 kg dm^{-3} of density, 6.0 of pH, 3.0 mg dm^{-3} of phosphorus, 101.0 mg dm^{-3} of potassium, 2.4 mg dm^{-3} of sodium, 1.7 $cmol_c$ dm^{-3} of calcium, 1.1 $cmol_c$ dm^{-3} of magnesium, 2.1 $cmol_c$ dm^{-3} of potential acidity, 3.1 $cmol_c$ dm^{-3} of sum of exchangeable bases, 3.1 $cmol_c$ dm^{-3} of effective cation exchange capacity, 5.2 $cmol_c$ dm^{-3} of effective cation exchange capacity at pH 7.0, and 59% of base saturation. After the characterization, the soil was dried in shade, homogenized with a 2.0 mm mesh sieve and separated into samples of 10 dm^3. These samples were used to fill plastic pots, of 14 L of capacity, where the seedlings of Arabica coffee were transplanted. The availability of phosphorus in the soil was modulated through the application of solutions of dibasic calcium phosphate (dihydrate) to the levels of 0.00, 0.18, 0.36, 0.72 and 1.44 grams of P_2O_5 per kilogram of soil. The phosphorus fertilization was done at the time of sowing while the others nutrients were added in three parcels, at 15, 25, and 35 days after sowing, following the recommendations for essays in controlled environments (Novais, 1991). Irrigation was performed by keeping the soil moisture near 60% of the total pore volume during the experiment, replenishing the available water daily. The total pore volume was obtained using the particle density and soil density, determined by the test tube method, according to Embrapa (1997). The other cultural practices were performed manually according to the need.

Traits measured

The plants were cultivated for 150 days in the modified environments, for phosphorus supply. At the end of this period, the chlorophyll content of their leaves was determined using a portable chlorophyllometer (ClorofiLOG 1030, Falker), being expressed as total content (chlorophyll *a* + *b*). Afterwards, the plants were collected, the roots washed to remove the soil, and the vegetal compartments were separated. The leaves were evaluated to determine the total leaf area developed by the plants, using a digital integrator (Area meter, Licor 3100, precision: 0.01 cm^2). The vegetal organs were placed in paper bags and dried in a laboratory oven (STF SP-102/2000 CIR), with forced air circulation at temperature of 65 ºC, until constant weight in order to determine the total accumulation of biomass, weighed on analytical balance (precision: 0.0001 g).

After drying, the leaves were triturated in laboratory mill (CIENLAB CE-430, 8 blades, 1,725 rpm, 20 mesh size) to obtain a homogeneous powder. To quantify the nutritional contents, the prepared material were separated in triplicate samples (400 mg of dry matter each), transferred to Taylor tubes (25 x 200 mm) and submitted to stages of nitric-perchloric acid digestion (65% and 70%). The determination of the nutrients were done by atomic absorption spectrophotometry (Spectrophotometer, VARIAN AA-240-FS, Agilent Technologies, USA), following the appropriate standards (Embrapa, 1997). According to the significance and expression of variability by genotypes of Arabica coffee in pre-tests, the leaf content of phosphorus, potassium, calcium, magnesium, zinc, copper, iron, and magnesium were used as nutritional components in the study.

Data analysis

The data were subject to analyses of variance, using the model $Y_{ijk}=\mu+G_i+E_j+GE_{ij}+\varepsilon_{ijk}$, with fixed genotypes, where: Y_{ijk} represents the phenotypic value of the character for the ijk^{th} observation; μ is the general mean; G_i represents the effect of the i^{th} genotype; E_j represents the effect of the j^{th} environment; GE_{ij} represents the effect the interaction between the i^{th} genotype and the j^{th} environment; and ε_{ijk} is the random error. The genetic correlations between the variables were estimated according to the methodology described by Steel and Torrie (1980). The correlations were unfolded between direct and indirect effects over the accumulation of biomass, development of leaf area, and chlorophyll content, through path analysis (Fig. 1), following the methodology described by Cruz and Carneiro (2003). The multicollinearity of the matrix was established based on the diagonal elements of the matrix and the component of residual variance. To reduce the effect of high variances, the system of normal equations was modified by the implementation of a constant *k*, multiplied by the diagonal elements of the matrix (Hoerl and Kennard, 1970). The value of *k* was established following the methodology described by Cruz and Carneiro (2003), using graphics to choose values to which most of the patch analysis coefficients were stabilized (Carvalho et al., 2002). The analyses were done following the recommendations of Cruz (2006), using the statistical software "GENES" (Cruz, 2013).

Conclusions

Significant correlations were observed between nutritional components, and these correlations are modulated by environmental factors, different levels of phosphorus fertilization promotes interactions between P×Mg, K×Ca, Ca×Mg, Ca×Mn, Ca×Zn; Mg×Mn, Cu×Fe, Cu×Mn, and Mg×Zn. Some nutritional components cause strong positive effects over the early growth of genotypes of *Coffea arabica* L.; highlighting the content of K for accumulation of biomass and development of leaf area, and Fe for chlorophyll synthesis; being possible to be explored in the indirect selection aiming to improve the early growth simultaneously to improvement of nutritional parameters.

Acknowledgments

The authors are grateful to Centro de Ciencias Agrárias of the Universidade Federal do Espírito Santo (CCAUFES) for providing access to the necessary facilities and laboratories. Moreover, would like to thank the Fundação de Amparo à Pesquisa do Espírito Santo (FAPES) for awarding postdoctoral scholarships for the first author and financially supporting this research.

References

Amorim EP, Ramos NP, Ungaro MRG, Kiihl TAM (2008) Correlações e análise de trilha em girassol. Bragantia. 67(2):307-316.

Carvalho FIF, Lorencetti C, Benin G (2004) Estimativas e implicações da correlação no melhoramento vegetal. UFPEL, Pelotas. 142p.

Carvalho CGP, Arias CAA, Toledo JFF, Oliveira MF, Vello NA (2002) Correlações e análise de trilha em linhagens de soja semeadas em diferentes épocas. Pesq Agropec Bras. 3(37):311-320.

Clarkson DT (1988) The uptake and translocation of manganese by plant roots. In: Grahan RD, Hannan RJ, Uren NC (1988) Manganese in soil and plants. Kluwer Academic, Dordrecht. p.101-111.

CONAB – Companhia Nacional de Abastecimento. Acompanhamento da safra brasileira de café: safra 2015, primeira estimativa, fevereiro/2015. CONAB, Brasília. 41p.

Cruz CD (2013) GENES: a software package for analysis in experimental statistics and quantitative genetics. Acta Sci Agron. 35(1):271-276.

Cruz CD (2006) Programa GENES: estatística experimental e matrizes. UFV, Viçosa. 285p.

Cruz CD, Carneiro PCS (2003) Modelos biométricos aplicados ao melhoramento genético. UFV, Viçosa. 585p.

EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária (1997) Manual de métodos de análises de solo. 2nd Edn. Ministério da Agricultura e do Abastecimento, Rio de Janeiro. 212p.

Epstein E, Bloom AJ (2006) Nutrição mineral de plantas: princípios e perspectivas. 2nd Edn. Sinauer, Sunderland. 400p.

Fonseca AFA (1999) Análises biométricas em café Conilon (*Coffea canephora* Pierre). Universidade Federal de Viçosa. Viçosa. 1999.

Fränzle S (2010) Chemical elements in plants and soil: parameters controlling essentiality. Springer, Netherlands. 196p.

Furtado MR, Cruz CD, Cardoso AA, Coelho ADF, Peternelli LA (2002) Análise de trilha do rendimento do feijoeiro e seus componentes primários em monocultivo e em consórcio com a cultura do milho. Cienc Rural. 32(1):217-220.

Hänsch R, Mendel RR (2009) Physiological functions of mineral micronutrients (Cu, Zn, Mn, Fe, Ni, Mo, B, Cl). Curr Opin Plant Biol. 12(1):259-266.

Hoerl AE, Kennard RW (1970) Ridge regression: applications to nonorthogonal problems. Technometrics. 12(1):69-82.

ICO – International Coffee Organization (2015) Breakdown of exports of Arabica and Robusta: for countries exporting significant volumes of both types of coffee (January 2015). ICO, London.

Lana RMQ, Oliveira AS, Lana ÂMQ, Faria MV (2010) Levantamento do estado nutricional de plantas de *Coffea arabica* L. pelo DRIS, na região do Alto Paranaíba – Minas Gerais. Rev Bras Ciênc Solo. 34(4):1147-1156.

Malavolta E, Vitti GC, Oliveira AS (1997) Avaliação do estado nutricional de plantas: princípios e aplicações. POTAFOS, Piracicaba. 319p.

Martinez HEP, Souza RB, Abadia JB, Venegas VHA, Sanz M (2001) Diagnose nutricional do cafeeiro por meio da análise de flores. In: 2nd Simpósio de Pesquisa dos Cafés do Brasil, Vitória, 2001. Anais do Simpósio de Pesquisa dos Cafés do Brasil. vol 1. Embrapa Café, Brasília, p.2449-2456.

Martins LD, Tomaz MA, Amaral JFT, Bragança SM, Rodrigues WN, Reis EF (2013) Nutritional efficiency in clones of Conilon coffee for phosphorus. J Agr Sci. 5(1):130-140.

Moore DP (1972) Mechanisms of micronutrient uptake by plants. In: Motverdt JJ, Giordano PM, Lindsay WL. Micronutrients in agriculture. Soil Science Society of America, Madison. p.171-1988.

Novais RF, Neves JCL, Barros NF (1991) Ensaio em ambiente controlado. In: Oliveira AJ, Garrido WE, Araújo JDE, Lourenço S. Métodos de pesquisa em fertilidade do solo. Embrapa/SAE, Brasília. p.189-254.

Novais RF, Smyth TJ, Nunes FN (2007) Fósforo. In: Novais RF, Alvarez VH, Barros NF, Fontes RLF, Cantarutti RB, Neves JCL. Fertilidade do solo. Sociedade Brasileira de Ciência de Solo, Viçosa. p.471-550.

Oladiran O, Olajire F, Robert CA, Nnenna I (2012) Phosphorus response efficiency in cowpea genotypes. J Agr Sci. 4(1):81-90.

Olsen SR (1972) Micronutrients interactions. In: Motverdt JJ, Giordano PM, Lindsay WL. Micronutrients in agriculture. Soil Science Society of America, Madison. p.243-264.

Ranade-Malvi U (2011) Interaction of micronutrients with major nutrients with special reference to potassium. Karnataka J Agr Sci. 24(1):106-109.

Rodrigues WN, Tomaz MA, Amaral JFT, Ferrão MAG, Colodetti TV, Apostolico MA, Christo LF (2014) Biometrical studies on characteristics of plagiotropic branches in *Coffea arabica* L. cultivated with high plant density. Aust J Crop Sci. 8(1):1239-1247.

Steel RGD, Torrie JL (1980) Principles and procedures of statistics. Macgraw-Hill, New York. 418p.

Taiz L, Zeiger E (2013) Fisiologia vegetal. 5th Edn. Artmed, Porto Alegre. 918p.