INITIAL GROWTH OF COFFEE PLANTS (*Coffea arabica* L.) SUBMITTED TO DIFFERENT PHOSPHATE DOSES IN NUTRITIVE SOLUTION

Sylvana Naomi Matsumoto[1], Fábio Martins de Carvalho[2], Anselmo Eloy Silveira Viana[3], Marcelo Ribeiro Malta[4], Luciana Gomes Castro[5]

(Recebido: 27 de fevereiro de 2008; aceito: 5 de maio de 2008)

ABSTRACT: The objective of this study was to evaluate growth alterations and water relations in coffee plants (*Coffea arabica* L.) at the initial stage of development, grown in nutritive solution (hydroponics) and submitted to a wide variation of P doses. The various doses of P applied to the coffee plants similarly affected the growth characteristics evaluated (number of leaves, height, total leaf area, and dry and green mass accumulation), fitting a logarithmic model, with a direct relationship between P doses and growth. The logarithmic model was also fitted to the leaf water potential module, evaluated in the pre-dawn period and at noon. However, the direct relationship between P doses and water potential was only verified for determinations made at noon; the opposite behavior occurred with readings made in the pre-dawn period, since values decreased as P doses increased. Interactions between P and N nutritional status as well as between P and the water status of plants are discussed, with emphasis on the importance of future investigations.

Key words: *Coffea arabica*, mineral nutrition, water relations.

CRESCIMENTO INICIAL DE CAFEEIROS CULTIVADOS EM SOLUÇÃO NUTRITIVA SOB DIFERENTES DOSES DE FÓSFORO

RESUMO: *Objetivou-se neste estudo avaliar as alterações no crescimento e relações hídricas de plantas de cafeeiros (*Coffea arabica *L.) na fase inicial de desenvolvimento, cultivadas em solução nutritiva e submetidas a uma ampla faixa de variação de doses de P. As características de crescimento avaliadas (número de folhas, altura, área foliar total e acúmulo de massa seca e fresca) foram afetadas de modo semelhante, em função das doses de P aplicadas, sendo definido o modelo logarítmico, com relação direta entre as doses de P e crescimento. O modelo logarítmico também foi delineado para o módulo de potencial hídrico foliar, avaliado no período antemanhã e ao meio-dia. Entretanto, a relação direta entre doses de P e o potencial hídrico foi verificada apenas para as determinações realizadas ao meio-dia; para as leituras realizadas no período antemanhã, ocorreu um comportamento inverso, sendo verificada redução de valores com aumento das doses de P.Interações entre status nutricional relativo a P e N, assim como relações com o status hídrico das plantas, foram discutidas, sendo ressaltada a importância de futuras investigações.*

Palavras-chave: Coffea arabica *, nutrição mineral, relações hídricas.*

1 INTRODUCTION

In a time when the sustainability of systems is in the spotlight, being constantly questioned, production system inputs should have their efficiency maximized, in order to maintain the environmental and economic stability of agricultural crops. In today's agriculture, the balance between cost and benefit of management practices related to fertilizations and irrigation systems are also under new concepts, mainly determined by the high economic and environmental cost of those practices. According to Runge-Metzger

[1]Agronomist, Ph.D., full professor at Universidade Estadual do Sudoeste da Bahia – Laboratório de Fisiologia Vegetal – Departamento de Fitotecnia e Zootecnia – Estrada do Bem Querer, km 04 – Cx. P. 95 – 45000-000 – Vitória da Conquista, Bahia – Brazil – snaomi@uesb.br,
[2]Agronomist, M.Sc., student in the Graduate Program at Universidade Federal de Lavras – Cx. P. 176 – 37200-000 – Lavras, Minas Gerais – Brazil,
[3]Agronomist, Ph.D., full professor at Universidade Estadual do Sudoeste da Bahia, Laboratório de Produção e Melhoramento Vegetal – Departamento de Fitotecnia e Zootecnia – Estrada do Bem Querer, km 04 – Cx. P. 95 – 45000-000 – Vitória da Conquista, Bahia – Brazil – aviana@uesb.br
[4]Agronomist, Ph.D., researcher at Empresa de Pesquisa Agropecuária de Minas Gerais – CTSM – Laboratório de Qualidade do Café – Cx. P. 176 – 37200-000 – Lavras, Minas Gerais – Brazil – marcelomalta@epamig.br
[5]Agronomist, Ph.D., full professor at Universidade Estadual do Sudoeste da Bahia – Departamento de Engenharia Agrícola e Solos – Laboratório de Física do Solo – Estrada do Bem Querer, km 04 – Cx. P. 95 – 45000-000 – Vitória da Conquista, Bahia – Brazil – lucastro@uesb.br

(1995), the exploitation of inorganic phosphate sources such as phosphate rocks deserves pondering, since deposits are expected to be depleted within a period from 50 to 80 years.

The intense weathering that occurred during the genesis of Brazilian soils results in increased retention of phosphates, decreasing their availability to plants (NOVAIS & SMYTH, 1999). Technological innovations involving fertilizations with high doses of P have been prescribed as a form of increasing the acquisition of this element by coffee plants, under the argument of reaching higher productivity and quality indices. In a study conducted by Melo et al. (2005) in Acaiá coffee grown on a Typic Hapludox, it was observed that the application of phosphate sources with high solubility resulted in higher productivity when applied at doses higher than 2.5 tons ha^{-1}. However, the limits of the optimal concentration range should be taken into consideration, since high P availability may result in negative interactions with other nutrients. Studies on the interactions between P and N, P and Fe, and between P and Zn were described previously by several authors (GROOT et al., 2003; MARROCOS et al., 2003; REIS JÚNIOR & MARTINEZ, 2002). Although a lower requirement of P in relation to N and K for the development of plagiotropic branches and nodes containing buds per cv. Rubi MG1192 coffee plant was reported by Nazareno et al. (2003), the indirect effects of P contents on the plant water relations must be taken into consideration. In high-elevation regions, characterized by intense transpiration and acid Oxisols, knowledge about P nutrition aspects and its interactions with plant water relations in the soil-plant-atmosphere system is indispensable.

The environmental impact of this relation is another aspect to be addressed when the application of high doses of P to crops is recommended. Such practice may result in pollution of local water streams due to the eutrophication process described by Bennett et al. (2001).

Although many studies have been recorded in the literature on the interaction between water relations and the nutritional status of several plant species, in Brazil the knowledge acquired about such interaction is still incipient. Because of the inherent particularities of biotic and abiotic factors, addressing this subject is a pressing matter, either by means of basic studies (on physiological phenomena) or applied ones (involving fertilization doses, application methods, and sources), especially in relation to P, due to the non-renewable nature of phosphate fertilizers. The knowledge about processes relating to P absorption and assimilation by plants needs to be improved and validated so that management practices will result in greater fertilization efficiency when using P sources.

The objective of this study was to evaluate growth alterations and water relations in coffee plants (*Coffea arabica* L.) at the initial stage of development, when submitted to a wide variation of P doses.

2 MATERIAL AND METHODS

The assay was carried out in the agricultural/livestock field of Universidade Estadual do Sudoeste da Bahia, Campus de Vitória da Conquista, located at 870 m of altitude, 14°53' south latitude, and 40°48' west longitude, during the period from March to June 2005. The mean annual rainfall index is 733.9 mm, concentrated in the months from November to March. The mean maximum and minimum temperatures were 25.3 and 16.1°C, respectively. In the greenhouse, cv. Catuaí Vermelho (IAC 144) coffee plantlets obtained from a commercial nursery, with three pairs of leaves, were transplanted to containers containing 2,7l of nutritive solution (CLARK, 1975) (composition described in Table 1), with modifications that determined differentiated doses of phosphorus (P): 0mM, 0,01mM, 0,1mM, and 1mM, using sodium phosphate as a source of the element. pH measurements and adjustments were made daily, and varied between 5.0 and 6.0. The solution was renewed weekly until 30 days after installation of the experiment, and twice a week after that period.

Plant growth characteristics were evaluated 90 days after the study was implemented, including height, number of leaves, main root length, total leaf area (measurement of all leaves in the plot, using a leaf area integrator - model LI-3100, LI-COR, Nebraska, USA), and green and dry mass of roots and above-ground part (determined after drying in a forced air circulation oven at 65°C until constant weight was reached). The SPAD index was determined with a portable chlorophyll meter (Spad, Minolta, Japan), and leaf water potential was obtained by means of a pressure chamber (PMS1000, PMS,

Table 1 – Nutrients and their respective concentrations in the nutritive solution used in initial cultivation of coffee plants. Vitória da Conquista – BA, 2005.

Macronutrients	Concentrations (mM)	Micronutrients	Concentrations (μM)
$N\text{-}NO_3^-$	5.8	B	19
$N\text{-}NH_4^+$	1.0	Cu	0.5
K^+	2.4	Fe	40
Ca^{++}	1.2	Mn	07
Mg^{++}	0.6	Mo	0.086
$S\text{-}SO_4^{--}$	0.6	Zn	2.0

Note: $P\text{-}H_2PO_4^-$ and Na^+ had differentiated concentrations according to the treatments.

England), with a maximum supporting capacity of 75 bars, in the pre-dawn and noon periods.

A random block design was adopted, with four treatments and five replicates; the usable plot consisted of two pots, containing one plant per pot. The data were submitted to analysis of variance and the Pearson's correlation analyses were applied to independent parameters, using *Programa para Análises Estatísticas e Genéticas* (Program for Statistical and Genetic Analyses - SAEG, version 9.0).

3 RESULTS AND DISCUSSION

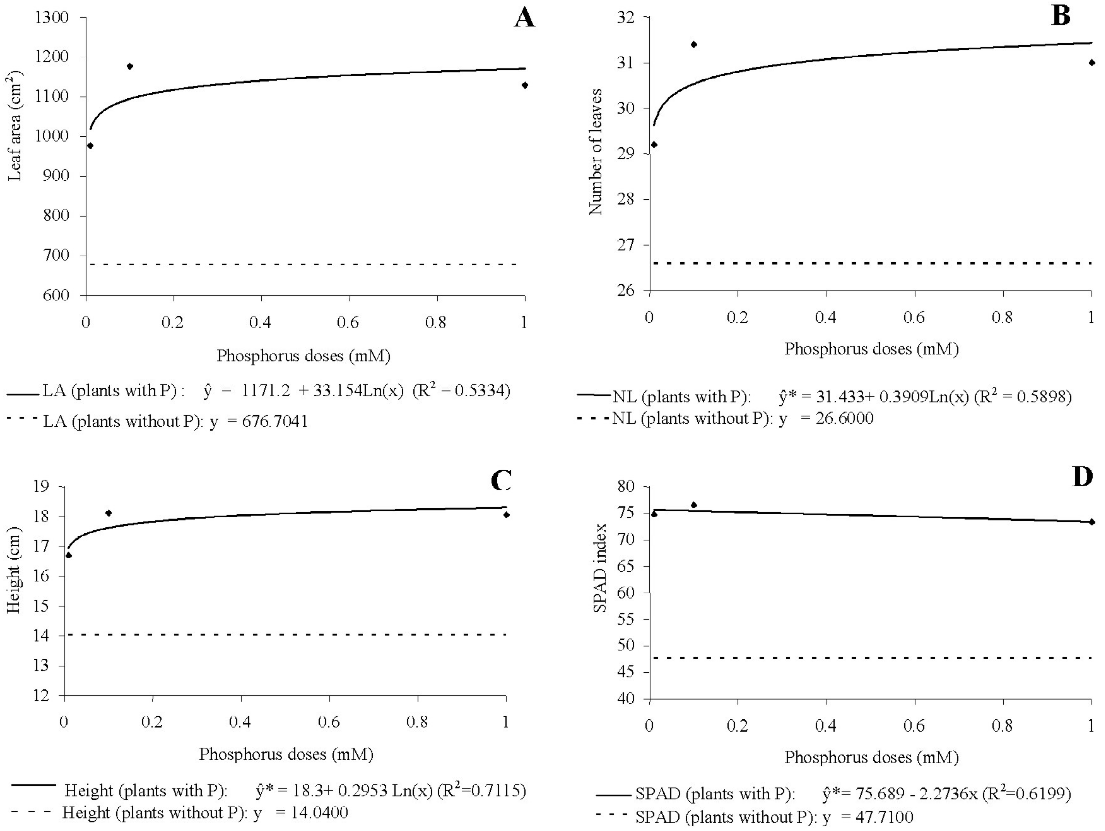
A similar behavior was observed for leaf area, number of leaves, and plant height in relation to P doses; the increasing doses of P induced alterations represented by a logarithmic model (Figure 1A, 1B, 1C). When the plants were submitted to P deprivation, the values for the parameters mentioned above were lower than in plants supplied with P.

The relationship between unavailable P and leaf area reduction was previously defined in studies on cotton plants conducted by Radin & Boyer (1982), Radin & Eidenbock (1984), and Radin & Mathews (1989). These authors demonstrated that reduced hydraulic conductivity in the xylem decreases water availability, restricting the cell elongation capacity of the above-ground part of plants.

As to the Spad index, a negative linear regression model was defined, with values between 75.69 and 73.4 when the phosphorus levels ranged between 0.01 and 1mM (Figure 1D). Moorby et al. (1988), in studies about young rape plants verified that the optimum concentration of phosphate in the leaves for activity of nitrate reductase was about 0.7 dag kg^{-1}. Both high and low concentrations of phosphate within the leaves inhibited activity of nitrate reductase in those leaves. The effect of the interaction between P and Fe could be related to such decreases in chlorophyll contents. Sahu et al. (1988) studied *Pisum sativum* L. plants and observed that high concentrations of P and Cu in the leaves would interfere with Fe transport, making this element unavailable for chlorophyll synthesis.

In the evaluation between the lack and presence of P, a high differential was observed between both conditions, with an observed value of 47.71 for plants maintained without P. The relationship between Spad indices and leaf N contents in coffee plants has been dealt with in many studies (GONÇALVES, 2007; REIS et al., 2006). It was suggested that smaller Spad indices were induced by a lack of P. In studies on the interaction between N and P in tomato plants, Groot et al. (2003) observed that leaf N contents decreased as a result of limited P availability. The main factor mediating that interaction was a decrease in cytokinin levels, with the reduction in free available energy being considered a secondary effect. Because of reduced levels of cytokinins, reductions were also observed in the activity of the nitrate reductase enzyme (JACOB & LAWLOR, 1991), protein synthesis, and N assimilation in the above-ground part of plants (SIMPSON et al., 1982).

Because growth is affected by changes in the levels of cytokinins, reductions in the levels of this hormone in the tissues result in cell expansion inhibition in the leaves, due to its effects on wall distension, reducing growth of the above-ground part

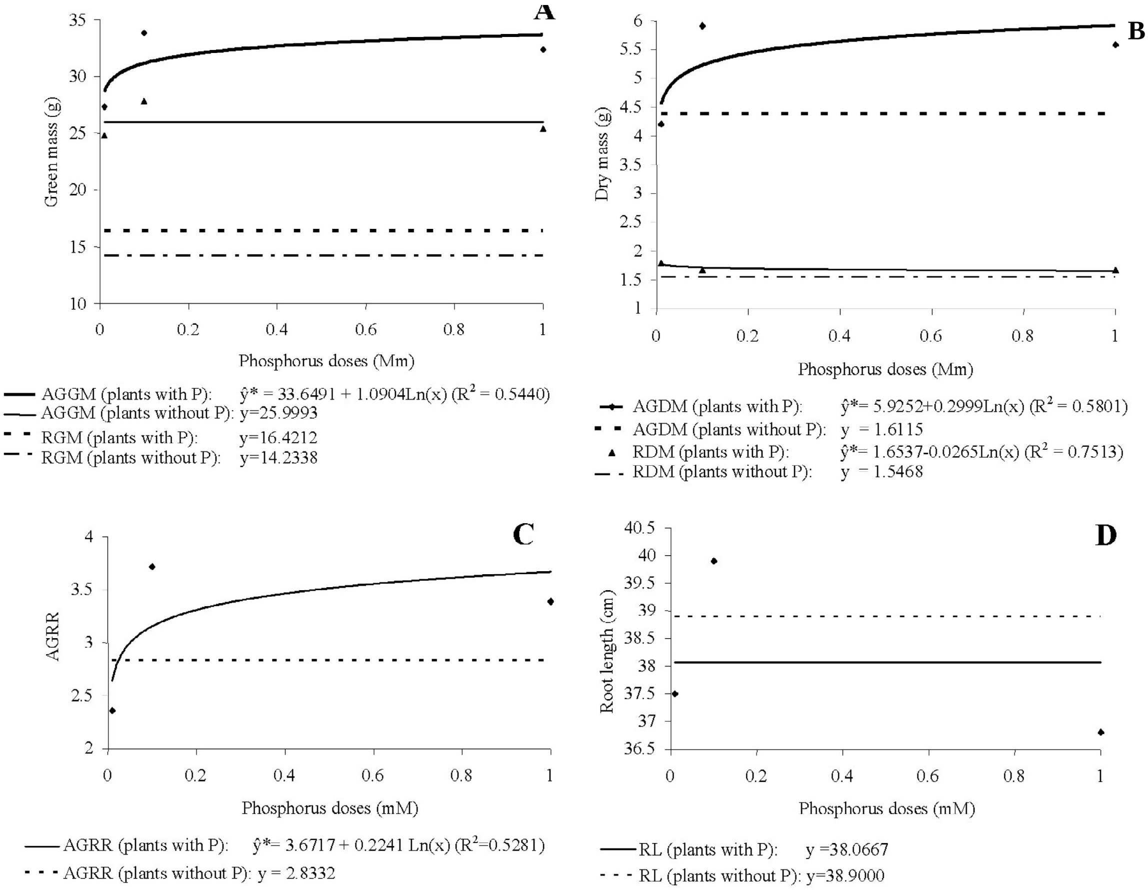


*Significant at 5% by the analysis of variance for the regression.

Figure 1 – Leaf area (A), number of leaves (B), height (C) and Spad index (D) of coffee plants, grown in nutritive solution at the initial stage of development, as a function of phosphorus doses. Vitória da Conquista, BA. 2005.

(RAYLE et al., 1982). Low cytokinin levels were also related to decreases in the assimilation of N in leaf proteins, resulting in more intense transport of amino acids from the above-ground part toward the root system and a reduction in the transport of N from the roots into the above-ground part of plants (JESCHKE et al., 1997). Consequently, N accumulation in the roots would result in N absorption inhibition, reducing its concentration in the plant (RUFTY JUNIOR et al., 1990).Therefore, in the present study, the decline of Spad index was not be accompanied by a reduction of shoot growth as observed in Figure 1, contesting the observed results by the authors previously cited.

The relationship between P doses and green and dry mass of the above-ground part was similar, and a logarithmic model was fitted for the plants submitted to the various doses of P (Figure 2A and 2 B). In plants under lack of P, all mass values remained lower than in plants that received different doses of this nutrient. Although we could not adjust a model for root green mass, the dry mass values fitted the logarithmic model, with smaller values as P doses increased. However, within the interval of observed values, root dry mass remained higher than in P-deprived plants. The ratio between dry mass of the above-ground part and dry mass of the root system (AGRR) in plants submitted to 0.01mM P was lower when compared with P-deprived plants (Figure 2C). Under greater availability of this element, the AGRR values in the plants increased, and superior values were only reached when doses above 0.0234mM P were supplied. Beyond that limit, superior AGRR values were maintained for the increasing doses of P applied to the coffee plants.



*Significant at 5% by the analysis of variance for the regression.

Figure 2 – Green (A) and dry mass (B) of the above-ground part (AGGM, AGDM) and root (RGM, RDM), ratio between dry mass of the above-ground part: dry mass of root (AGRR) (C), and root length (RL) (D) of coffee plants, grown in nutritive solution at the initial stage of development, as a function of phosphorus doses. Vitória da Conquista, BA. 2005.

According to Hammond et al. (2004), the events related to P deficiency begin by a rapid and generalized initial response of genes associated with stresses. As the nutrient remains unavailable, morphological alterations take place, followed by metabolic changes, finally interfering with physiological mechanisms. The morphological alterations are caused by hormonal modifications that result in a reduction of the ratio between mass allocation in the above-ground part and the root, proliferation of the number of root hairs, and greater formation of side roots. Nielsen et al. (2001) observed a change in the plant's capacity to direct and accumulate photoassimilates in the root system. In P-assimilation-effective bean genotypes (*Phaseolus vulgaris* L.), the authors verified that biomass accumulation in the roots of plants submitted to low levels of P (10 µM) was caused by lower respiration rates in those organs.

No one model could not be fitted to length of primary roots in plants submitted to treatments involving P in relation to plants under a suppression of this element (Figure 2D). According to Lacerda et al. (2006), in studies about salinity-phosphorus interaction in forage sorghum, the growth of roots in dry mass was inhibited in higher doses of phosphorus. The authors supposed that it could be an adjustment between size of organ responsible for absorption and the availability of the nutrient in the growth medium.

According to Pozza et al. (2002) in early stages of development the coffee seedlings have a limited root system resulting in a low efficiency of P absorption. The P disponibility is reduced by Fe, Ca and Al fixation, reducing P diffusion to the roots.

However, this is a question that involves not only mass or nutrient alteration, but a series of modification in architecture and form of roots controlled by hormones. According to Lopez-Búcio et al. (2005) and Williamson et al. (2001), effects such as a dramatic reduction in primary root growth, as well as modifications in the formation of side roots are frequent in P deficiency situations. Hormonal alterations associated with auxins, ethylene, and cytokinins, and interactions with sugars have been described as important causes related to this root system architecture change in plants under P deficiency (AL-GHAZI et al., 2003; FRANCO-ZORRILLA et al., 2005; LÓPEZ-BUCIO et al., 2005; NACRY et al., 2005). Jani et al. (2007) observed that wild *Arabdopsis* plants (non-mutant) submitted to P deprivation and supplied with sucrose had a reduced main root development, but a greater number and length of side roots was observed in relation to plants maintained without sucrose.

Root system architecture also seems to be modified by P availability. In studies on the fate of nutrients in montane tropical forests it was observed that fine root biomass or fine root length density was inversely related to doses of P and Ca in the soil (OSTERTAG, 2001). Those observations corroborate the hypothesis of Hertel et al. (2003), according to which a high root biomass would be attributed to low availability of nutrients. Therefore, studies on P availability and its relation with transport of photoassimilates and formation in coffee plants should be conducted.

In the coffee plants analyzed, it was observed that the leaf water potential evaluated in the pre-dawn period had a differentiated behavior relative to determinations made at noon (Figure 3A and 3B). This relation was corroborated by the negative correlation observed between both characteristics evaluated (Table 2).

The smallest $Ø_w$ values in module observed in the pre-dawn period (period in the absence of light) were negatively correlated with all growth parameters, and were significant for height, root length, and number of leaves (Table 2). In determinations performed at noon, when tension forces became more intense, $Ø_w$ reached a higher index, characterizing a lack of water availability for cell elongation. Under such condition, water flow velocity defeated water availability for growth-related phenomena. Significant positive correlations were observed between $Ø_w$ at noon and height, number of leaves, leaf area, and ratio between dry mass of the above-ground part and root dry mass (Table 2). Therefore, although the lowest $Ø_w$ values in module occurred in readings made at noon for the P deprivation treatment and for restrictive P doses supplied to plants, higher growth parameter values were associated with plants submitted to higher doses of P.

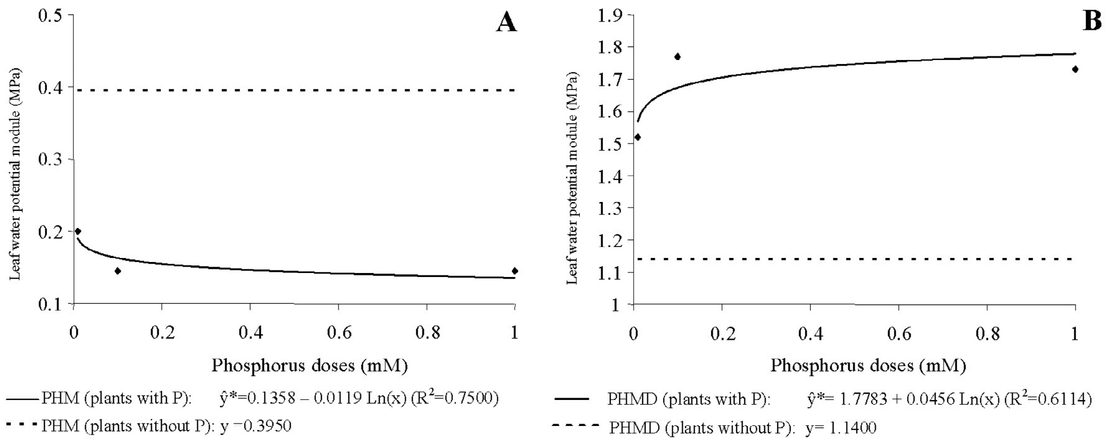
Lovelock et al. (2006) verified that limited P availability in *Avicennia germinans* (L.) L. plants induced water absorption restriction and caused alterations in specific physiological functions and mechanisms under a P resupplying condition. Radin & Eidenbock (1984) verified that the lack of P availability to cotton plants resulted in reduced hydraulic conductivity in the root system. Singh & Sale (2000) related this effect to a reduction in diameter of xylem elements, observed in white clover roots (*Trifolium repens* L.). This effect affected leaf blade growth, restricting cell expansion. In that study, it was observed that leaf growth rates during the day were more sensitive to P availability variations than those determined in the night period.

During the pre-dawn period in the present study, at which time the stomata remain closed and root pressure only occurs in the xylem's vessel elements, the magnitude of $Ø_w$ values was much lower than in the readings made at noon. Transpiration at noon is intense as a result of stomatal opening, and water ascends mainly due to the transpiration stream. Therefore, water is more available for cell elongation mainly during the period in which there is no light. In a study involving sunflower (*Helianthus annuus* L.) by Tanner & Beevers (2001), it was demonstrated that root pressure and pressure flow were mechanisms as effective as transpiration in the long-distance transport of nutrients. Therefore, the occurrence of interaction between P and N was demonstrated to be possible in this study and should be evaluated in coffee plants during the period without light, since plant growth processes as well as N metabolism were intensified.

Table 2 – Correlation values between LWPD (leaf water potential at pre-dawn), LWPN (leaf water potential at noon), HGHT (height), NL (number of leaves), RL (root length), RTGM (root green mass), AGGM (above-ground green mass), SPAD, LA (leaf area), AGDM (above-ground dry mass), RTDM (root dry mass), and AGRR (ratio between dry mass of the above-ground part and root dry mass) evaluated in coffee plants (*Coffea arabica*) submitted to different phosphate doses in nutritive solution.

	LWPN	HGHT	NL	RL	RTGM	AGGM	SPAD	LA	AGDM	RTDM	AGRR
LWPD	-0.603**	-0.4715*	-0.4254*	-0.5275*	-0.3721	-0.3443	0.0393	-0.4096	-0.2117	-0.0554	-0.1012
PHMD		0.4446*	0.5268*	0.0665	-0.0958	0.3327	-0.0098	0.4541*	0.7660**	-0.2085	0.5929**
HGHT			0.6861**	-0.0030	0.0014	0.7401**	-0.1015	0.5060**	0.3390	0.1079	0.1845
NL				0.3647	0.3598	0.8888**	0.3864	0.6464**	0.4479*	0.0746	0.2541
RL					0.5362*	0.2184	0.2055	0.4536*	-0.0103	-0.2847	0.2198
RTGM						0.3801	0.5011*	0.1657	-0.3205	-0.0101	-0.2129
AGGM							0.2649	0.7896**	0.2759	-0.0807	0.2762
SPAD								0.0759	0.0933	0.1071	0.0387
LA									0.4031	-0.2925	0.4942*
AGDM										-0.1377	0.7062**
RTDM											-0.7764**

**, * Significant at 1% and 5%, respectively, by Pearson's correlation analysis.



*Significant at 5% by the analysis of variance for the regression.

Figure 3 – Leaf water potential module at pre-dawn (PHM) (A) and leaf water potential module determined at 1200 hours (PHMD) (B), as a function of the presence or lack of phosphorus in coffee plants (*Coffea arabica*) grown in nutritive solution at the initial stage of development. Vitória da Conquista, BA. 2005.

4 REFERENCES

AL-GHAZI, Y.; MULLER, B.; PINLOCHE, S.; TRANBARGER, T. J.; NACRY, P.; ROSSIGNOL, M.; TARDIEU, F.; DOUMAS, P. Temporal responses of Arabidopsis root differential effects of suc and auxin in Pi starvation architecture to phosphate starvation: evidence for the involvement of auxin signaling. **Plant Cell and Environment**, Oxford, v. 26, p. 1053-1066, 2003.

BENNETT, E. M. M.; CARPENTER, S. R. M.; CARACO, N. F. Human impact on erodable phosphorus and eutrophication: a global perspective. **Bioscience**, Washington, v. 51, n. 3, p. 227, 2001.

CLARK, R. B. Characterization of phosphatase of intact maize roots. **Journal of Agricultural and Food Chemistry**, Easton, v. 23, p. 458-460, 1975.

FRANCO-ZORRILLA, J. M.; MARTÝN, A. C.; LEYVA, A.; PAZ-ARES, J. Interaction between phosphate starvation, sugar, and cytokinin signaling in Arabidopsis and the roles of cytokinin receptors CRE1/AHK4 and AHK3. **Plant Physiology**, Washington, v. 138, p. 847-857, 2005.

GONÇALVES, J. C. **Cultivo em campo de *Coffea arabica* L. cv. Obatã a pleno sol x sombreamento**: avaliações bioquímicas fisiológicas e nutricionais. 2007. 116 f. Tese (Doutorado em Ciências - Fisiologia e Bioquímica de Plantas) – Escola Superior de Agricultura de Luiz de Queiroz, Piracicaba, 2007.

GROOT, C. C.; MARCELIS, L. F. M.; BOOGARD, R. van deer; KAISER, W. M.; LAMBERS, H. Interaction of nitrogen and phosphorus nutrition in determining growth. **Plant and Soil**, The Hague, v. 248, p. 257-268, 2003.

HAMMOND, J. P.; BROADLEY, M. R.; WHITE, P. J. Genetic responses to phosphorus deficiency. **Annals of Botany**, London, v. 94, p. 323-332, 2004.

HERTEL, D.; LEUSCHNER, C.; HOLSCHER, D. Size and structure of fine root systems in old-growth and secondary tropical montane forests (Costa Rica). **Biotropica**, v. 35, p. 143-153, 2003.

JACOB, J.; LAWLOR, D. W. Dependence of photosynthesis of sunflower and maize leaves on phosphate supply, ribulose-1, 5-biphosphate carboxylase/ oxygenase activity, and ribulose-1, 5-bisphosphate pool size. **Plant Physiology**, Washington, v. 98, p. 801-807, 1991.

JANI, A.; POLING, M. D.; KARTHIKEYAN, A. S.; BLAKESLEE, J. J.; PEER, W. A. M.; TITAPIWATANAKUN, B.; MURPHY, A. S.; RAGHOTHAMA, K. G. Differential Effects of sucrose and auxin on localized phosphate deficiency-induced modulation of different traits of root system architecture in Arabidopsis. **Plant Physiology**, Washington, v. 144, p. 232-247, 2007.

JESCHKE, W. D.; KIRKBY, E. A.; PEUKE, A. D.; PATE, J. S.; HARTUNG, W. Effects of P deficiency on assimilation and transport of nitrate and phosphate in intact plants of castor bean (*Ricinus communis* L.). **Experimental Botany**, Oxford, v. 48, p. 75-91, 1997.

LACERDA, C. F.; MORAIS, H. M. M.; PRISCO, J. T.; GOMES FILHO, E.; BEZERRA, M. A. Interação entre salinidade e fósforo em plantas de sorgo forrageiro. **Revista Ciência Agronômica**, Fortaleza, v. 37, n. 2, p. 258-263, 2006.

LOPEZ-BUCIO, J.; HERNANDEZ-ABREU, E.; SANCHEZ-CALDERON, L.; PEREZ-TORRES, A.; RAMPEY, R. A.; BARTEL, B.; HERRERA-ESTRELLA, L. An auxin transport independent pathway is involved in phosphate stress-induced root architectural alterations in Arabidopsis: identification of BIG as a mediator of auxin in pericycle cell activation. **Plant Physiology**, Washington, v. 137, p. 681-691, 2005.

LOVELOCK, C. E.; BALL, M. C.; CHOAT, B.; ENGELBRECHT, B. M. J.; HOLBROOK, M. N.; FELLER, I. C. Linking physiological processes with mangrove forest structure: phosphorus deficiency limits canopy development, hydraulic conductivity and photosynthetic carbon gain in dwarf *Rhizophora mangl*. **Plant, Cell and Environment**, Oxford, v. 29, p. 793-802, 2006.

MARROCOS, P. C.; MATINEZ, H. E. P.; VENEGAS, V. H. A.; BRUCKNER, C. H. M.; CANTARUTTI, R. B. Interação P x Fe em mudas de macadâmia. **Revista Brasileira de Fruticultura**, Brasília, v. 25, n. 2, p. 323-325, 2003.

MELO, B.; MARCUZZO, K. V.; TEODORO, R. E. F.; CARVALHO, H. P. Fontes e doses de fósforo no desenvolvimento e produção do cafeeiro em um solo originalmente sob vegetação de cerrado de Patrocínio, MG. **Ciência e Agrotecnologia**, Lavras, v. 29, n. 2, p. 315-321, 2005.

MOORBY, H.; NYE, P. H.; WHITE, R. E. The effect of phosphate nutrition of young rape plants on nitrate reductase activity and xylem exudation, and their relation to H ion efflux from the roots. **Plant and Soil**, The Hague, v. 105, n. 2, p. 257-263, 1988.

NACRY, P.; CANIVENC, G.; MULLER, B.; AZMI, A.; ONCKELEN, H. V.; ROSSIGNOL, M.; DOUMAS, P. A role for auxin redistribution in the response of the root system architecture to phosphate starvation in Arabidopsis. **Plant Physiology**, Washington, v. 138, p. 2061-2074, 2005.

NAZARENO, R. B.; OLIVEIRA, C. A. S.; SANZONOWICZ, C.; SAMPAIO, J. B. R.; SILVA, J. C. P.; GUERRA, A. F. Crescimento inicial do cafeeiro Rubi em resposta a doses de nitrogênio, fósforo e potássio e a regimes hídricos. **Pesquisa Agropecuária Brasileira**, Brasília, v. 38, n. 8, p. 903-910, 2003.

NIELSEN, K. L.; ESHEL, A.; LYNCH, J. P. The effect of phosphorus availability on the carbon economy of contrasting common bean (*Phaseolus vulgaris* L.) genotypes. **Journal of Experimental Botany**, Oxford, v. 52, n. 355, p. 329-339, 2001.

NOVAIS, R. F.; SMYTH, T. J. **Fósforo em solo e planta em condições tropicais**. Viçosa: UFV, 1999. 399 p.

OSTERTAG, R. Effects of nitrogen and phosphorus availability on fine-root dynamics in hawaiian montane forests. **Ecology**, Durham, v. 82, n. 2, p. 485-499, 2001.

POZZA, A. A. A.; GUIMARÃES, P. T. G.; ROMANIELLO, M. M.; POZZA, E. A.; CARVALHO, J. G. Suprimento de fósforo na produção e intensidade de cercosporiose de mudas de cafeeiro em tubetes. **Ciência e Agrotecnologia**, Lavras, v. 26, n. 5, p. 970-976, 2002.

RADIN, J. W.; BOYER, J. S. Control of leaf expansion by nitrogen nutrition in sunflower plants. Role of hydraulic conductivity and turgor. **Plant Physiology**, Washington, v. 69, p. 771-775, 1982.

RADIN, J. W.; EIDENBOCK, M. P. Hydraulic conductance as a factor limiting leaf expansion of phosphorus-deficient cotton plants. **Plant Physiology**, Washington, v. 75, p. 372-377, 1984.

RADIN, J. W.; MATTHEWS, M. A. Water transport properties of cortical cells in roots of nitrogen and phosphorus deficient cotton seedlings. **Plant Physiology**, Washington, v. 89, p. 264-268, 1989.

RAYLE, L.; ROSS, C. W.; ROBINSON, N. estimation of osmotic parameters accompanying zeatin-induced growth of detached cucumber cotyledons. **Plant Physiology**, Washington, v. 70, p. 1634-1636, 1982.

REIS, A. R.; FURLANI JUNIOR, E. F.; BUZETTI, S.; ANDREOTTI, M. Diagnóstico da exigência do cafeeiro em nitrogênio pelo uso de um clorofilômetro portátil. **Bragantia**, Campinas, v. 65, n. 1, p. 163-171, 2006.

REIS JÚNIOR, R. A.; MARTINEZ, H. E. P. Adição de Zn e absorção, translocação e utilização de Zn por cultivares de cafeeiro. **Scientia Agricola**, Piracicaba, v. 59, n. 3, p. 537-542, 2002.

RUFTY JUNIOR; MacKOWN, C. T.; ISRAEL, D. W. Phosphorus stress effects on assimilation of nitrate. **Plant Physiology**, Washington, v. 94, p. 328-333, 1990.

RUNGE-METZGER, A. Closing the cycle: obstacles to efficient P management for improved global security. In: TIESSEN, H. (Ed.). **Phosphorus in the global environment**: transfers, cycles, and management. New York: J. Wiley and Sons, 1995. p. 27-42.

SAHU, M. P.; SHARMA, D. D.; JAIN, G. L. Phosphorus-copper interactions in the incidence of chlorosis in garden peas (*Pisum sativum* L.) on calcareous soil. **Plant and Soil**, The Hague, v. 108, n. 2, p. 291-293, 1988.

SIMPSON, R. J.; LAMBERS, H. M.; DALLING, M. J. Kinetin application to roots and its effect on uptake, translocation and distribution of nitrogen in wheat (*Triticum aestivum*) grown with a split root system. **Physiologia Plantarum**, Copenhagen, v. 56, p. 430-435, 1982.

SINGH, D. K.; SALE, P. W. Growth and potential conductivity of white clover roots in dry soil with increasing phosphorus supply and defoliation frequency. **Agronomy Journal**, Madison, v. 92, p. 868-874, 2000.

TANNER, W.; BEEVERS, H. Transpiration, a prerequisite for long-distance transport of minerals in plants? **Proceedings of National Academy of Sciences of the United States of America**, Washington, v. 98, n. 16, p. 9443-9447, 2001.

WILLIAMSON, L. C.; RIBRIOUX, S.; FITTER, A. H.; LEYSER, O. Phosphate availability regulates root system architecture in Arabidopsis. **Plant Physiology**, Washington, v. 126, p. 875-882, 2001.