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"Luiz de Queiroz" College of Agriculture

Biomass partition and nutrient demand of coffee in different conditions and fertilization according to nutrient demand from simultaneous sinks - fruits and vegetative growth

Laís Teles de Souza

Thesis presented to obtain the degree of Doctor in Science. Area: Crop Science

Piracicaba
2023

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versão revisada de acordo com a Resolução CoPGr 6018 de 2011

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DEDICATION

To all coffee growers who dedicate their lives to the cultivation of this complex crop and constantly seek to improve management techniques to achieve the maximum productive potential of the plant and the efficient use of resources.

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RESUMO

Partição de biomassa e demanda de nutrientes do café em diferentes condições e adubação de acordo com a demanda de nutrientes dos drenos simultâneos - frutos e crescimento vegetativo

A eficiência no uso de nutrientes é um grande desafio para reduzir custos e economizar recursos. Uma maneira de aumentar essa eficiência é aplicar os nutrientes na dose certa, o que requer conhecer a demanda de nutrientes da planta com base na biomassa produzida. No entanto, a biomassa e a demanda de nutrientes pode variar de acordo com fatores como carga de frutos, idade, manejo de poda, densidade de plantas, cultivar, localização, uso de irrigação, etc. Por isso, nos últimos anos, estudamos a demanda de nutrientes do café (*Coffea arabica* L.) em relação à biomassa produzida para melhorar as estratégias de adubação do cafeeiro. Desenvolvemos vários experimentos para medir a biomassa produzida e a demanda de nutrientes das plantas sob diferentes condições. Aqui, apresentamos os estudos com lavouras de café no primeiro ano de produção e com ramos podados (esqueletamento). Além disso, desenvolvemos um método de fertilização - EsalqCafé - para o café arábica baseado em dados de demanda de nutrientes de pesquisas preliminares que consideram a demanda de nutrientes dos dois drenos simultâneos (carga de frutos e crescimento vegetativo ativo), fertilizamos lavouras de café adultas e comparamos com métodos oficiais de fertilização para validar o método EsalqCafé. O primeiro estudo foi realizado em uma lavoura de café no primeiro ciclo de produção para avaliar o efeito da carga de frutos no crescimento vegetativo e na demanda de nutrientes. O delineamento experimental foi em blocos casualizados com carga de frutos controlada em cinco níveis e oito repetições. Este estudo revelou que uma alta carga de frutos diminui cerca de três vezes a biomassa vegetativa, considerando que a planta deixa de produzir 0,43 g de matéria seca de vegetação para cada grama de fruto produzido. As concentrações de nutrientes na vegetação e nos frutos não foram dependentes da carga de frutos, e a demanda de nutrientes variou de acordo com a carga de frutos. O segundo estudo foi realizado em cafeeiros com ramos plagiotrópicos podados, a fim de determinar a biomassa vegetativa anual e a demanda de macronutrientes em manejo de sequeiro e irrigado. O delineamento experimental foi inteiramente casualizado com dois tratamentos (sequeiro e irrigado) e onze repetições. A biomassa vegetativa e suas concentrações de macronutrientes foram medidas para detemrinar os nutrientes acumulados na biomassa vegetativa e a demanda total de nutrientes. Sob manejo de sequeiro ou irrigado, o crescimento da biomassa vegetativa e as concentrações de nutrientes não variaram. No entanto, houve uma quantidade satisfatória de chuva durante o ciclo de crescimento. A demanda de nutrientes foi a mesma para manejo irrigado e sequeiro. Potássio, nitrogênio e cálcio foram os nutrientes mais demandados, correspondendo a 87% da demanda total de macronutrientes. O terceiro estudo foi realizado em três experimentos de campo. O delineamento do experimento foi em blocos casualizados com quatro tratamentos, que foram métodos de adubação: EsalqCafé, Boletim 100 (1997), Boletim 100 versão atualizada e 5ª Aproximação com cinco repetições. As variáveis analisadas foram: produtividade, concentração foliar de nitrogênio e teor de fósforo e potássio no solo na época da colheita. Comparado aos métodos de adubação existentes, os resultados revelaram que o EsalqCafé foi suficiente para suprir a demanda de nutrientes da planta, mantendo a concentração de nitrogênio na folha e o teor de fósforo e potássio no solo na faixa ideal após a colheita. No entanto, mais estudos são necessários.

Palavras-chave: *Coffea arabica* L., Eficiência, Dose, Poda, Nitrogênio, Potássio

ABSTRACT

Biomass partition and nutrient demand of coffee in different conditions and fertilization according to nutrient demand from simultaneous sinks - fruits and vegetative growth

Nutrient use efficiency is a big challenge to reduce costs and save resources. One way to enhance this efficiency is to apply nutrients at the right rate, which requires knowing the plant nutrient demand based on its produced biomass. However, the biomass and nutrient demand can vary according to factors such as fruit load, age, pruning management, plant density, cultivar, location, irrigation use, etc. Therefore, in the last few years, we have studied the coffee (*Coffea arabica* L.) nutrient demand regarding the biomass produced to improve coffee fertilization strategies. We developed several experiments to measure the biomass produced and plant nutrient demand under different conditions. Here, we present the studies with coffee orchards in the first production cycle and with pruning branches. Furthermore, we developed a fertilization method - EsalqCafé - for arabica coffee based on nutrient demand data from preliminary research that considers the nutrient demand of the two simultaneous sinks (fruit load and the active vegetative growth) and we fertilize mature coffee orchards comparing with official fertilization methods to validate the EsalqCafé method. The first study was carried out in a coffee orchard in the first production cycle to measure the effect of fruit load on vegetative growth and nutrient demand. The experimental design was in randomized blocks with controlled fruit load in five levels and eight replicates. This study revealed that a high fruit load decreases vegetative biomass about three-fold, considering that the plant no longer produces 0.43 g of vegetation dry matter for each gram of fruit produced. The nutrient concentrations in the vegetative and fruiting tissues were not dependent on the fruit load and the nutrient demand varied according to the fruit load. The second study was carried out on coffee plants with plagiotropic branches pruned to determine the annual vegetative biomass and the macronutrient demand in rainfed and irrigated management. The experimental design was completely randomized with two treatments (rainfed and irrigated) and eleven replicates. Vegetative biomass and its macronutrient concentrations were measured to predict nutrients accumulated in vegetative biomass and total nutrient demand. Under rainfed or irrigated management, the vegetative biomass growth and nutrient concentrations did not vary. However, there was a satisfactory amount of rain during the growth cycle. The nutrient demand was the same for irrigated and rainfed management. Potassium, nitrogen and calcium were the nutrients most demanded, corresponding to 87% of the total macronutrient demand. The third study was carried out in three field experiments. The experiment design was in randomized blocks with four treatments, which were fertilization methods: EsalqCafé, Boletim 100 (1997), Boletim 100 updated version and 5ª Aproximação with five replications. The variables analyzed were: crop yield, nitrogen leaf concentration and phosphorus and potassium content in the soil at harvest time. Compared to existing fertilization methods, the results revealed the EsalqCafé was sufficient to supply the plant nutrient demand, maintaining nitrogen concentration in the leaf and the phosphorus and potassium content in the soil in the ideal range after harvest. However, further studies are needed.

Keywords: *Coffea arabica* L., Efficiency, Rate, Pruning, Nitrogen, Potassium

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1. INTRODUCTION

The world produced 167 million 60-kilogram bags of coffee beans and consumed 165 million 60-kilogram bags in 2020/2021 (USDA, 2022). Brazil, the largest producer, harvested 48 million bags, almost 30% of the total production, grown on over 2 million hectares with *Coffea arabica* L. and *Coffea canephora* Pierre species (CONAB, 2022). The volume of coffee traded in 2021 by the country has internalized more than US$ 8 billion in foreign exchange revenues (CECAFÉ, 2022). Despite impressive numbers, growing all this coffee is a big challenge. One of the bottlenecks to production is cultivating low fertility soils, which demand high nutrient rates every year. The average financial expenditure on fertilizers represents 20-30% of the total production cost (CONAB, 2017). Moreover, Brazil imports more than 80% of the fertilizers for agricultural production (Brasil, 2021), which causes insecurity to the sector due to heavy dependence from other countries, since fertilizers are strategic products for food security. Therefore, awareness and interest in improve nutrient use efficiency has never been greater and has been a prominent issue in national politics. One way to enhance this efficiency is to apply nutrients at the right rate, which requires knowing the plant nutrient demand based on its biomass.

Nitrogen (N) and potassium (K) are the elements required in greater quantity by the plant compared to the need for phosphorus (P), calcium (Ca), magnesium (Mg), sulfur (S) and the micronutrients boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo) and zinc (Zn) (Epstein, 1965; Marschner, 1995a; Raij, 2011). Maximum rates can reach 450 kg ha^{-1} N and 450 kg ha^{-1} K to 4800 kg ha^{-1} green beans according to São Paulo state recommendations (Raij et al., 1996) or 3600 kg ha^{-1} green beans according to Minas Gerais state recommendations (Guimarães et al., 1999), Brazil's largest coffee producers. However, in recent years, high yields (>5000 kg ha^{-1}) have been reported (Celestino and Veiga, 2019; Sakai et al., 2015; Silva et al., 2008, 2011) and the amount of extra nutrients that must be supplied is not clear because previous studies have not taken into account the current crop yield (Guimarães et al., 1999; Raij et al., 1996). Therefore, coffee growers have applied excessive nutrient rates without specifications, such as 800 kg ha^{-1} N and 630 kg ha^{-1} K, which are much higher than the maximum rates indicated by official recommendations. Furthermore, to our knowledge, there is no information about nutrient rates required for pruned coffee, a practice widely used in coffee crops, especially for the zero-harvest system.

Besides the lack of information about nutrient demand for high yields and pruned plants, there is no information about coffee nutrient demand according to the fruit load. It is important to consider this because *Coffea arabica* L. is a perennial plant and active vegetative and reproductive growth co-occurs. However, fruits are the major physiological sink regulating carbohydrate allocation (Bote and Jan, 2016). Then, biomass partition between vegetative and reproductive growth is often described in a negative relationship (Amaral et al., 2001; Bote and Jan, 2016; Cannell, 1985a; Nicolas Franck et al., 2006; Vaast et al., 2006, 2005, 2002). The nutrient rate to supply the coffee demand in production must be obtained by adding the demand for fruiting and the amount required by the active vegetative grown. The values of these demands are obtained by the product between the fruit and vegetation biomass and its nutrient concentration. Therefore, a better understanding of these sinks' relationship can be useful for predicting nutrient rates for efficient fertilization management.

To fertilize coffee more efficiently and overcome the limitations of past attempts, we determine the coffee nutrient demand in different conditions, like crops in the first year of production and after pruning branches. Also, we fertilize mature coffee crops according to nutrient demand for vegetation and fruiting based on nutrient demand data from preliminary research. This method is described as EsalqCafé and is based on the ecophysiological relationship of the coffee plant between the sinks, fruits and vegetation. This relationship incorporates improved descriptions of the amount of vegetative mass as a function of fruit load to support the calculation of the amount of nutrients for developing and maintaining the productive coffee tree during its useful life. The physiological rigor used to design our method permits us to reliably estimate the nutrient demand, which vary according to the stage of cultivation, management and fruit load.

References

Amaral, J.A.T., da Matta, F.M., Rena, A.B., 2001. Effects of fruiting on the growth of arabica coffee trees as related to carbohydrate and nitrogen status and to nitrate reductase activity. Brazilian Journal of Plant Physiology 13, 66–74. https://doi.org/10.1590/S0103-31312001000100008

Bote, A.D., Jan, V., 2016. Branch growth dynamics, photosynthesis, yield and bean size distribution in response to fruit load manipulation in coffee trees. Trees 30, 1275–1285. https://doi.org/10.1007/s00468-016-1365-x

Brasil, 2021. Plano nacional de fertilizantes 2050, Secretaria Especial de Assuntos Estratégicos. Brasília: SAE.

Cannell, M.G.R., 1985. Coffee: botany, biochemistry and production of beans and beverage., in: Clifford, M., Wilson, K. (Eds.), Physiology of the Coffee Crop. Croom Helm Ltd, London, pp. 108–134.

CECAFÉ, 2022. Relatório mensal 2022.

Celestino, S.M.C., Veiga, A.D., 2019. Physical-chemical characterization and coffee grain yield of the EMBRAPA cerrados germplasm bank. X Brazilian Coffee Research Symposium, Vitória, ES.

CONAB - Companhia Nacional de Abastecimento, 2017. A Cultura do Café: análise dos custos de produção e da rentabilidade nos anos-safra 2008 a 2017.

CONAB, C.N. de A., 2022. Acompanhamento da safra brasileira de café. Brasília, DF.

Epstein, E., 1965. Mineral metabolism, in: Bonner, J., Varner, J.E. (Eds.), Plant Biochemistry. Academic press, London, pp. 438–466.

Franck, N., Vaast, P., Génard, M., Dauzat, J., 2006. Soluble sugars mediate sink feedback down- regulation of leaf photosynthesis in field-grown Coffea arabica. Trees 26, 517–525. https://doi.org/10.1093/treephys/26.4.517

Guimarães, P.T.C., Garcia, A.W.R., Alvarez, V.H., Prezotti, L.C., Viana, A.S., Malavolta, E., Corrêa, J.B., Lopes, A.S., Nogueira, F.D., Monteiro, A.V.C., 1999. Coffee, in: Ribeiro, A.C., Guimarães, P.T.G., Alvarez, V.H. (Eds.), Recommendations for the Use of Correctives and Fertilizers in Minas Gerais State. Viçosa, pp. 289–302.

Marschner, H., 1995. Mineral nutrition of higher plants. Academic Press, San Diego, USA.

Raij, B. van, 2011. Fertilidade do solo e manejo de nutrientes. International Plant Nutrition Institute, Piracicaba.

Raij, B. van, Cantarella, H., Quaggio, J.A., 1996. Coffee, in: Technical Bulletin 100: Fertilization and Liming Recommendations for the São Paulo State. Campinas Agronomic Institute, Campinas, pp. 97–101.

Sakai, E., Barbosa, E.A.A., Silveira, J.M. de C., Pires, R.C. de M., 2015. Coffee productivity and root systems in cultivation schemes with different population arrangements and with and without drip irrigation. Agric Water Manag 148, 16–23. https://doi.org/10.1016/j.agwat.2014.08.020

Silva, C.A., Teodoro, R.E.F., Melo, B., 2008. Produtividade e rendimento do cafeeiro submetido a lâminas de irrigação. Pesqui Agropecu Bras 43, 387–394. https://doi.org/10.1590/S0100-204X2008000300014

Silva, A.C. da, Lima, L.A., Evangelista, A.W.P., Martins, C. de P., 2011. Productive Characteristics of Arabic Coffee Irrigated By Central Pivot in the Region of Lavras/Mg. Coffee Sci 6, 128–136.

USDA (United States Department of Agriculture), 2022. Coffee: world markets and trade.

Vaast, P., Angrand, J., Franck, N., Dauzat, J., Génard, M., 2005. Fruit load and branch ring-barking affect on carbon allocation and photosynthesis of leaf and fruit of *Coffea arabica* in the field. Tree Physiol 25, 753–760. https://doi.org/10.1093/treephys/25.6.753

Vaast, P., Bertrand, B., Perriot, J.J., Guyot, B., Génard, M., 2006. Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica* L.) under optimal conditions. J Sci Food Agric 86, 197–204. https://doi.org/10.1002/jsfa.2338

Vaast, P., Génard, M., Dauzat, J., 2002. Modeling the effects of fruit load, shade and plant water status on coffee berry growth and carbon partitioning at the branch level. Acta Hortic 584, 57–62. https://doi.org/10.17660/ActaHortic.2002.584.5

2. FRUIT LOAD INFLUENCE ON DRY MATTER PARTITIONING, HARVEST INDEX AND NUTRIENT DEMAND OF COFFEE IN THE FIRST YIELD CYCLE

Abstract

Fruits are the coffee (*Coffea arabica* L.) strongest sink that regulates the dry matter partitioning. A high fruit load often results in low vegetative growth and vice versa, also influencing the coffee harvest index (HI) and the nutrient demand. However, the total biomass of fruits and vegetation of young coffee plants over a growth cycle is unknown, considering the relationship between both. The present study measured the effect of fruit load on vegetative growth, green bean yield, HI and nutrient demand of young coffee plants, generating allometric models. The study was carried out from November 2018 to April 2019 in a young coffee orchard in southeastern Brazil. The experimental design was in randomized blocks with controlled fruit load in five levels (100, 75, 50, 25 and 0%) and eight replicates. The treatments were imposed manually when the fruits were in the pinhead development stage, as well as the branch labeled on the insertion of the last pair of the leaf of each branch for further evaluation of vegetative development. The variables analyzed were: vegetation dry matter, fruit dry yield, green beans, HI and macronutrient concentration in vegetation and fruiting to estimate the nutrient demand. The study revealed that a high fruit load decreases vegetative biomass about three-fold, considering that for each gram of fruit produced, the plant no longer produces ~ 0.43 g of vegetation dry matter. The HI of young coffee plants varies from 0.13 to 0.72 according to the fruit load. Furthermore, the nutrient concentrations in the vegetative and fruiting tissues were not dependent on fruit load and nutrient demand varies according to the fruit load due to the different yield proportions of mass between fruiting and annual vegetation. These results can help improve crop nutrition strategies for young coffee orchards, which should be based on nutrient demand in expected yield, support plant breeding programs and yield predict and integrate into mechanistic growth models.

Keywords: *Coffea arabica* L.; Sinks; Allometric models; Biomass; Macronutrients

2.1. Introduction

It is widely acknowledged that in fruit crops such as *Coffea arabica* L., active vegetative and reproductive growth, leading sinks, co-occur. These sinks themselves regulate the assimilates allocation in mature trees (Bote and Jan, 2016). However, fruits are the major physiological sink regulating carbohydrate allocation in the other plant organs. Therefore, the biomass partition between vegetative and reproductive growth is often described in a negative relationship (Amaral et al., 2001; Bote and Jan, 2016; Cannell, 1985b; Nicolas Franck et al., 2006; Vaast et al., 2006, 2005, 2002). This influence of fruit load on dry matter partitioning has also been observed for other fruit crops, e.g. olive (Fernández et al., 2015; Haouari et al., 2013), apple (Haller and Magness, 1933; Meland, 2009; Palmer, 1992), sweet pepper (González-Real et al., 2008), persimmon (SeongTae et al., 2016), cherry (Cittadini et al., 2008; Whiting and Lang, 2004), almond (Saa and Brown, 2014) and citrus (Martínez-Alcántara et al., 2015; Martínez-Fuentes et al., 2010; Verreynne and Lovatt, 2009).

A high fruit load is a desirable trait in the current harvest from the production perspective. However, the negative effect on vegetative growth is potentially detrimental to the yield and volume of the following season. Low vegetative biomass growth is associated with the reduced source and bud development, both important to yield formation for upcoming years (Moscardini et al., 2020; Vaast et al., 2005). It is noteworthy that, although the significant influence of coffee fruits on the assimilates partition is qualitatively documented, there is still a need for an allometric model that describes active vegetative growth regarding the fruit load. The significant influence of coffee fruits on the assimilated partition of mature plants has already been studied (unpublished data); however, there is still a need for an empirical model estimating vegetation growth based on the current fruit load of young plants. This tool would support plant breeding programs, yield prediction, improve crop nutrition strategies and integrate mechanistic growth models. Here we propose a methodology that determines the active vegetative growth regarding the fruit load of young plants (first yield cycle) to characterize the dry matter partitioning of coffee and the plant nutrient demand at this development stage.

The difficulty of developing a biomass partitioning model for tree crops arises from the classical approach to assessing the crop harvest index (HI). This concept was first proposed by Beaven (1920) and it is the proportion of the total biomass devoted to fruit at harvest. Later, the "migration coefficient" was defined as the ratio of grain yield to the total biomass of the entire aboveground plant and has been used as production estimation in crop models (Holzworth et al., 2014; Jones et al., 2003; Raes et al., 2011; Stöckle et al., 2003; Williams et al., 1989). However, these concepts are most useful for annual seed crops. Attempts to determine HI in perennial crops are discouraged because it is difficult to measure this parameter at harvest without using non-destructive methods, which are costly and time-consuming. To our knowledge, coffee HI has not been described. Therefore, a method for estimating active vegetative biomass and HI regarding fruit load would represent a novelty for coffee research and offer a doable methodology for supporting crop management, mainly to determine the plant's nutrient demand at this stage of development, which is obtained by the product between the fruit and vegetation biomass and its nutrients concentration.

Biomass can be estimated by employing allometric models, which express correlations between tree biomass and easily measurable variables (Cornet et al., 2015; Kuyah et al., 2016; Temesgen et al., 2015). Firstly, allometric equations require a large destructive sampling. Nevertheless, afterward, the equations are helpful as a non-destructive approach to estimate active vegetative growth and, subsequently, the HI and the plant nutrient demand. Furthermore, developing new allometric models can enhance the precision of biomass assessment protocols and increase our knowledge about architectural constraints on plant development (Chave et al., 2014). Hence, our objective was to develop an allometric model to estimate vegetative growth based on the reproductive biomass to better understand the competition between the active vegetative and fruit load, quantify the HI and the nutrient demand of coffee plant in the first yield cycle based on this model.

2.2. Material and Methods

2.2.1. Plant material and growth conditions

The field experiment was conducted during the 2018/2019 growing season on arabica coffee (*Coffea arabica* L. cv Catuaí amarelo IAC 62) in Monte Sião-MG, Brazil (22°21'57,82"S; 46°28'12,71"W and 885 m above sea level). This genotype is one of the most productive in Brazil and is planted in a wide environmental condition. The local climate is classified as Cwb - Humid subtropical with dry winters and temperate summers (Köppen). The total rainfall was 1065 mm and the average temperature of 21.9 °C during the experimental period (Figure 1).

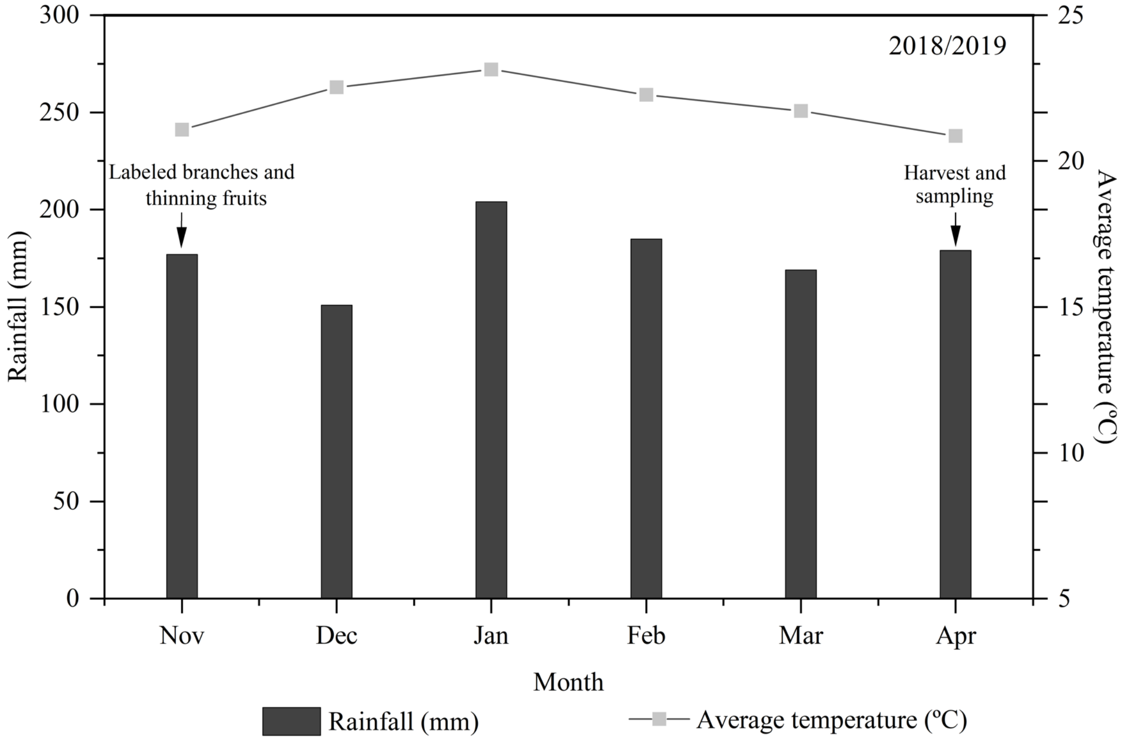


Figure 1. Mean monthly temperature and rainfall along the period of field experiment. Black bars refer to rainfall and gray line to temperature.

The water balance from 2018 to 2019 is shown in Figure 2, which includes the experimental period. The region showed a water surplus of 606 mm and no water deficit during the plant's growth in the experimental period.

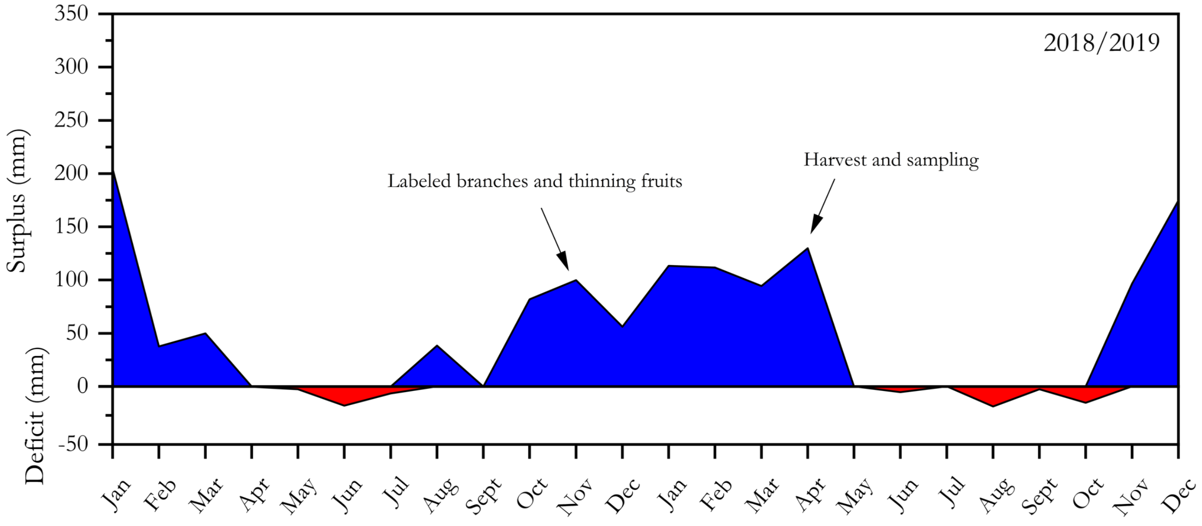


Figure 2. Water balance based on monthly climatology evapotranspiration and rainfall obtained according to Thornthwaite and Mather (1955) and two years of growing, which include the experimental period, in Monte Sião, Minas Gerais. We assumed 120 mm for soil water holding capacity as the monthly water balance (Sentelhas, 2020).

The coffee orchard was in the first production cycle with a plant arrangement of 3.7 x 0.7 m spacing. The soil chemical and physical constitution was characterized according to Table 1 before the installation of the experiment. After soil sampling and chemical analysis, fertilization was carried out according to recommendations for the Minas Gerais state (Guimarães et al., 1999).

Table 1. Soil chemical and physical properties of field experimental. Values describes 0-20 cm depth.

pH	O.M	P	S	K	Ca	Mg	Al	H	CEC	Clay	Silt	Sand
$CaCl_2$ 0.01mol L^{-1}	g dm^{-3}	--- mg dm^{-3} ---		-------------------- $mmol_c$ dm^{-3} --------------------						--------- % ---------		
5.7	32	19	20	3.2	28	11	0	20	62	42	17	41

2.2.2. Experimental design

The experimental design was in randomized blocks with controlled fruit load in five levels (100, 75, 50, 25 and 0%) and eight replicates. Each tree consisted of an independent experimental unit. The plants were selected for the fruit load manipulation based on uniformity and vigor. After flowering in early November, when the fruits were in the pinhead development stage (Camargo and Camargo, 2001), five fruit loads were manually imposed on all reproductive branches of the respective plant. The insertion of the last pair of the fully expanded leaf of each branch was labeled for further evaluation of vegetative growth.

2.2.3. Crop yield and measurements

The fruits were in harvest maturity at the end of April 2019 (Figure 3A). Then, fruits were harvested manually and all branches were cut from the wire label. Stem, branches, leaves (fresh vegetative biomass) and fruits were dried (Figure 3B) at 60°C in a forced air oven for 72h to determine the dry matter. After drying, fruits were de-husked (Figure 3C) and mass corrected to 12% water concentration (commercialized bean moisture) to obtain ready-to-be-roast coffee beans, hereafter called green beans. Then, the material was crushed and all samples were ground into fine powder in a Wiley mill with a 20 mesh for measurement of P, K, Ca, Mg and S. Nitric-perchloric digestion was accomplished (Mills and Jones, 1996) and the total of these nutrients measured via radial visualization through an inductively coupled plasma optical emission spectrometer (ICP-OES; JobinYvon, JY50P Longjumeau, France) provided with a nebulization chamber. To determine the total-N concentration, the samples were subjected to digestion with sulphuric acid (Jackson, 1958) and N was determined according to the analytical semi-micro Kjeldahl method (Bremner, 1965).

Figure 3. Coffee fruits in harvest maturity (A), dried (B) and de-husked (green beans) (C).

Nutrients accumulated (NA) in vegetative biomass and the fruits were estimated by multiplying nutrient concentrations in the tissue and the amount of dry matter accumulated (Vymazal, 2016) (Equation 1):

$$\text{NA} = \text{nutrient concentration (g kg}^{-1}\text{) x dry matter (kg per plant)} \qquad \text{eq. 1}$$

Nutrient demand (ND) per hectare was estimated by multiplying the nutrient accumulated per plant and the number of plants per hectare (Equation 2):

$$\text{ND} = \text{ nutrient accumulated (g per plant) x number of plants per hectare} \qquad \text{eq. 2}$$

Harvest index (HI) (dimensionless) was calculated as the ratio of the fruit dry yield (g) to the total above-ground plant biomass (g) produced over the growth cycle (Equation 3):

$$\text{HI} = \frac{\text{Fruit dry yield (g per plant)}}{\text{Total plant biomass (g per plant)}} \qquad \text{eq. 3}$$

2.2.4. Data analysis

The datasets were subjected to residual normality and variance homogeneity tests. The Analysis of Variance (ANOVA) and regression model assumptions were met and no transformation was performed. The ANOVA F test was performed considering <0.05 probability through SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). When F probability was significant, the means were fitted to linear regression using Origin software version 9.6 (OriginLab Corporation 2019).

2.3. Results

2.3.1. Fruit load effects on vegetation, coffee production and harvest index

Fruit load significantly affected coffee vegetation dry matter, fruit dry yield, green beans and harvest index. All these variables were significant at less than 1% of probability of error by the F test and the averages are shown in table 2.

Table 2. Summary of analysis of variance of fruit load on coffee vegetation dry matter, fruit dry yield, green beans and harvest index.

	Average	*P*
Vegetation dry matter (g per plant)	316	<.0001**
Fruit dry yield (g per plant)	181	<.0001**
Green beans (g per plant)	119	<.0001**
Harvest index	0.44	<.0001**

** Significant at less than 1% of error probability by F test.

The reduction of fruit load increased vegetation dry matter about three-fold in the coffee plants in the first production cycle. As expected, the reduction of fruit load decreased coffee production linearly about seven-fold under field growing conditions (Figure 4). Vegetation dry matter ranged from 483 g with 0% fruit load to 150 g per plant with full fruit load (Figure 4A). Green beans production ranged from no yield with 0% fruit load to 340 g with full fruit load or 468 g of fruit dry yield per plant (Figure 4B). With 100% fruit load treatment, dry matter accumulation by fruits accounted for about three-fold the matter accumulated by vegetation over the annual production cycle (Figure 4).

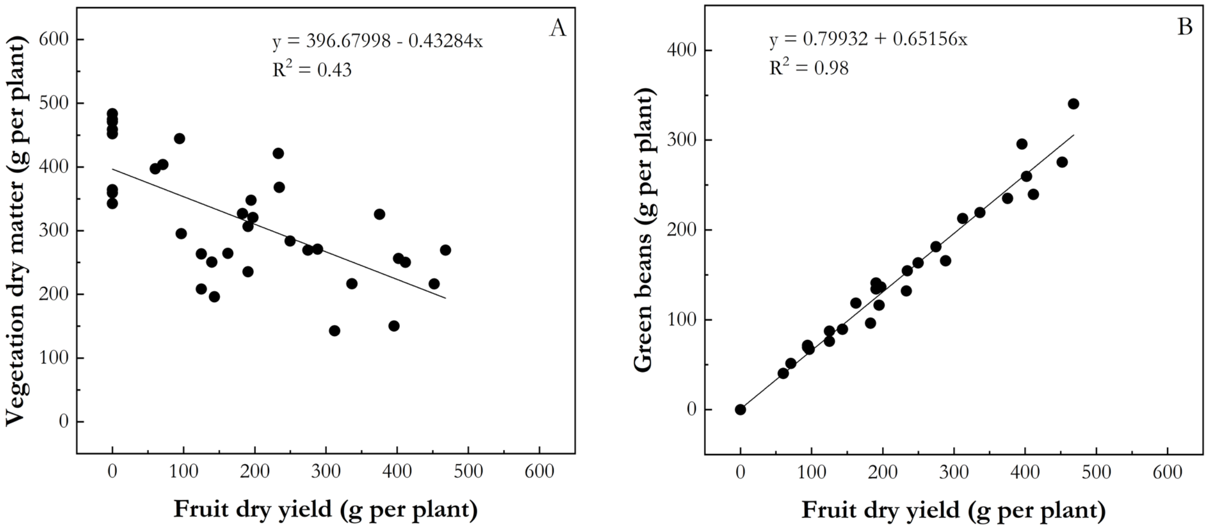


Figure 4. Vegetation dry matter (A) and green beans (B) per plant regarding fruit dry yield of coffee plants in the first production cycle. Data are all observations of eight replicates collected from each coffee plant under coffee-growing conditions and manipulation of the fruit load (100%, 75%, 50%, 25% and 0%). Significant for fruit load at $p \leq 0.01$ by ANOVA F test.

The fruit load significantly affected HI (Table 2 and Figure 5). Among the loads, the maximum HI was 0.72, while the minimum HI was 0.13. Generally, the greatest HI was recorded with full fruit load, corresponding to 395 g of fruit dry yield (Figure 5A) or 296 g of green beans per plant (Figure 5B). In contrast, the lowest fruit load resulted in the lowest HI with 60 g of fruit dry yield (Figure 5A) or 40 g of green beans per plant (Figure 5B).

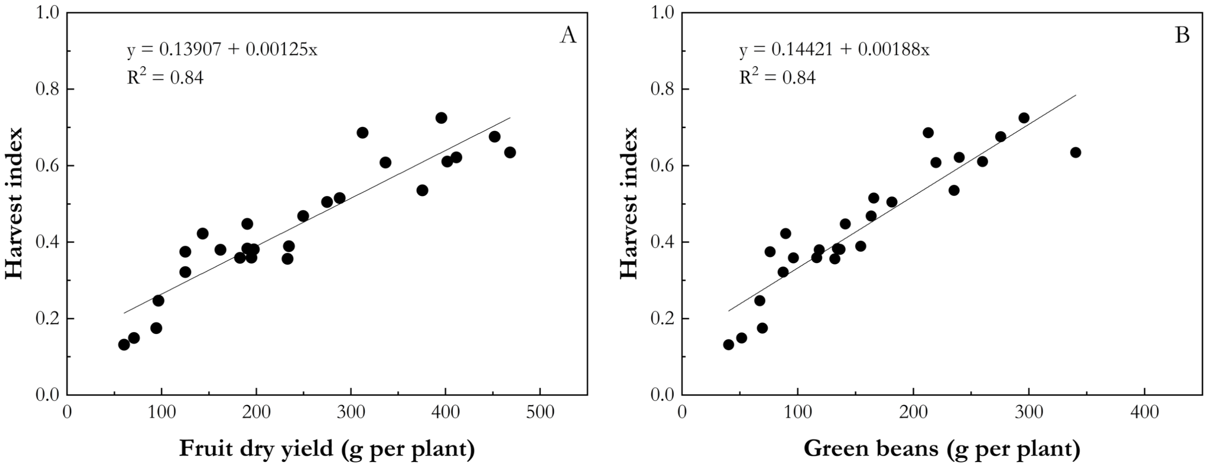


Figure 5. Harvest index regarding fruit dry yield (A) and green beans (B) of coffee plants in the first production cycle. Data are all observations of eight replicates collected from each coffee plant under coffee-growing conditions and manipulation of the fruit load (100%, 75%, 50%, 25% and 0%). Significant for fruit load at $p \leq 0.01$ by ANOVA F test.

2.3.2. Nutrient concentration and accumulation

No significant effect was observed in all nutrient concentrations evaluated in the vegetative biomass by fruit load. The average concentrations of N (35.5 g kg^{-1}) and K (19.8 g kg^{-1}) were the highest compared to the other nutrients. The average concentration of P among the treatments was 2.7 g kg^{-1}. The average concentrations of secondary macronutrients in the vegetative biomass of plants were: 16.0 g kg^{-1} Ca, 6.1 g kg^{-1} Mg and 0.6 g kg^{-1} S (Table 3).

Table 3. Summary of analysis of variance and average of concentration of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) in the coffee **vegetative biomass** of plants grown with different fruit loads in south of Minas Gerais, Brazil. Values are means of eight replicates.

	N	P	K	Ca	Mg	S
	g kg^{-1}					
Average	35.5	2.7	19.8	16.0	6.1	0.6
			ANOVA			
Pr > F	0.5458^{ns}	0.3880^{ns}	0.1039^{ns}	0.0618^{ns}	0.3773^{ns}	0.1496^{ns}
CV (%)	10.9	15.4	10.9	9.9	14.4	4.7

ns: not significant by the F test.

In the same way, as in vegetative biomass, no significant effect was observed in all nutrient concentrations evaluated in the fruits by fruit load. The average concentrations of N (23.0 g kg^{-1}) and K (12.4 g kg^{-1}) also were the highest compared to the other nutrients. The average concentration of P among the treatments was 1.5 g kg^{-1}. The average concentrations of secondary macronutrients in the fruits were: 2.1 g kg^{-1} Ca, 1.7 g kg^{-1} Mg and 0.5 g kg^{-1} S (Table 4).

Table 4. Summary of analysis of variance and average of concentration of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) in the coffee **fruits** of plants grown with different fruit loads in the south of Minas Gerais, Brazil. Values are means of eight replicates.

	N	P	K	Ca	Mg	S
	--- g kg^{-1} ---					
Average	23.0	1.5	12.4	2.1	1.7	0.5
			ANOVA			
Pr > F	0.8619^{ns}	0.6703^{ns}	0.8981^{ns}	0.3328^{ns}	0.7272^{ns}	0.2611^{ns}
CV (%)	9.3	11.6	8.9	9.3	10.0	11.4

ns: not significant by the F test.

As expected, nutrient accumulation in the vegetative biomass of coffee plants varies with different fruit loads (Table 5) due to the variation in the amount of vegetative biomass (Figure 4). All nutrients showed the same trend as vegetative biomass versus fruit load, which was a negative linear correlation (Figure 6). Naturally, there was also a significant accumulation of all nutrients in the fruits by fruit load (Table 5) and all nutrients showed a positive linear correlation with fruit load (Figure 7).

Table 5. Summary of analysis of variance and average of **accumulation** of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) in the coffee vegetative biomass and fruits of plants grown with different fruit loads in south of Minas Gerais, Brazil. Values are means of eight replicates ± SE.

	N	P	K	Ca	Mg	S
	--- g per plant ---					
Vegetative biomass	12.1	0.7	6.3	5.1	1.9	0.2
Pr > F	0.0329*	0.0394*	<.0001**	0.0206*	0.0039**	0.0002**
Fruits	6.4	0.4	3.1	0.5	0.4	0.1
Pr > F	0.0289*	0.0139*	0.0055**	0.0102*	0.0105*	0.0076**

* significant at 5% and ** significant at less than 1% of probability of error by the F test.

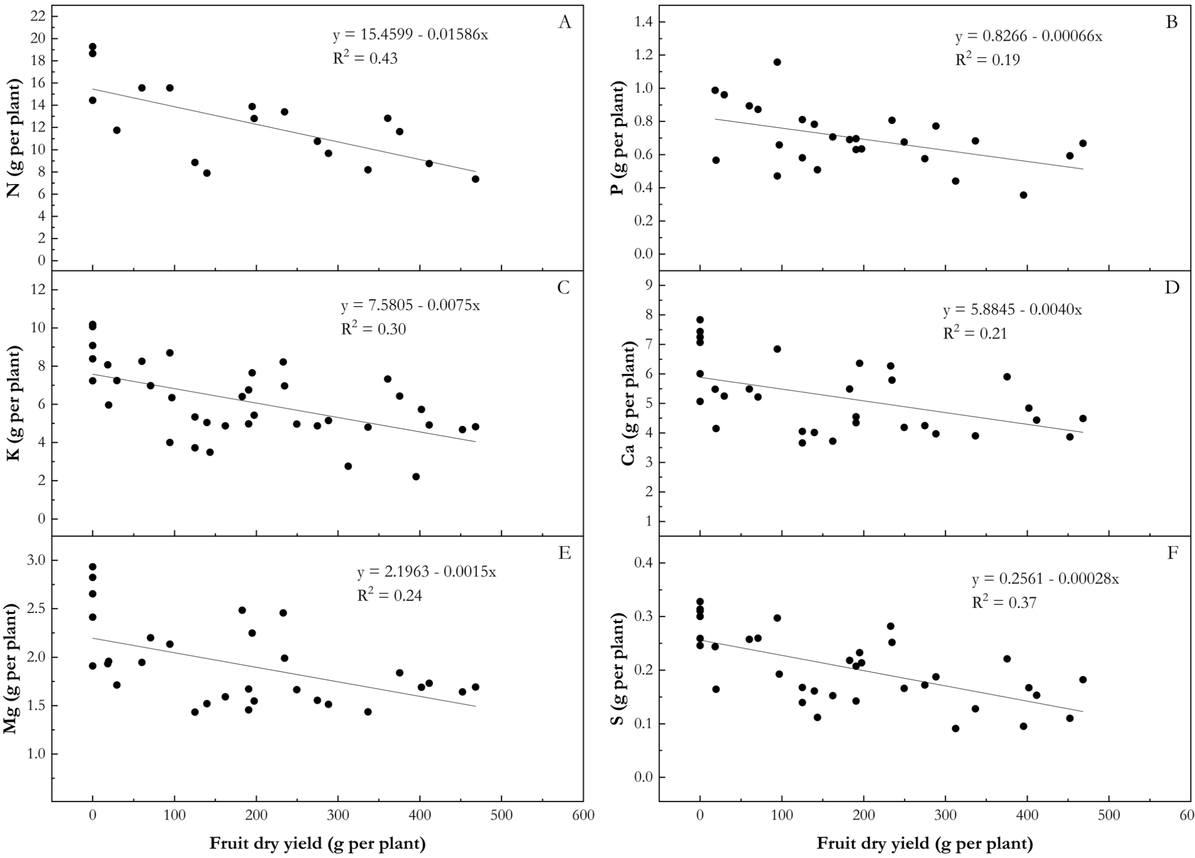


Figure 6. Nutrient accumulation in the coffee **vegetative biomass** of plants grown with different fruit loads in south of Minas Gerais, Brazil. Nitrogen (A), phosphorus (B), potassium (C), calcium (D), magnesium (E) and sulfur (F). Values are all observations.

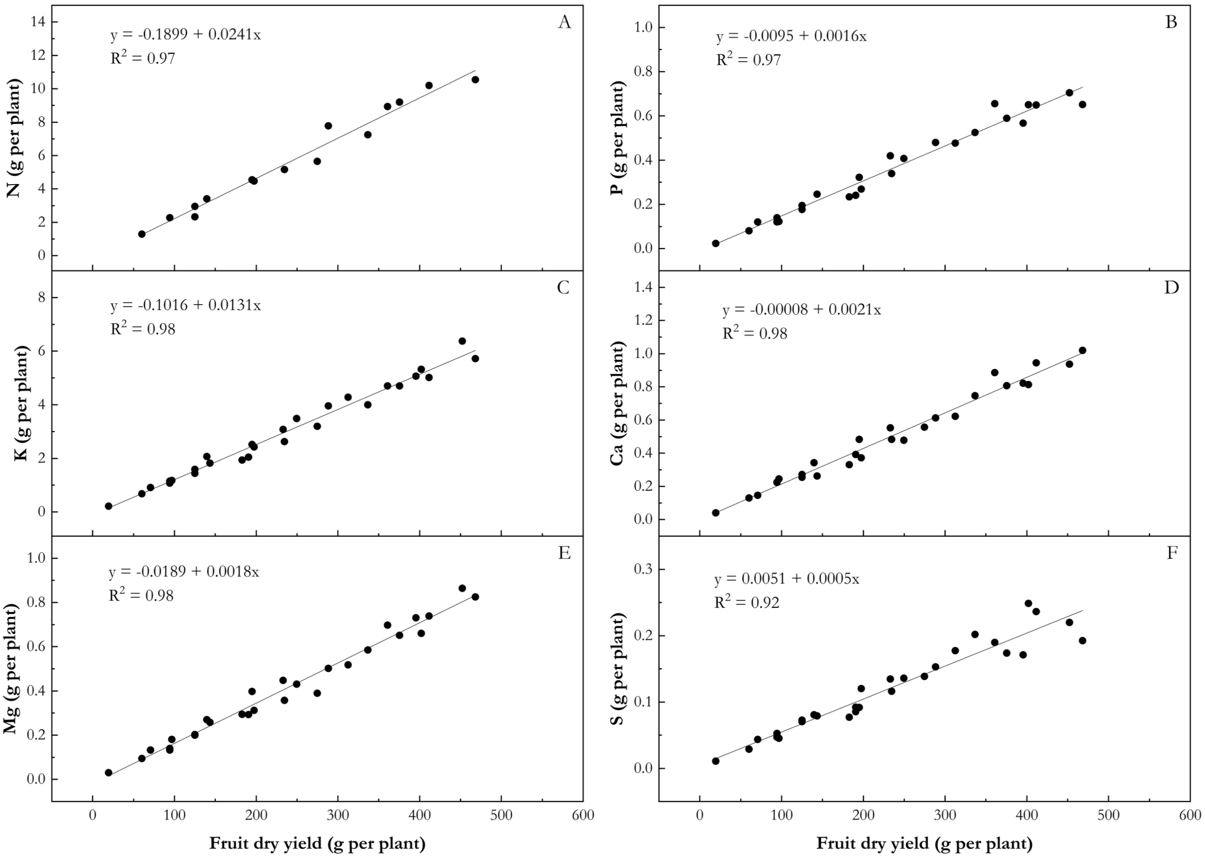


Figure 7. Nutrient accumulation in the coffee **fruits** of plants grown with different fruit loads in south of Minas Gerais, Brazil. Nitrogen (A), phosphorus (B), potassium (C), calcium (D), magnesium (E) and sulfur (F). Values are all observations.

2.3.3. Nutrient demand

Nutrient demand of coffee crops to vegetate and fruit over one growth cycle in the first year of production was estimated for green bean yield of 1200 kg ha^{-1}, as an example, by multiplying nutrient accumulated per plant and the number of plants per hectare. N, K and Ca were the crop's most demanded nutrients. They corresponded to 90% of total macronutrient demand. Mg, P and S, demanded in smaller quantities, corresponded to 10% of the total macronutrient demand. The fruits required the greatest amount of all nutrients, except Ca and Mg, which were most demanded by the vegetative biomass (Table 6).

Table 6. Annual nutrient demand of coffee plants* in the first year of production to growth 1200 kg ha^{-1} of green beans. Abreviations: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S).

	N	P	K	Ca	Mg	S
	-- kg ha^{-1} --					
Vegetation	26.2	2.0	14.6	11.8	4.5	0.5
Fruiting	42.2	2.7	22.8	3.9	3.1	0.9
TOTAL	68.5	4.7	37.4	15.7	7.6	1.4

* Catuaí amarelo IAC 62 - 3.7 x 0.7 m spacing.

2.4. Discussion

This study illustrates the effect of fruit load on vegetative growth, green bean yield, HI and plant nutrient demand of coffee plants under coffee-growing conditions over the first yield cycle. Fruit thinning strongly modulated vegetative growth, fruit dry yield, green beans and harvest index (Table 2). The removal of fruits at an early stage stimulated branch growth and production of additional apical leaves. Comparing the vegetation dry matter with full fruit load versus no fruit clearly revealed the influence of fruits on dry matter accumulation (Figure 4A). Naturally, fruit thinning reduced green bean yield (Figure 4B). These results indicate coffee tree source-sink interactions, which are modulated by carbon assimilation and partitioning during growth and development besides that, the effect of fruit load on vegetative growth is consistent with previous observations for coffee (Amaral et al., 2001; Bote and Jan, 2016; Cannell, 1971; Chaves et al., 2012; DaMatta et al., 2008; Toro-Herrera et al. 2022; Nicolás Franck et al., 2006; Kumar and Tieszen, 1976; Vaast et al., 2005). This happens because there is a high energy cost to produce fruit and, therefore, the plant focuses its energy flow on production instead of vegetation. In a specific way, this dynamic represents a negative correlation between vegetative growth and fruit production, since the reproductive structures have a high capacity to import carbohydrates, constituting strong competing sinks.

The carbohydrates produced by the leaves are allocated according to the priority principle to the growth centers of plant, fruits and then vegetation (Bote and Jan, 2016; Moscardini et al., 2020). Fruit thinning can reduce the consumption of carbon and nitrogen nutrient by fruits, promoting the current vegetative growth and increasing the reserve of carbon and nutrients in the vegetative organs, mainly nitrogen, which is essential to support the plant's growth at the beginning of the new cycle, usually in spring of the (Ding et al., 2017; Lima Filho and Malavolta, 2003). The high load of fruits is a great stress for the coffee tree, since the increasing fruit load can decrease the nutrients stored in the trees by the competition intensification for the carbohydrate, which is not beneficial to enhancing the drought stress resistance and formation of new organs, fruit yield and quality, mainly when environmental factors restrict the soil nutrient uptake, lack of transpiration and limited root growth (Basile et al., 2007; Millard and Grelet, 2010).

HI, calculated as the ratio of the fruit dry yield to the total aboveground plant biomass produced over one cycle, has been widely used as an efficiency indicator of assimilate distribution to fruit and as a measure of crop breeding for maximizing crop yield (Hay, 1995; Sinclair, 1998). In the present study, there was a relationship between HI and fruit dry yield (Figure 5A) and coffee green beans (Figure 5B), indicating that the index is strongly variable for coffee in the first yield cycle. In general, the coffee plant with a high fruit load invests 72% of its energy in fruit production and only 13% of the energy when the fruit load is low. To estimate coffee HI is necessary to evaluate or estimate the fruit load over a growth cycle. It is important to bear in mind that in seed-producing crops, the crucial basis of HI is carbon centric and dictates that total shoot dry matter determines aboveground “sources” of photoassimilate and harvested grain represents the “sinks” (Smith et al., 2018). However, this concept does not fully apply to perennial plants such as coffee, once it has more than one sink - fruits, active vegetative growth (annual branches and leaves) and storage organs (roots and perennial branches) (Camargo and Camargo, 2001; Millard and Grelet, 2010). These HI data evidence the biennial trait of coffee and can help predict the yield of the next harvests since the vegetative growth in the previous harvest is known, because it will be responsible for the production in the following harvest.

We observed no effect of fruit thinning on macronutrient concentration in vegetation biomass (Table 3). Moreover, our results are in line with previous studies, which suggest that quantitatively macronutrient concentration of plant shoot should be N> K>Ca>Mg>P>S for adequate growth (Epstein, 1965; Marschner, 1995b; Raij, 2011). In the same way, no significant effect was observed in all macronutrients concentration evaluated in the fruits by fruit load (Table 4) and a similar result was found in previous studies with adult plants (unpublished data). Naturally, nutrient accumulation in the vegetative and fruit varied with different fruit loads due to the variation in the amount of biomass in both (Table 5), which followed the trend of negative linear correlation for vegetation (Figure 6) and positive linear correlation for fruits (Figure 7). Previous studies have already shown that coffee plants have high N and K requirements (Catani et al., 1967; Catani and Moraes, 1958; Corrêa et al., 1986; Lima Filho and Malavolta, 2003; Malavolta et al., 1963) since N plays an essential role for starch and other carbohydrate production needed for fruit formation and growth (Martinez et al., 2019) and K plays an essential role in enzyme activation, stomatal function, photosynthesis, protein synthesis, stabilization of internal pH, turgor-related processes and transport of metabolites (Alva et al., 2006; Mancuso et al., 2014; Wakeel et al., 2011).

Once the biomass of fruits and vegetation as a function of the fruit load is known and, also, the nutrient concentration in these organs, it is possible to estimate the nutrient demand for coffee plants in the first growth cycle with any fruit load. Here, we estimated plant nutrient demand for a green bean yield of 1200 kg ha^{-1}, as an example and we observed that fruits account for the largest fraction of the N, P, K and S annual uptake in coffee (Table 6). As a percentage of both sinks annual nutrient demand (total fruit and vegetative biomass growth), we observed that 62% N, 58% P, 61% K and 64% S were partitioned into fruits. In contrast, 75% Ca and 59% Mg were partitioned into vegetative biomass. However, as mentioned earlier, the percentage of plant nutrients partitioned to fruit and vegetation in coffee is variable. This is due to the different fruit loads that are produced each year. In the years of lower fruit load, greater vegetative growth occurs and, consequently, greater nutrients partitioned to vegetation. The percentage of tree nutrients partitioned to fruit and vegetation was described in several perennial crops, such as almond (Muhammad et al., 2015), apple (Cheng and Raba, 2009) and orange (Roccuzzo et al., 2012). However, these studies do not consider the variation in fruit load and the nutrient partition in young plants, which differ from adult plants.

2.5. Conclusion

This research is a pioneer study to understand the relationship between fruit load and active vegetative growth of young coffee plants, as well as present a simple and potentially sound method for estimating total biomass produced and a method to estimate HI and the plant nutrient demand of coffee. It is shown that fruit load shapes the vegetative growth of coffee plants under coffee-growing conditions over the first yield cycle, whereas, for each gram of fruit produced, ~ 0.43 g of vegetation dry matter is no longer produced by the plant. The harvest index of young coffee plants, which has not been described, varies from 0.13 to 0.72 according to the fruit load. Macronutrient concentrations in the vegetative and fruiting tissues are not dependent on fruit load and the nutrient demand varies according to the fruit load due to the different proportions of mass between fruiting and annual vegetation. These results can help in the fertilizer rate decisions in young coffee orchards, which should be based on nutrient demand in expected yield, support plant breeding programs and yield predict and integrate into mechanistic growth models.

References

Alva, A.K., Mattos, D., Paramasivam, S., Patil, B., Dou, H., Sajwan, K.S., 2006. Potassium management for optimizing citrus production and quality. International Journal of Fruit Science 6, 3–43. https://doi.org/10.1300/J492v06n01_02

Amaral, J.A.T., da Matta, F.M., Rena, A.B., 2001. Effects of fruiting on the growth of arabica coffee trees as related to carbohydrate and nitrogen status and to nitrate reductase activity. Brazilian Journal of Plant Physiology 13, 66–74. https://doi.org/10.1590/S0103-31312001000100008

Basile, B., Bryla, D.R., Salsman, M.L., Marsal, J., Cirillo, C., Johnson, R.S., Dejong, T.M., 2007. Growth patterns and morphology of fine roots of size-controlling and invigorating peach rootstocks. Tree Physiol 27, 231–241. https://doi.org/10.1093/treephys/27.2.231

Beaven, E.S., 1920. Breeding cereals for increased production. Journal Farmers' Club Part VI.

Bote, A.D., Jan, V., 2016. Branch growth dynamics, photosynthesis, yield and bean size distribution in response to fruit load manipulation in coffee trees. Trees 30, 1275–1285. https://doi.org/10.1007/s00468-016-1365-x

Bremner, J.M., 1965. Total nitrogen, in: Methods of Soil Analysis. American society of agronomy, Madison, pp. 1149–1178.

Camargo, Â.P. de, Camargo, M.B.P. de, 2001. Definition and outline for the phenological phases of arabic coffee under Brazilian tropical conditions. Agrometeorology 60, 65–68.

Cannell, M., 1971. Production and distribuition of dry matter in trees of *Coffea arabica* L. in Kenya as affected by seasonal climatic differences and the presence of fruits. Ann Appl Biol 67, 99–120.

Cannell, M.G.R., 1985. Physiology of the coffee crop, in: Clifford, N.M., Willson, K.C. (Eds.), Botany, Biochemistry and Production of Beans and Beverage. London, pp. 108–134.

Catani, R.A., Moraes, F.R.P., 1958. The coffee chemical composition. Revista de agricultura 33, 45–52.

Catani, R.A., Pellegrino, D., Alcarde, J., Graner, C., 1967. Variation in the concentration and amount of macro and micronutrients in the coffee fruit during development. Anais da E.S.A. "Luiz de Queiroz."

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Chang Biol 20, 3177–3190. https://doi.org/10.1111/gcb.12629

Chaves, A.R.M., Martins, S.C.V., Batista, K.D., Celin, E.F., DaMatta, F.M., 2012. Varying leaf-to-fruit ratios affect branch growth and dieback, with little to no effect on photosynthesis, carbohydrate or mineral pools, in different canopy positions of field-grown coffee trees. Environ Exp Bot 77, 207–218. https://doi.org/10.1016/j.envexpbot.2011.11.011

Cheng, L., Raba, R., 2009. Accumulation of macro- and micronutrients and nitrogen demand-supply relationship of "Gala'/'Malling 26" apple trees grown in sand culture. Journal of the American Society for Horticultural Science 134, 3–13. https://doi.org/10.21273/jashs.134.1.3

Cittadini, E.D., de Ridder, N., Peri, P.L., van Keulen, H., 2008. Relationship between fruit weight and the fruit-to-leaf area ratio, at the spur and whole-tree level, for three sweet cherry varieties, in: Acta Horticulturae. International Society for Horticultural Science (ISHS), Leuven, Belgium, pp. 669–672. https://doi.org/10.17660/ActaHortic.2008.795.105

Cornet, D., Sierra, J., Tournebize, R., 2015. Assessing allometric models to predict vegetative growth of yams in different environments. Agron J 107, 241–248. https://doi.org/10.2134/agronj14.0370

Corrêa, J.B., Garcia, A.W.R., Costa, P.C., 1986. Nutrient extraction by Mundo Novo and Catuaí coffee trees, in: Brazilian Congress of Coffee Research. São Lourenço, pp. 35–41.

DaMatta, F.M., Cunha, R.L., Antunes, W.C., Martins, S.C.V., Araujo, W.L., Fernie, A.R., Moraes, G.A.B.K., 2008. In field-grown coffee trees source-sink manipulation alters photosynthetic rates, independently of carbon metabolism, via alterations in stomatal function. New Phytologist 178, 348–357. https://doi.org/10.1111/j.1469-8137.2008.02367.x

Ding, N., Chen, Q., Zhu, Z., Peng, L., Ge, S., Jiang, Y., 2017. Effects of crop load on distribution and utilization of 13C and 15N and fruit quality for dwarf apple trees. Sci Rep 7, 1–9. https://doi.org/10.1038/s41598-017-14509-3

Epstein, E., 1965. Mineral metabolism, in: Bonner, J., Varner, J.E. (Eds.), Plant Biochemistry. Academic press, London, pp. 438–466.

Fernández, F.J., Ladux, J.L., Searles, P.S., 2015. Dynamics of shoot and fruit growth following fruit thinning in olive trees: Same season and subsequent season responses. Sci Hortic 192, 320–330. https://doi.org/10.1016/j.scienta.2015.06.028

Franck, Nicolas, Vaast, P., Génard, M., Dauzat, J., 2006. Soluble sugars mediate sink feedback down- regulation of leaf photosynthesis in field-grown *Coffea arabica* L. Trees 26, 517–525. https://doi.org/10.1093/treephys/26.4.517

Franck, Nicolás, Vaast, P., Génard, M., Dauzat, J., 2006. Soluble sugars mediate sink feedback down-regulation of leaf photosynthesis in field-grown Coffea arabica. Tree Physiol 26, 517–525.

González-Real, M.M., Baille, A., Liu, H.Q., 2008. Influence of fruit load on dry matter and N-distribution in sweet pepper plants. Sci Hortic 117, 307–315. https://doi.org/10.1016/j.scienta.2008.05.026

Guimarães, P.T.C., Garcia, A.W.R., Alvarez, V.H., Prezotti, L.C., Viana, A.S., Malavolta, E., Corrêa, J.B., Lopes, A.S., Nogueira, F.D., Monteiro, A.V.C., 1999. Coffee, in: Ribeiro, A.C., Guimarães, P.T.G., Alvarez, V.H. (Eds.), Recommendations for the Use of Correctives and Fertilizers in Minas Gerais State. Viçosa, pp. 289–302.

Haller, M.H., Magness, J.R., 1933. Relation of leaf area and position to quality of fruit and to bud differentiation in apples. Washington, D. C.

Haouari, A., van Labeke, M., Steppe, K., Mariem, F. ben, 2013. Fruit thinning affects photosynthetic activity, carbohydrate levels, and shoot and fruit development of olive trees grown under semiarid conditions. Functional Plant Biology 40(11), 1179–1186.

Hay, R.K.M., 1995. Harvest index: a review of its use in plant breeding and crop physiology. Annals of Applied Biology 126, 197–216. https://doi.org/10.1111/j.1744-7348.1995.tb05015.x

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., Dalgliesh, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F.Y., Wang, E., Hammer, G.L., Robertson, M.J., Dimes, J.P., Whitbread, A.M., Hunt, J., van Rees, H., McClelland, T., Carberry, P.S., Hargreaves, J.N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., Keating, B.A., 2014. APSIM - Evolution towards a new generation of agricultural systems simulation. Environmental Modelling and Software 62, 327–350. https://doi.org/10.1016/j.envsoft.2014.07.009

Jackson, M.L., 1958. Soil Chemical Analysis. Englewood Cliffs, New Jersey.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model, European Journal of Agronomy. https://doi.org/10.1016/S1161-0301(02)00107-7

Kumar, D., Tieszen, L.T., 1976. Some aspects of photosynthesis and related processes in *Coffea arabica* L. Kenya coffee 41, 309–315.

Kuyah, S., Sileshi, G.W., Rosenstock, T.S., 2016. Allometric models based on bayesian frameworks give better estimates of aboveground biomass in the miombo woodlands. Forests 7, 1–13. https://doi.org/10.3390/f7020013

Lima Filho, O.F., Malavolta, E., 2003. Studies on mineral nutrition of the coffee plant (*Coffea arabica* L. cv. catuaí vermelho). LXIV. Remobilization and re-utilization of nitrogen and potassium by normal and deficient plants. Brazilian Journal of Biology 63, 481–490.

Malavolta, E., Graner, E.A., Sarruge, J.R., Gomes, L., 1963. Macro and micronutrient extraction at harvest by the “Bourbon Amarelo”, “Caturra Amarelo” and “Mundo novo” varieties, in: Studies on Coffee Mineral Nutrition. Turrialba, Piracicaba, pp. 188–189.

Mancuso, M.A.C., Soratto, R.P., Crusciol, C.A.C., Castro, G.S.A., 2014. Effect of potassium sources and rates on arabica coffee yield, nutrition, and macronutrient export. Rev Bras Cienc Solo 38, 1448–1456.

Marschner, H., 1995. Mineral nutrition pf higher plants. Academic press, London.

Martinez, H.E.P., Neves, J.C.L., Alvarez, V.H., Shuler, J., 2019. Mineral Nutrition and Fertilization, in: Farah, A. (Ed.), Coffee: Production, Quality and Chemistry. Royal Society of Chemistry, London, pp. 163–201. https://doi.org/DOI https://doi.org/10.1039/9781782622437

Martínez-Alcántara, B., Iglesias, D.J., Reig, C., Mesejo, C., Agustí, M., Primo-Millo, E., 2015. Carbon utilization by fruit limits shoot growth in alternate-bearing citrus trees. J Plant Physiol 176, 108–117. https://doi.org/10.1016/j.jplph.2014.12.001

Martínez-Fuentes, A., Mesejo, C., Reig, C., Agustí, M., 2010. Timing of the inhibitory effect of fruit on return bloom of “Valencia” sweet orange (*Citrus sinensis* (L.) Osbeck). J Sci Food Agric 90, 1936–1943. https://doi.org/10.1002/jsfa.4038

Meland, M., 2009. Effects of different crop loads and thinning times on yield, fruit quality, and return bloom in Malus × domestica Borkh. ‘Elstar.’ J Hortic Sci Biotechnol 84, 117–121. https://doi.org/10.1080/14620316.2009.11512607

Millard, P., Grelet, G.A., 2010. Nitrogen storage and remobilization by trees: Ecophysiological relevance in a changing world. Tree Physiol 30, 1083–1095. https://doi.org/10.1093/treephys/tpq042

Mills, H.A., Jones, J.B.Jr., 1996. Plant nutrition manual II. MicroMacro Publishing, Athens, GA.

Moscardini, D.B., Souza, L.T., Mazzafera, P., Favarin, J.L., 2020. Total soluble sugars dynamics in coffee fruits under development. Journal of Agricultural Science 12, 94–100. https://doi.org/10.5539/jas.v12n5p94

Muhammad, S., Sanden, B.L., Lampinen, B.D., Saa, S., Siddiqui, M.I., Smart, D.R., Olivos, A., Shackel, K.A., DeJong, T., Brown, P.H., 2015. Seasonal changes in nutrient content and concentrations in a mature deciduous tree species: Studies in almond (*Prunus dulcis* (Mill.) D. A. Webb). European Journal of Agronomy 65, 52–68. https://doi.org/10.1016/j.eja.2015.01.004

Palmer, J.W., 1992. Effects of varying crop load on photosynthesis, dry matter production and partitioning of Crispin/M.27 apple trees. Tree Physiol 11, 19–33. https://doi.org/10.1093/treephys/11.1.19

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2011. AquaCrop reference manual, FAO–Land and water division.

Raij, B. van, 2011. Fertilidade do solo e manejo de nutrientes. International Plant Nutrition Institute, Piracicaba.

Roccuzzo, G., Zanotelli, D., Allegra, M., Giuffrida, A., Torrisi, B.F., Leonardi, A., Quiñones, A., Intrigliolo, F., Tagliavini, M., 2012. Assessing nutrient uptake by field-grown orange trees. European Journal of Agronomy 41, 73–80. https://doi.org/10.1016/j.eja.2012.03.011

Saa, S., Brown, P.H., 2014. Fruit presence negatively affects photosynthesis by reducing leaf nitrogen in almond. Functional Plant Biology 41, 884–891. https://doi.org/10.1071/FP13343

Sentelhas, P.C., 2020. Influence of climate on agricultural production. Piracicaba.

SeongTae, C., SeongCheol, K., GwangHwan, A., DooSang, P., EunSeok, K., 2016. Effects of different leaf-fruit ratios on uptake and partitioning of N and K in "Uenishiwase" persimmon trees. Sci Hortic 212, 69–73.

Sinclair, T.R., 1998. Historical changes in harvest index and crop nitrogen accumulation. Crop Sci 38, 638–643. https://doi.org/10.2135/cropsci1998.0011183X003800030002x

Smith, M.R., Rao, I.M., Merchant, A., 2018. Source-sink relationships in crop plants and their influence on yield development and nutritional quality. Front Plant Sci 871, 1–10. https://doi.org/10.3389/fpls.2018.01889

Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. European Journal of Agronomy 18, 289–307. https://doi.org/10.1016/S1161-0301(02)00109-0

Temesgen, H., Affleck, D., Poudel, K., Gray, A., Sessions, J., 2015. A review of the challenges and opportunities in estimating above ground forest biomass using tree-level models. Scand J For Res 30, 326–335. https://doi.org/10.1080/02827581.2015.1012114

Toro-Herrera, M.A., 2022. Source-sink patterns on coffee trees related to annual climate variability: an approach through isotopes, carbohydrates, and spectral analysis. Tese (doutorado) - Universidade Federal de Lavras, 164 p.

Vaast, P., Angrand, J., Franck, N., Dauzat, J., Génard, M., 2005. Fruit load and branch ring-barking affect on carbon allocation and photosynthesis of leaf and fruit of *Coffea arabica* in the field. Tree Physiol 25, 753–760. https://doi.org/10.1093/treephys/25.6.753

Vaast, P., Bertrand, B., Perriot, J.J., Guyot, B., Génard, M., 2006. Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica* L.) under optimal conditions. J Sci Food Agric 86, 197–204. https://doi.org/10.1002/jsfa.2338

Vaast, P., Génard, M., Dauzat, J., 2002. Modeling the effects of fruit load, shade and plant water status on coffee berry growth and carbon partitioning at the branch level. Acta Hortic 584, 57–62. https://doi.org/10.17660/ActaHortic.2002.584.5

Verreynne, J.S., Lovatt, C.J., 2009. The effect of crop load on budbreak influences return bloom in alternate bearing “Pixie” mandarin. Journal of the American Society for Horticultural Science 134, 299–307. https://doi.org/10.21273/jashs.134.3.299

Vymazal, J., 2016. Concentration is not enough to evaluate accumulation of heavy metals and nutrients in plants. Science of the Total Environment 544, 495–498. https://doi.org/10.1016/j.scitotenv.2015.12.011

Wakeel, A., Farooq, M., Qadir, M., Schubert, S., 2011. Potassium substitution by sodium in plants. CRC Crit Rev Plant Sci 30, 401–413. https://doi.org/10.1080/07352689.2011.587728

Whiting, M.D., Lang, G. a, 2004. ‘Bing’ sweet cherry on the dwarfing rootstock ‘Gisela 5’: thinning affects fruit quality and vegetative growth but not net CO_2 exchange. Journal of American Society of Horticultural Science 129, 407–415.

Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model. Transactions of the ASAE 32, 497–511. https://doi.org/https://doi.org/10.13031/2013.31032

3. VEGETATIVE GROWTH AND NUTRIENT DEMAND OF COFFEE AFTER PRUNING OF THE PLAGIOTROPIC BRANCHES - RAINFED AND IRRIGATED

Abstract

Pruning the plagiotropic branches of coffee trees is widely used to rejuvenate plants and boost berry production in irrigated and rainfed management. However, the vegetative growth and the nutrient demand are still unknown in pruned coffee crops, which hinders the development of crop fertilization strategies in these conditions. Therefore, this study aimed to determine the annual vegetative biomass and the macronutrient demand of coffee plants with plagiotropic branches pruned in rainfed and irrigated management. The experiment was carried out on arabica coffee with all plagiotropic branches pruned. The experimental design was completely randomized with two treatments (rainfed and irrigated) and eleven replicates. Vegetative biomass and its concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) were measured to predict nutrients accumulated in vegetative biomass and total nutrient demand. Under rainfed or irrigated management, the vegetative biomass growth and nutrient concentrations did not vary. However, it is important to consider that there was a satisfactory amount of rain during the growth cycle. The nutrient demand was the same for irrigated and rainfed management. K, N and Ca were the nutrients with the crop's highest concentration and most demanded, corresponding to 87% of the total macronutrient demand.

Keywords: Biomass; Nitrogen; Phosphorus; Potassium; Calcium; Magnesium; Sulfur

3.1. Introduction

Coffee is one of the most widely consumed beverages worldwide and one of the most marketed agricultural commodities globally, representing an important source of income for several Latin American, African and Asian countries (FAO, 2021). Brazil is the largest world coffee producer, followed by Vietnam and Colombia (USDA, 2022). The coffee grown in Brazil is over 2 million hectares and *Coffea arabica* L. and *Coffea canephora* Pierre species are responsible for the production (CONAB, 2020). The volume of coffee traded in 2021 by the country has internalized more than US$ 8 billion in foreign exchange revenues (CECAFÉ, 2022).

Pruning of the plagiotropic branches of coffee is widely used in Brazil. This practice modulates the plants' growth and helps translocate the nutrients to flowering parts or yield branches, rejuvenating old coffee plants and boosting berry production. Also, it improves plant architecture, which facilitates crop management, mainly mechanized; concentrates biannual production in just one year (zero harvest system), eliminating the need for costly harvests in the low year's harvest. Furthermore, nowadays, a greater number of plants per unit area has been used to increase productivity (Braccini et al., 2005; Pereira et al., 2007) and, under these conditions, plants present different characteristics compared to plants grown on a broader spacing, such as smaller canopy diameters and thinner stems (Martinez et al., 2007), which demand pruning management to reduce the effects of an excessive narrowing in the plants.

Although pruning the plagiotropic branches is a widely used practice in the coffee grown in Brazil, there are doubts about the vegetative growth and nutrient rates under these conditions. Studies on coffee nutrient demand are currently poor, so our ability to optimize fertilization strategies is limited. Most of the previous studies used standards fertilizer rate and to our knowledge, the nutrient demand of plants pruned to predict the fertilizer rates have not been studied. Some studies have also focused on the N rates and only a few have studied P and K rates, while there are no reports about the rates of other nutrient elements, such as Ca, Mg and S (Garcia et al., 2007; Japiassú, 2009; Matiello et al., 2007). In addition, more than 12% of the coffee cultivated area in Brazil is irrigated and is responsible for 30% of Brazil's total production (FENICAFÉ, 2020), which means the most productive areas. However, there is also no information about the nutrient demand for irrigated pruned coffee trees.

Determining the plant's vegetative growth and nutrient demand is essential to establishing adequate fertilization rates to support efficient fertilization management and improve nutrient use efficiency, which has been one of the biggest concerns lately. The annual nutrient demand of pruned coffee plants can be predicted by multiplying the total vegetative biomass produced in a growth cycle by its nutrient concentration. Therefore, this study aimed to determine the total vegetative biomass and the macronutrient demand of coffee plants with plagiotropic branches pruned over the growth cycle in rainfed and irrigated management.

3.2. Material and Methods

3.2.1. Plant material and growth conditions

The field experiment was carried out during the 2018/2019 growing season on arabica coffee (*Coffea arabica* L. cv Catucaí 2SL) in the municipality of Pedregulho, São Paulo state, Brazil (20°15'12.17"S; 47°33'54.17"W and 964 m above sea level). This genotype is one of the most productive in Brazil and is planted in wide environmental conditions. The local climate is classified as Cwb - Humid subtropical with dry winters and temperate summers (Köppen). Total rainfall was 1448 mm and the average temperature of 21.8 °C during the experimental period (Figure 8).

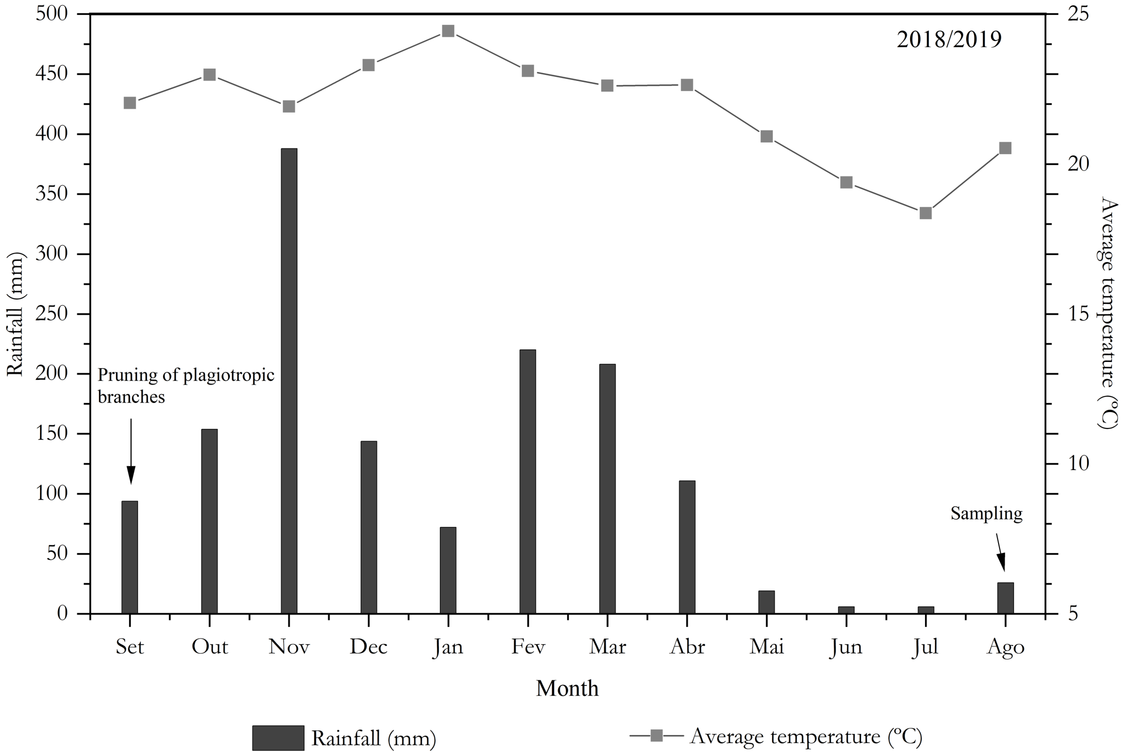


Figure 8. Mean monthly temperature and rainfall along the period of the field experiment. Black bars refer to total rainfall and gray line to average temperature.

The water balance from 2018 to 2019 is shown in Figure 9, including the experimental period. There was a 192 mm water deficit in the region during the two years, but only 92 mm during the experimental period.

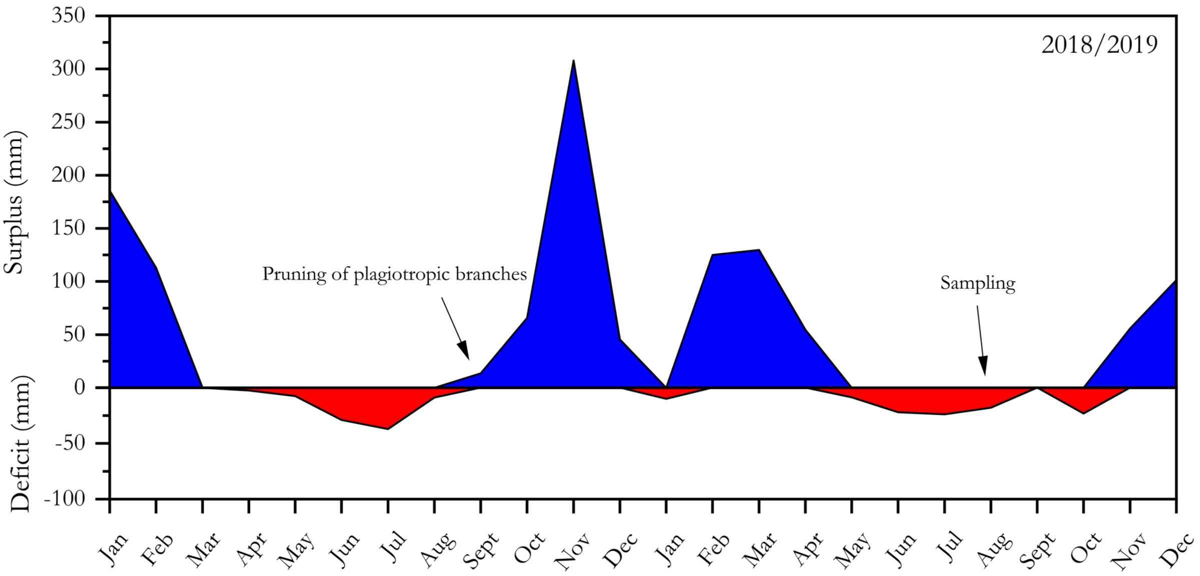


Figure 9. Water balance based on monthly climatology evapotranspiration and rainfall obtained according to Thornthwaite and Mather, (1955) and two years of growth, including the experimental period, in Pedregulho, São Paulo. We assumed 30 mm for soil water holding capacity as the monthly water balance (Sentelhas, 2020).

The coffee orchard was in the fourteenth production cycle with a tree arrangement of 3.2 x 0.6 m spacing (5208 plants per hectare) and in September 2018, after harvest, the plants were pruned and all plagiotropic branches were cut. Part of the crop was subsurface drip-irrigated with a flow rate of 8.000 L h^{-1} ha^{-1} and received an irrigation water depth of 99 mm from September 2018 to August 2019; another part was not irrigated - rainfed. The soil chemical and physical properties were characterized according to Table 7 before the installation of the experiments. After soil sampling and chemical analysis, fertilization was characterized and carried out according to the usual rate used by growers and recommended by the responsible agronomist, which was 310 kg ha^{-1} N and 270 kg ha^{-1} K_2O for both areas.

Table 7. Soil chemical and physical properties of the field experiment. Values describe 0-20 cm depth.

Field	pH	O.M	P	S	K	Ca	Mg	Al	H	CEC	Clay	Silt	Sand
	$CaCl_2$ 0.01mol L^{-1}	g dm^{-3}	-- mg dm^{-3} --		------------------- $mmol_c$ dm^{-3} -------------------						------- % -------		
Rainfed	4.6	25	60	44	2.2	19	6	0	40	67	19	4	77
Irrigated	5.2	23	67	21	2.0	29	8	0	26	65			

3.2.2. Experimental design

The experiment design was completely randomized with two treatments (rainfed and irrigated) and eleven replicates. Each tree consisted of an independent experimental unit. The plants were selected based on uniformity and vigor in both the irrigated and rainfed fields.

3.2.3. Growth parameters and nutrients measurements

In August 2019, all plagiotropic branches were cut from the orthotropic branch to determine vegetative biomass. Stem tips, branches and leaves (fresh vegetative biomass) were dried at 60°C in a forced-air oven for 72h to determine the dry matter. After dried, the material was crushed and all samples were ground into fine powder in a Wiley mill with a 20 mesh for measurement of P, K, Ca, Mg and S. Nitric-perchloric digestion was accomplished (Mills and Jones, 1996) and the total of these nutrients measured via radial visualization through an inductively coupled plasma optical emission spectrometer (ICP-OES; JobinYvon, JY50P Longjumeau, France) provided with a nebulization chamber. The samples were subjected to digestion with sulphuric acid (Jackson, 1958) and N was determined according to the analytical semi-micro Kjeldahl method (Bremner, 1965).

Nutrients accumulated (NA) in vegetative biomass were calculated by multiplying nutrient concentrations in the tissue and the amount of dry matter accumulated (Vymazal, 2016) (Equation 4):

$$\text{NA} = \text{nutrient concentration (g kg}^{-1}\text{) x dry matter (kg per plant)} \qquad \text{eq. 4}$$

Nutrient demand (ND) per hectare was estimated by multiplying the nutrient accumulated per plant and the number of plants per hectare (Equation 5):

$$\text{ND} = \text{nutrient accumulated (g per plant) x number of plants per hectare} \qquad \text{eq. 5}$$

3.2.4. Data analysis

Data were submitted to descriptive analysis using the SAS version 9.4 procedure PROC MEANS (SAS Institute Inc., Cary, NC, USA). The student's t-test was used to compare the mean values from non-paired samples growth of plants irrigated and rainfed. PROC TTEST (SAS Institute Inc.) procedure was applied at a significance level of 5% for all analyses.

3.3. Results

Table 8 depicts the dry matter measurements of vegetative biomass per plant in the rainfed and irrigated fields. There was no significant difference in vegetative biomass growth between irrigated and rainfed plants after one year of pruning the plagiotropic branches. Vegetative biomass per tree was 1574 ± 125 g and 1738 ± 110 g for the rainfed and irrigated fields, respectively. On average, each plant produced 1656 g of vegetative biomass over one growth cycle.

Table 8. Vegetative biomass per coffee plant grown over one year after pruning of the plagiotropic branches in the rainfed and irrigated fields in northeast São Paulo, Brazil (n = 11).

Field	**Minimum**	**Maximum**	**Mean (SE)**
	---------- g per plant ----------		
Rainfed	1045	2479	1574 (±125)
Irrigated	1234	2425	1738 (±110)
P value (Pr > F)			0.8183^{ns}

ns = comparison through the Student's t-test was not significant for P>0.05.

No significant effect was also observed in nutrient concentration evaluated in the vegetative biomass of plants grown in the rainfed and irrigated fields. K and N concentrations were the highest compared to the other nutrients. On average, K was 29.0 g kg^{-1} and N was 19.4 g kg^{-1}. The average concentration of P between the treatments was 3.6 g kg^{-1}, whereas for secondary macronutrients in the vegetative biomass of plants were: 16.2 g kg^{-1} Ca, 4.2 g kg^{-1} Mg and 1.1 g kg^{-1} S (Table 9).

Table 9. The concentration of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) in the vegetative coffee biomass of plants grown over one year after pruning of the plagiotropic branches in the rainfed and irrigated fields in northeast São Paulo, Brazil. Values are means of 11 replicates ± SE.

Nutrient	Rainfed	Irrigated	Average	P value
	---------- g kg^{-1} ----------			Pr > F
N	19.5 (±1.1)	19.4 (±1.2)	19.4	0.8028^{ns}
P	3.7 (±0.1)	3.6 (±0.1)	3.6	0.1841^{ns}
K	28.9 (±1.5)	29.2 (±2.2)	29.0	0.3816^{ns}
Ca	17.2 (±0.9)	15.3 (±0.9)	16.2	0.9752^{ns}
Mg	4.5 (±0.4)	4.0 (±0.4)	4.2	0.8978^{ns}
S	1.1 (±0.1)	1.1 (±0.1)	1.1	0.2406^{ns}

ns = comparisons through the Student's t-test were not significant for P>0.05.

Nutrient accumulation in the vegetative biomass of pruned coffee plants did not vary in a rainfed or irrigated field. K and N were the most accumulated nutrients in vegetative biomass due to the higher concentrations. On average, K was 44.7 g and N was 32.7 g per tree. The average accumulation of P between the treatments was 6.0 g per plant and the secondary macronutrients were: 26.7 g Ca, 6.9 g Mg and 1.9 g S per tree (Table 10).

Table 10. Accumulation of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) in the vegetative coffee biomass of trees grown over one year after pruning of the plagiotropic branches in the rainfed and irrigated fields in northeast São Paulo, Brazil. Values are means of 11 replicates ± SE.

Nutrient	Rainfed	Irrigated	Average	Pr > F
	---------- g per plant ----------			
N	30.6 (±2.5)	34.9 (±4.1)	32.7	0.1926^{ns}
P	5.7 (±0.4)	6.3 (±0.6)	6.0	0.3228^{ns}
K	45.4 (±1.8)	44.1 (±4.1)	44.7	0.0702^{ns}
Ca	27.6 (±1.7)	25.9 (±3.1)	26.7	0.1323^{ns}
Mg	6.8 (±0.5)	7.0 (±0.9)	6.9	0.1184^{ns}
S	1.7 (±0.1)	2.0 (±0.1)	1.9	0.9318^{ns}

ns = comparisons through the Student's t-test were not significant for P>0.05.

Macronutrient demand of coffee crop to vegetate over one year after pruning the plagiotropic branches in the rainfed or irrigated fields was estimated by multiplying nutrient accumulated per tree and the number of trees per hectare. K, N and Ca were the nutrients most demanded by the crop, respectively, corresponding to 87% of total macronutrient demand. Mg, P and S, demanded in smaller quantities, corresponded to 13% of the total macronutrient demand (Table 11).

Table 11. Nutrient demand of coffee plants per hectare* over one year after pruning the plagiotropic branches. Acronyms: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S).

N	P	K	Ca	Mg	S
kg ha^{-1}					
171	32	233	139	36	10

* Catucaí 2SL - 3.2 x 0.6 m spacing (5208 plants per hectare).

3.4. Discussion

In this study, we determined the vegetative biomass and the macronutrient demand of coffee plants with plagiotropic branches pruned, in rainfed and irrigated management, over the growth cycle. No significant difference between irrigated and rainfed plants was observed in vegetative biomass growth (Table 8). However, it is important to clarify that the total rainfall was above 1200 mm (1477 mm) with regular distribution over the growth cycle (Figure 8), which are conditions considered favorable for the commercial cultivation of coffee (Alègre, 1959; Camargo, 1977, 1974). The rainfall distribution was synchronized to the vegetation period from September/October (spring) to April/May (autumn). There was only a 10 mm water deficit in the rainy season, but this amount did not affect the vegetative growth of the plants in the rainfed field. From June to August, the humidity decreased (Figure 9), but it is normal due to the characteristic of dry winter in the region. By the way, a water deficit in this period, the phase prior to anthesis, does not cause damage to the plant and can become beneficial, favoring a more uniform flowering in the first rains of September (Camargo and Camargo, 2001). So, we can consider that there were no conditions that characterize an irrigated plot and another truly rainfed due to the high amount of rainfall during the experiment. Furthermore, we measure an average of 1.4 kg of vegetative biomass per coffee plant under rainfed management in other three experiments evaluating the vegetative growth in adult plants with no fruit load by manual de-fruiting (unpublished data). This value is close to the 1.6 kg per plant found in pruned plants (without fruit load) in this experiment (Table 8).

We also observed no effect of field management on nutrient concentration in the vegetative biomass (Table 9). The amount of rainfall favorable for the crop development during the experimental period may have also contributed to these results. In other experiments that we evaluated, the concentration of the nutrients in the vegetative biomass in plants with no fruit load and enough rainfall did not differ either (Souza and Favarin, 2018). K and N were the nutrients with the highest concentration in the vegetative biomass (Table 9) and, consequently, most required and accumulated by the pruned coffee plant (Table 10). Previous studies have shown that N and K are the nutrients required in most considerable amounts by coffee crops (Catani et al., 1967; Catani and Moraes, 1958; Corrêa et al., 1986; Lima Filho and Malavolta, 2003; Malavolta et al., 1963). In perennial plants such as coffee, N can be stored in various vegetative storage proteins, including bark storage proteins (Cooke and Weih, 2005; Millard and Grelet, 2010). It will support the starch and other carbohydrate production needed for fruit formation and growth in the next yield cycle (Martinez et al., 2019). K also plays an essential role in enzyme activation, stomatal function, photosynthesis, protein synthesis, stabilization of internal pH, turgor-related processes and transport of metabolites (Alva et al., 2006; Mancuso et al., 2014; Wakeel et al., 2011); therefore, it is also highly demanded by plants.

It is important to highlight that a part of the nutrient demand by fruiting can be supported by reserves when flower buds begin to develop (Lima Filho and Malavolta, 2003; Moscardini et al., 2020; Muhammad et al., 2020). Hence, it is possible that pruned plants with no fruit load, which is the strongest sink, vegetate and store nutrients for use during the reproductive cycle. This assumption is physiologically based because macronutrients, except Ca (i.e., N, P, K, Mg and S), are known to be highly mobile in the phloem, as reported by White, (2012). The remobilization of these nutrients has also been reported in unpruned coffee plants (Favarin et al., 2013; Lima Filho and Malavolta, 2003) and other woody species (Cherbuy et al., 2001; Maillard et al., 2015; Millard et al., 2006; Millard and Grelet, 2010). This may also be related to the high productivity of the pruned coffee plants in the next yield cycle since the plant accumulates reserves when it has no fruit (Chaves Filho and Oliveira, 2008).

A high amount of K was absorbed by plants since the K average concentration (Table 9) and, consequently, the accumulation in the vegetative biomass (Table 10) was the highest. This might be related to the high mobile of K in plants, accumulating in growing parts, including leaves, flowers and fruits, when there is high nutrient availability in the soil (Ragel et al., 2019). It is worth mentioning that K is an essential cation to support the mass production in the plant biomass and there are two main pools of this nutrient in plant cells: the vacuole and the cytosol. K concentration in the vacuole is variable and depends on K availability, while K concentration in the cytosol remains constant (Walker et al., 1996). Furthermore, plant root cells absorb K+ from the soil against the K+ concentration gradient, a process led by a set of transport systems and the K+ translocation from roots to shoots inside plants is also mediated by K+ transporters and channels, which facilitates its high concentration and, consequently, its accumulation in the plant (Wang and Wu, 2013). The K available to plants in this study was high since the K amount applied by the farm's fertilization program was 270 kg ha^{-1} K_2O (equivalent to 2.8 mmol$_c$ dm^{-3}) and the soil had an average of 2.1 mmol$_c$ dm^{-3} K (Table 7). The K average range of 1.5 to 3.0 mmol$_c$ dm^{-3} in the soil is considered adequate for productive coffee (Guimarães et al., 1999; Raij et al., 1996), demonstrating that the average content in the soil should have been sufficient for the vegetative growth of the pruned plants. The K fertilization was made to meet plant demand and maintain adequate levels in the soil for the next production cycle. However, the plants may have absorbed more than necessary, surpassing nutritional requirements, by K accumulation in the cells, causing luxury consumption. In addition, there was high availability of water during the crop cycle (Figure 9), which increased soil moisture and facilitated hydraulic conductivity, facilitating the mass flow and diffusion process.

Once the vegetative biomass and its nutrient concentration are known, it is possible to predict the nutrient demand for coffee after pruning the plagiotropic branches over a growth cycle. Here, we calculated the nutrient demand according to the density of plants in the orchard - 5208 plants per hectare. K, N and Ca were the nutrients most demanded by the crop, respectively, corresponding to 87% of total macronutrient demand and Mg, P and S were demanded in smaller quantities, corresponding to 13% of the total macronutrient demand (Table 11). We suppose this amount of nutrients accumulated in vegetation can be variable under different conditions such as plant age, genotypes, crop density, radiation availability, climatic conditions, nutrient content in the soil and water availability. Therefore, further studies are required to clarify the nutrient demand under different conditions. Nonetheless, this study may already assist in interpreting nutrient budgets and developing fertilization programs to adjust fertilizer application to nutrient demand and soil nutrient content for pruned coffee orchards.

3.5. Conclusion

This study demonstrated that with adequate amount (above 1200 mm) and rainfall distribution the coffee plant produces, on average, 1656 g of vegetative biomass over a growth cycle after pruning of the plagiotropic branches and the macronutrient demand for 5208 plants per hectare is 171 kg ha^{-1} N, 32 kg ha^{-1} P, 233 kg ha^{-1} K, 139 kg ha^{-1} Ca, 36 kg ha^{-1} Mg and 10 kg ha^{-1} S. However, there was a luxury consumption for K and more studies are needed to verify the demand for K without excessive availability of the nutrient.

References

Alègre, C., 1959. Climates et caféiers d'Arabie. Agronomie Tropicale 14, 23–58.

Alva, A.K., Mattos, D., Paramasivam, S., Patil, B., Dou, H., Sajwan, K.S., 2006. Potassium management for optimizing citrus production and quality. International Journal of Fruit Science 6, 3–43. https://doi.org/10.1300/J492v06n01_02

Braccini, A.D.L. e, Scapim, C.A., Vidigal Filho, P.S., Braccini, M.D.C.L., Borges, S.C., Albrecht, L.P., 2005. Agronomic traits and fruit and grain yield related to the increase of coffee plant density. Acta Sci Agron 27, 269–279. https://doi.org/10.4025/actasciagron.v27i2.1845

Bremner, J.M., 1965. Total nitrogen, in: Methods of Soil Analysis. American society of agronomy, Madison, pp. 1149–1178.

Camargo, Â.P. de, 1977. Climatic suitability zoning for arabica and robusta coffee in Brazil, in: Brazilian Institute of Geography and Statistics Foundation. SUPREN, Rio de Janeiro, pp. 68–76.

Camargo, Â.P. de, 1974. Coffee crop in Brazil: recommendations manual, in: Clima. Brazilian Coffee Institute, Rio de Janeiro, pp. 20–35.

Camargo, Â.P. de, Camargo, M.B.P. de, 2001. Definition and outline for the phenological phases of arabic coffee under Brazilian tropical conditions. Agrometeorology 60, 65–68.

Catani, R.A., Moraes, F.R.P., 1958. The coffee chemical composition. Revista de agricultura 33, 45–52.

Catani, R.A., Pellegrino, D., Alcarde, J., Graner, C., 1967. Variation in the concentration and amount of macro and micronutrients in the coffee fruit during development. Anais da E.S.A. "Luiz de Queiroz."

CECAFÉ. Council of Brazil Coffee Exporters, 2022. Monthly report: June 2022.

Chaves Filho, J.T., Oliveira, R.F. de, 2008. Seasonal variation of starch stored in plagiotropic branches of coffee. Goiania studies 35, 85–102.

Cherbuy, B., Joffre, R., Gillon, D., Rambal, S., 2001. Internal remobilization of carbohydrates, lipids, nitrogen and phosphorus in the Mediterranean evergreen oak Quercus ilex. Tree Physiol 21, 9–17. https://doi.org/10.1093/treephys/21.1.9

CONAB - National Supply Company, 2020. Monitoring the Brazilian crop: Coffee. Third Survey 2019/2020.

Cooke, J.E.K., Weih, M., 2005. Nitrogen storage and seasonal nitrogen cycling in Populus: Bridging molecular physiology and ecophysiology. New Phytologist 167, 19–30. https://doi.org/10.1111/j.1469-8137.2005.01451.x

Corrêa, J.B., Garcia, A.W.R., Costa, P.C., 1986. Nutrient extraction by Mundo Novo and Catuaí coffee trees, in: Brazilian Congress of Coffee Research. São Lourenço, pp. 35–41.

FAO, 2021. Food and Agriculture Organization of the United Nations [WWW Document]. URL http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor

Favarin, J.L., Tezotto, T., Neto, P., 2013. Nutritional balance in coffee: a case study. Visão Agrícola 79–81.

Garcia, A.L.A., Carvalho, C.H.S., Garcia, A.W.R., Souza, T., Reis, R.P., Padilha, L., 2007. Nitrogen fertilization levels for large coffee trees in the "safra zero" system, in: 33o Brazilian Congress of Coffee Research.

Guimarães, P.T.C., Garcia, A.W.R., Alvarez, V.H., Prezotti, L.C., Viana, A.S., Malavolta, E., Corrêa, J.B., Lopes, A.S., Nogueira, F.D., Monteiro, A.V.C., 1999. Coffee, in: Ribeiro, A.C., Guimarães, P.T.G., Alvarez, V.H. (Eds.), Recommendations for the Use of Correctives and Fertilizers in Minas Gerais State. Viçosa, pp. 289–302.

Jackson, M.L., 1958. Soil Chemical Analysis. Englewood Cliffs, New Jersey.

Japiassú, L.B., 2009. Pruning cycles and nitrogen fertilization in coffee fields conducted in the "Safra Zero" system. Universidade Federal de Lavras. Federal University of Lavras, Lavras.

Lima Filho, O.F., Malavolta, E., 2003. Studies on mineral nutrition of the coffee plant (*Coffea arabica* L. cv. catuaí vermelho). LXIV. Remobilization and re-utilization of nitrogen and potassium by normal and deficient plants. Brazilian Journal of Biology 63, 481–490.

Maillard, A., Diquélou, S., Billard, V., Laîné, P., Garnica, M., Prudent, M., Garcia-Mina, J.M., Yvin, J.C., Ourry, A., 2015. Leaf mineral nutrient remobilization during leaf senescence and modulation by nutrient deficiency. Front Plant Sci 6, 1–15. https://doi.org/10.3389/fpls.2015.00317

Malavolta, E., Graner, E.A., Sarruge, J.R., Gomes, L., 1963. Macro and micronutrient extraction at harvest by the "Bourbon Amarelo", "Caturra Amarelo" and "Mundo novo" varieties, in: Studies on Coffee Mineral Nutrition. Turrialba, Piracicaba, pp. 188–189.

Mancuso, M.A.C., Soratto, R.P., Crusciol, C.A.C., Castro, G.S.A., 2014. Effect of potassium sources and rates on arabica coffee yield, nutrition, and macronutrient export. Rev Bras Cienc Solo 38, 1448–1456.

Martinez, H.E.P., Augusto, H.S., Cruz, C.D., Pedrosa, A.W., Sampaio, N.F., 2007. Vegetative growth of the coffee plant (*Coffea arabica* L.) and its correlation with the production in narrower spacing. Acta Sci Agron 29, 481–489. https://doi.org/10.4025/actasciagron.v29i4.404

Matiello, J.B., Mendonça, S.M., Filho, S.L., 2007. "Esqueletamento" pruning cycles and coffee fertilization levels, in: 33o Brazilian Congress of Coffee Research. pp. 1–3.

Millard, P., Grelet, G.A., 2010. Nitrogen storage and remobilization by trees: Ecophysiological relevance in a changing world. Tree Physiol 30, 1083–1095. https://doi.org/10.1093/treephys/tpq042

Millard, P., Wendler, R., Grassi, G., Grelet, G.A., Tagliavini, M., 2006. Translocation of nitrogen in the xylem of field-grown cherry and poplar trees during remobilization. Tree Physiol 26, 527–536. https://doi.org/10.1093/treephys/26.4.527

Mills, H.A., Jones, J.B.Jr., 1996. Plant nutrition manual II. MicroMacro Publishing, Athens, GA.

Moscardini, D.B., Souza, L.T., Mazzafera, P., Favarin, J.L., 2020. Total soluble sugars dynamics in coffee fruits under development. Journal of Agricultural Science 12, 94–100. https://doi.org/10.5539/jas.v12n5p94

Muhammad, S., Sanden, B.L., Lampinen, B.D., Smart, D.R., Saa, S., Shackel, K.A., Brown, P.H., 2020. Nutrient Storage in the Perennial Organs of Deciduous Trees and Remobilization in Spring – A Study in Almond (Prunus dulcis) (Mill.) D. A. Webb. Front Plant Sci 11, 1–15. https://doi.org/10.3389/fpls.2020.00658

Pereira, S.P., Guimarães, R.J., Bartholo, G.F., Guimarães, P.T.G., Alves, J.D., 2007. Vegetative growth and yield of coffee plants (*Coffea arabica* L.) in two different pruning times, conducted at different spacings. Science and Agrotechnology 643–649.

Ragel, P., Raddatz, N., Leidi, E.O., Quintero, F.J., Pardo, J.M., 2019. Regulation of K+ nutrition in plants. Front Plant Sci 10. https://doi.org/10.3389/fpls.2019.00281

Raij, B. van, Cantarella, H., Quaggio, J.A., 1996. Coffee, in: Technical Bulletin 100: Fertilization and Liming Recommendations for the São Paulo State. Campinas Agronomic Institute, Campinas, pp. 97–101.

Sentelhas, P.C., 2020. Influence of climate on agricultural production. Piracicaba.

Souza, L.T. de, Favarin, J.L., 2018. Nutrient demand for vegetation and fruiting of *Coffea arabica* L. University of São Paulo, Piracicaba.

Thornthwaite, C.W., Mather, J.R., 1955. The water balance. Centerton, NJ: Drexel Institute of Technology - Laboratoryof Climatology VIII, 104.

USDA (United States Department of Agriculture), 2022. Coffee: world markets and trade.

Vymazal, J., 2016. Concentration is not enough to evaluate accumulation of heavy metals and nutrients in plants. Science of the Total Environment 544, 495–498. https://doi.org/10.1016/j.scitotenv.2015.12.011

Wakeel, A., Farooq, M., Qadir, M., Schubert, S., 2011. Potassium substitution by sodium in plants. CRC Crit Rev Plant Sci 30, 401–413. https://doi.org/10.1080/07352689.2011.587728

Walker, D.J., Leigh, R.A., Miller, A.J., 1996. Potassium homeostasis in vacuolate plant cells. Proc Natl Acad Sci U S A 93, 10510–10514. https://doi.org/10.1073/pnas.93.19.10510

Wang, Y., Wu, W.H., 2013. Potassium transport and signaling in higher plants. Annu Rev Plant Biol 64, 451–476. https://doi.org/10.1146/annurev-arplant-050312-120153

White, P., 2012. Long-distance in the xylem and phloem, in: Marschner, P. (Ed.), Mineral Nutrition of Higher Plants. Elsevier, Berlin, pp. 47–70. https://doi.org/10.1016/B978-0-12-384905-2.00003-0

4. COFFEE FERTILIZATION ACCORDING TO NUTRIENT DEMAND FROM SIMULTANEOUS SINKS: FRUITS AND VEGETATIVE GROWTH

Abstract

Awareness and interest in improving nutrient use efficiency have never been greater and one way to enhance this efficiency is to apply nutrients at the right rate. First, however, it is necessary to consider the plant nutrient demand to use the right rate. In perennial crops such as coffee, nutrient demand depends mainly on two sinks, fruits and vegetative growth. Therefore, we developed a coffee fertilization method - EsalqCafé - which consists of plant fertilization according to nutrient demand for vegetating and fruiting, considering the fruit load variation presented throughout cultivation. Then, the objective of this study was to validate this fertilization method. Three field experiments were carried out during the 2019/2020 growing season on arabica coffee (*Coffea arabica* L.) in three sites, Jacuí-MG, Pedregulho-SP and São Sebastião do Paraíso-MG. The experiment design was in randomized blocks with four treatments, which were fertilization methods (i) EsalqCafé, (ii) Boletim 100 (1997) (SP-1), (iii) Boletim 100 updated version (SP-2) and (iv) 5ª Aproximação (MG) with five replications. The variables analyzed were: crop yield, N leaf concentration and P and K content in the soil at harvest time. Compared to existing fertilization methods, the results revealed the method was sufficient to supply the plant nutrient demand, maintaining the N concentration in the leaf and the P and K content in the soil in the ideal range after harvest. However, further studies should be carried out to improve the method.

Keywords: Fertilizer rates; Productivity; Nitrogen; Phosphorus; Potassium

4.1. Introduction

In perennial plants such as *Coffea arabica* L., the active vegetative and reproductive growth, leading sinks, co-occur, which generates competition between these sinks for assimilation products by the plant. However, the fruits are the greatest physiological sink in adult plants regulating assimilates allocation and biomass partitioning between the sinks and, consequently, the total plant nutrient demand (Amaral et al., 2001; Bote and Jan, 2016; Cannell, 1985a; Nicolas Franck et al., 2006; Taiz and Zeiger, 2013; Vaast et al., 2006, 2005, 2002). Nevertheless, it is important to consider that the fruit load varies each growth cycle due to the coffee biennial characteristic, changing the plant nutrient demand yearly (DaMatta et al., 2010).

Official fertilizer recommendations in Brazil from the main coffee-producing states are provided by Guimarães et al., (1999), Minas Gerais state, named 5ª Aproximação and Raij et al., (1996), São Paulo state, named Boletim 100. These recommendations were elaborated years ago from the nutrient response curve experiments for N and relative harvest as a function of nutrient content for the other elements. They propose fertilizer rates based on expected yield and N concentration in the leaves and nutrient contents in the soil for the other elements. However, for current coffee growing conditions, these recommendations present shortcomings such as a wide range of productivity (600 kg ha^{-1}) for the same rate; a fixed rate for productivity greater than 3600 kg ha^{-1} for MG and 4800 kg ha^{-1} for SP; the amount of the fertilizer rate destined for the active vegetation is not presented and do not consider plant density (Guimarães et al., 1999; Raij et al., 1996).

The nutrient rate applied in the field needs to supply the total plant demand, considering the demand for fruiting and active vegetative growth to improve the coffee fertilization strategy (Malavolta et al., 2002; Riaño-

Herrera et al., 2004). In this study, the values of these demands were obtained by the product of the fruit and vegetation biomass and its nutrient concentration in previous field experiments (Souza and Favarin, 2018). The total biomass was estimated by employing allometric models, which express correlations between plant biomass and easily measurable variables (Cornet et al., 2015; Kuyah et al., 2016; Temesgen et al., 2015) and predicted the vegetative growth regarding the fruit load.

Based on these allometric models, we elaborate a new coffee fertilization method, called EsalqCafé, which consists of plant fertilization according to nutrient demand for vegetating and fruiting, considering the fruit load and vegetative growth variation presented throughout cultivation. Therefore, the objective of this study was to validate the fertilization method EsalqCafé for arabica coffee that considers the nutrient demand of the two simultaneous sinks - fruit load and the active vegetative growth, to estimate the necessary amount of nutrients for the development and maintenance of the productive plant. Furthermore, we hypothesize that a coffee fertilization program based on the sinks nutrients demand of the plant (fruiting and active vegetative) can be more adjusted, avoiding under or overestimated fertilizers rates.

4.2. Material and Methods

4.2.1. Plant material and growth conditions

Three field experiments were carried out during the 2019/2020 growing season on arabica coffee (*Coffea arabica* L.) in three sites, (i) Jacuí-MG, (21°6'32.32"S; 46°41'11.79"W and 1098 m above sea level), the coffee orchard (cv. Catuaí amarelo IAC 62) was in the sixth production cycle with a tree arrangement of 3.5 x 0.7 m spacing, (ii) Pedregulho-SP, (20°15'12.60"S; 47°33'52.60"W and 964 m above sea level), the coffee orchard (cv. Catucaí 2SL) was in the ninth production cycle, with a tree arrangement of 3.2 x 0.6 m spacing and (iii) São Sebastião do Paraíso-MG, (21°00'50.8"S; 46°53'38.0"W and 982 m above sea level), the coffee orchard (cv. Mundo Novo 379-19) was in the first production cycle, with a tree arrangement of 3.5 x 0.7 m spacing. The crops were submitted to best agricultural practices for commercial coffee bean production. The local climate of all sites is classified as Cwb - Humid subtropical with dry winters and temperate summers (Köppen). Average rainfall and temperature in the experimental period of all sites are featured in Figure 10.

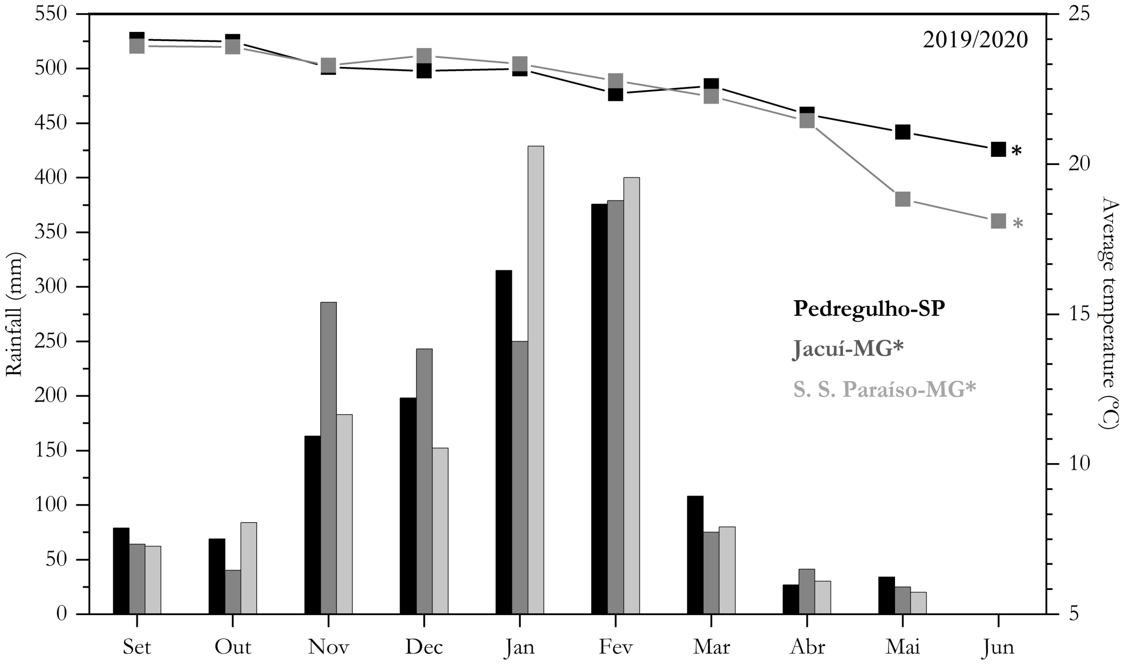


Figure 10. Mean monthly temperature and rainfall along the period of field experiments. Bars refer to total rainfall measured in each experimental field. * Lines refer to average temperature in the region: black line refers the region of Pedregulho-SP and gray lines refer the region of Jacuí-MG and S. S. Paraíso-MG.

4.2.1. Experimental design

The experiment design was in randomized blocks with four treatments, which were fertilization methods (i) EsalqCafé, (ii) Boletim 100 (1997) (SP-1), (iii) Boletim 100 updated version released in the "I Simpósio Sobre os Avanços na Nutrição de Citros e Café" (2018) of the Agronomic Institute of Campinas (SP-2) and (iv) 5ª Aproximação (MG) with five replications. Plots consisted of rows with 15 plants and the five central plants per plot were evaluated. Fertilization started in September, the beginning of the rainy season and was divided according to the recommendation of each method.

EsalqCafé consisted of several equations and was based on the total coffee demand for each nutrient (TDi, kg ha^{-1}) from other equations extracted from the ecophysiological model, as detailed below (Equation 6):

$$TD_i = (VD_i + FD_i) + \Delta X \qquad \text{eq. 6}$$

where: TD*i* represents the total coffee demand for nutrient *i* (kg ha^{-1}); VD*i* corresponds to the need for nutrient *i* to supply the active vegetative growth (kg ha^{-1}) (Equation 7), FD*i* refers to the amount of the same nutrient for the expected fruit yield (kg ha^{-1}) (Equation 8) and ΔX corresponds to the rate of element *i* necessary for raise the soil content to the content corresponding to 100% relative harvest, variable for each element (30 mg dm^{-3} P and 3 mmol$_c$ dm^{-3} K), except for N, when necessary. Considering the average utilization of 50% of the N applied to the soil, the determined rate will be corrected (TDnitrogen = TDnitrogênio x 2) (Fenilli et al., 2008; Pedrosa and Favarin, 2013).

$$VD_i = (VB \times VC_i)/1000 \qquad \text{eq. 7}$$

where: VD*i* represents the need for nutrient *i* to supply the active vegetative growth (kg ha^{-1}); VB corresponds to the active vegetation biomass (kg ha^{-1}) (Equation 9); VC*i* refers to the concentration of element *i* in the active vegetation biomass (g kg^{-1}) and the factor 1000 was used to obtain the result in kg ha^{-1};

$$FD_i = (FB \times FC_i)/1000 \qquad \text{eq. 8}$$

where: FD*i* represents the nutrient requirement for the expected fruit yield (kg ha^{-1}); FB corresponds to fruit biomass, based on the expected productivity (kg ha^{-1}) (Equation 10); FC*i* refers to the concentration of nutrient *i* in the fruit biomass (g kg^{-1}) and the factor 1000 was used to obtain the result in kg ha^{-1};

$$VB = [(c - bx + ax^2) \times NP]/1000 \qquad \text{eq. 9}$$

where: VB represents the active vegetation biomass (kg ha^{-1}); a, b and c correspond to the values obtained in the second-degree equation ($y = 1352.96 - 164.48x + 8.69x^2$) of the correlation between the fruit load (L per plant) and the vegetation dry matter (g per plant), x is the fruit load per plant (L per plant) (Appendix F); NP is the number of plants per hectare and the factor 1000 was introduced to obtain the result in kg ha^{-1};

$$FB = [(a + bx) \times NP]/1000 \qquad \text{eq. 10}$$

where: FB corresponds to fruit biomass, based on the expected productivity (kg ha^{-1}); a and b correspond to the values obtained in the first-degree equation ($y = 49.98 + 199.38x$) of the correlation between the fruit load (L per plant) and the fruit dry yield (g per plant) and x is the fruit load (L per plant) (Appendix F); NP is the number of plants per hectare and the factor 1000 was introduced to obtain the result in kg ha^{-1}.

4.2.2. Soil chemical analysis and plant nutritional status

Before the carry-out of experiments, soil samples (0-20 cm) were collected using a soil probe and sent to the analytical laboratory to assess the fertility of the coffee crop fields, necessary to adjust the rates of each treatment for nutrients. Chemical and physical properties were characterized according to Table 12. Dolomitic lime was used for soil-acidity correction and when necessary, boric acid was applied to raise B levels in the soil according to Quaggio and Raij, (1996). At harvest, soil samples were collected in the same way from each plot to perform chemical analysis and assess the soil fertility after fertilization and plant growth.

Table 12. Soil chemical and physical properties of field experiments before the carry out of experiments. Values describes 0-20 cm depth.

Site	pH	O.M	P	S	K	Ca	Mg	Al	H	CEC	Cu	Fe	Zn	Mn	B	Clay	Silt	Sand
	$CaCl_2$ 0.01mol L^{-1}		resin															
		g dm^{-3}	-- mg dm^{-3} --		------------ mmol$_c$ dm^{-3} -----------						---------- mg dm^{-3} ----------					--------- % ---------		
Jacuí	4.2	23	24	9	1.6	8	4	7	40	61	1.3	51	1.7	2.7	0.83	30	7	63
Pedregulho	4.3	14	18	8	4.2	13	4	4	30	55	3.0	33	3.7	4.8	0.37	19	4	77
S. S. Paraíso	4.9	25	7	14	4.4	23	11	1	27	66	1.5	38	2.0	5.1	1.45	34	29	37

In December 2019, approximately 200 leaves (50 leaves of each treatment) from the third and fourth pair of the fruitful branches (plagiotropic) were collected on both sides and at the average height of the plants of all treatments at each experimental site. Then, the leaves were washed in deionized water and dried at 60°C in a forced-air oven until constant weights. After drying, the material was crushed and all samples were ground into fine powder in a Wiley mill with a 20 mesh for measurement of P, K, Ca, Mg, S, B, Zn, Cu, Fe and Mn. Nitric-perchloric digestion was accomplished (Mills and Jones, 1996). The total of these nutrients was measured via radial visualization through an inductively coupled plasma optical emission spectrometer (ICP-OES; JobinYvon, JY50P Longjumeau, France) provided with a nebulization chamber. To determine the total-N concentration, the samples were subjected to digestion with sulphuric acid (Jackson, 1958) and N was determined according to the analytical semi-micro Kjeldahl method (Bremner, 1965) to evaluate the nutritional status of the plant to adjust the nitrogen rates according to the official manual's recommendations. The N concentrations of all treatments were above, but close, to the adequate range, 25-30 g kg^{-1}. Therefore, we decided to maintain the rates considering the N range at adequate concentration. At that time, the rates applied according to the plots in S. S. Paraíso-MG were still the same for all treatments. Therefore, one analysis was carried out for the entire experimental area. Nutrient concentration is described in Table 13. At harvest, approximately 50 leaves were collected in the same way from each plot to perform chemical analysis and evaluate the plant's nutritional status after fertilization.

Table 13. Plants nutritional status in December 2019.

Site		N	P	K	Ca	Mg	S	B	Zn	Cu	Fe	Mn
		------------------------------- g kg^{-1} --------------------------------						------------ mg kg^{-1} ------------				
Jacuí-MG	EsalqCafé	31.5	1.6	25.6	11.4	4.3	1.6	42	14	16	84	88
	SP-1	35.7	2.0	24.9	9.7	4.2	1.3	34	16	14	96	80
	SP-2	32.9	1.4	22.7	11.3	4.2	1.3	37	16	18	96	84
	MG	35.0	1.6	25.6	9.4	4.0	1.4	40	15	16	96	66
Pedregulho-SP	EsalqCafé	31.5	1.7	26.4	13.8	3.8	1.4	56	17	40	124	52
	SP-1	31.5	1.6	25.6	16.1	4.1	1.4	63	16	46	128	70
	SP-2	30.1	1.7	24.1	14.9	4.0	1.6	50	15	36	128	58
	MG	30.1	1.4	25.6	12.9	3.6	1.4	37	15	42	124	108
S. S. Paraíso-MG		35.0	1.4	17.7	10.2	3.3	1.3	46	9	16	120	102

The rates of nutrients (N, P_2O_5 and K_2O) calculated according to the described methods and the soil chemical results of each experimental site are presented in Table 14. In São Sebastião do Paraíso-MG, it was not possible to apply the rate recommended by the SP-1 method since two installments had already been made by the coffee grower, who had already applied 110 kg ha^{-1} K_2O and this rate exceeded the recommendation of the method that was 50 kg ha^{-1} K_2O.

Table 14. Fertilizer rates (N, P_2O_5 and K_2O) calculated according to each fertilization method and soil analysis for each experimental site.

Site	Expected productivity*		Fertilization method	N	P_2O_5	K_2O
	kg ha^{-1}	**Bags ha^{-1}			kg ha^{-1}	
Jacuí-MG 2019/2020	2700	45	EsalqCafé	220	27	181
			SP-1	200	40	140
			SP-2	220	60	180
			MG	260	0	260
Pedregulho-SP 2019/2020	3000	50	EsalqCafé	278	32	217
			SP-1	200	40	80
			SP-2	220	60	140
			MG	260	15	175
S. S. Paraíso-MG 2019/2020	2100	35	EsalqCafé	210	24	163
			SP-1	160	50	-
			SP-2	200	60	120
			MG	220	40	150

* Green beans, ** bags = 60 kg

4.2.3. Crop yield

The coffee fruits were harvested manually at the mature stage, packed in jute bags and then dried in the sun. At the end of approximately four weeks of drying and with ~12% water concentration (moisture of the commercialized beans), the fruits were weighed to obtain the weight of processed grains for calculating yield per hectare (productivity). Fruits were de-husked and beans were weighed to obtain ready-to-be-roast coffee beans, hereafter called green beans.

4.2.4. Data analysis

The datasets were subjected to residual normality and variance homogeneity tests. The Analysis of Variance (ANOVA) and regression model assumptions were met and no transformation was performed. The ANOVA F test was performed considering <0.05 probability through SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). When F probability was significant, the means were compared by Tukey's multiple range test ($P < 0.05$).

4.3. Results

4.3.1. Jacuí-MG

No significant effect was observed in fruit yield and, consequently, in green beans of the coffee plants fertilized by methods EsalqCafé, Boletim 100 (SP-1), Boletim 100 updated version (SP-2) and 5ª Aproximação (MG). On average, each plant produced 1.5 kg of fruit dry yield, corresponding to 6028 kg ha^{-1}. After being processed, this quantity of fruits corresponded to 859 g per plant of green beans and 3507 kg ha^{-1} or 58 bags ha^{-1} (Table 15).

Table 15. Effects of different fertilization methods on coffee fruit yield. Jacuí-MG, Brazil, 2019/2020 harvest. Values are means (n = 5) and the same letters indicate no significant differences among the samples by one-way ANOVA (Tukey, $p < 0.05$).

Fertilization method	Fruit dry		Green beans		
	kg per plant	kg ha^{-1}	g per plant	kg ha^{-1}	Bags* ha^{-1}
EsalqCafé	1.5 a	5945 a	844 a	3445 a	57 a
SP-1	1.6 a	6474 a	925 a	3775 a	63 a
SP-2	1.5 a	6119 a	870 a	3550 a	59 a
MG	1.4 a	5573 a	798 a	3259 a	54 a
AVERAGE	1.5	6028	859	3507	58
ANOVA					
P value (Pr > F)	0.5343^{ns}	0.5343^{ns}	0.5730^{ns}	0.5730^{ns}	0.5730^{ns}
CV	16.0	16.0	16.5	16.5	16.5

ns: not significant, * bags = 60 kg
cv. Catuaí amarelo IAC 62 - 3.7 x 0.7 m spacing.

The fertilization method also did not affect leaf N concentration in plants, where the average among all treatments was 25 g kg^{-1} dry leaf mass and the P and K content in the soil, which the average among all treatments was 24 mg dm^{-3} and 2.3 mmol$_c$ dm^{-3}, respectively, at harvest time (Table 16).

Table 16. Effects of different fertilization methods in the N nutrition status of coffee and P and K content in the soil. Jacuí-MG, Brazil, 2019/2020 harvest. Values are means (n = 5) and the same letters indicate no significant differences among the samples by one-way ANOVA (Tukey, $p < 0.05$).

Fertilization method	N	P	K
	g kg^{-1}	mg dm^{-3}	mmol$_c$ dm^{-3}
EsalqCafé	24 a	17 a	2.4 a
SP-1	24 a	23 a	2.1 a
SP-2	25 a	28 a	2.2 a
MG	27 a	29 a	2.4 a
AVERAGE	25	24	2.3
ANOVA			
P value (Pr > F)	0.4618^{ns}	0.5249^{ns}	0.5218^{ns}
CV	10.6	60.7	15.3

ns: not significant
cv. Catuaí amarelo IAC 62 - 3.7 x 0.7 m spacing.

4.3.2. Pedregulho-SP

No significant effect was also observed in fruit yield and green beans of the coffee plants fertilized by methods EsalqCafé, Boletim 100 (SP-1), Boletim 100 updated version (SP-2) and 5ª Aproximação (MG) in Pedregulho-SP. Each plant produced 1.4 kg of fruit dry yield in this experimental site, corresponding to 7236 kg ha^{-1}. After being processed, this quantity of fruits corresponded to 784 g per plant of green beans and 4081 kg ha^{-1} or 68 bags ha-1 (Table 17).

Table 17. Effects of different fertilization methods on coffee fruit yield. Pedregulho-SP, Brazil, 2019/2020 harvest. Values are means (n = 5) and the same letters indicate no significant differences among the samples by one-way ANOVA (Tukey, $p < 0.05$).

Fertilization method	Fruit dry		Green beans		
	kg per plant	kg ha^{-1}	g per plant	kg ha^{-1}	Bags* ha^{-1}
EsalqCafé	1.4 a	7352 a	800 a	4164 a	70 a
SP-1	1.4 a	7547 a	815 a	4247 a	71 a
SP-2	1.3 a	6802 a	734 a	3825 a	64 a
MG	1.4 a	7241 a	785 a	4087 a	68 a
AVERAGE	1.4	7236	784	4081	68
			ANOVA		
P value (Pr > F)	0.8776^{ns}	0.8738^{ns}	0.8783^{ns}	0.8783^{ns}	0.8695^{ns}
CV	20.3	20.2	21.0	21.0	20.8

ns: not significant, * bags = 60 kg
cv. Catucaí 2SL - 3.2 x 0.6 m spacing.

The fertilization method also did not affect leaf N concentration in plants in Pedregulho-SP, where the average among all treatments was 23 g kg^{-1} dry leaf mass and the P content in the soil, which the average among all treatments was 42 mg dm^{-3}, at harvest time. However, in this experimental site, the fertilization method affected the K content in the soil. EsalqCafé provided the highest content, 3.8 mmol$_c$ dm^{-3} and Boletim 100 (SP-1) the lowest, 1.6 mmol$_c$ dm^{-3} (Table 18).

Table 18. Effects of different fertilization methods in the N nutrition status of coffee and P and K content in the soil. Pedregulho-SP, Brazil, 2019/2020 harvest. Values are means (n = 5) and the same letters indicate no significant differences among the samples by one-way ANOVA (Tukey, $p < 0.05$).

Fertilization method	N	P	K
	g kg^{-1}	mg dm^{-3}	mmol$_c$ dm^{-3}
EsalqCafé	24 a	39 a	3.8 a
SP-1	24 a	42 a	1.6 b
SP-2	23 a	41 a	3.3 ab
MG	22 a	46 a	3.0 ab
AVERAGE	23	42	-
		ANOVA	
P value (Pr > F)	0.2539^{ns}	0.8799^{ns}	0.0189*
CV	7.5	34.8	31.9

ns: not significant
cv. Catucaí 2SL - 3.2 x 0.6 m spacing.

4.3.3. São Sebastião do Paraíso-MG

In the same way, no significant effect was also observed in fruit yield and green beans of the coffee plants fertilized by methods EsalqCafé, Boletim 100 (SP-1), Boletim 100 updated version (SP-2) and 5ª Aproximação (MG) in São Sebastião do Paraíso-MG. As a result, each plant produced 1.5 g of fruit dry yield in this experimental site, corresponding to 6007 kg ha^{-1}. After being processed, this quantity of fruits corresponded to 849 g per plant of green beans and 3467 kg ha^{-1} or 57 bags ha^{-1} (Table 19).

Table 19. Effects of different fertilization methods on coffee fruit yield. São Sebastião do Paraíso-MG, Brazil, 2019/2020 harvest. Values are means (n = 5) and the same letters indicate no significant differences among the samples by one-way ANOVA (Tukey, $p < 0.05$).

Fertilization method	Fruit dry		Green beans		
	kg per plant	kg ha^{-1}	g per plant	kg ha^{-1}	Bags* ha^{-1}
EsalqCafé	1.5 a	6063 a	859 a	3506 a	58 a
SP-1	1.4 a	5716 a	810 a	3305 a	55 a
SP-2	1.5 a	6002 a	843 a	3443 a	57 a
MG	1.5 a	6249 a	885 a	3615 a	60 a
AVERAGE	1.5	6007	849	3467	57
			ANOVA		
P value (Pr > F)	0.7877^{ns}	0.7841^{ns}	0.8402^{ns}	0.8402^{ns}	0.8252^{ns}
CV	13.8	13.7	15.8	15.8	15.9

ns: not significant, * bags = 60 kg
cv. Mundo Novo - 3.7 x 0.7 m spacing.

The fertilization method also did not affect leaf N concentration in plants, where the average among all treatments was 25 g kg^{-1} dry leaf mass and the P and K content in the soil, which the average among all treatments was 12 mg dm^{-3} and 3.9 mmol$_c$ dm^{-3}, respectively, at harvest time (Table 20).

Table 20. Effects of different fertilization methods in the N nutrition status of coffee and P and K in the soil. São Sebastião do Paraíso-MG, Brazil, 2019/2020 harvest. Values are means (n = 5) and the same letters indicate no significant differences among the samples by one-way ANOVA (Tukey, $p < 0.05$).

Fertilization method	N	P	K
	g kg^{-1}	mg dm^{-3}	mmol$_c$ dm^{-3}
EsalqCafé	25 a	10 a	4.6 a
SP-1	25 a	15 a	-
SP-2	25 a	11 a	3.8 a
MG	26 a	13 a	3.4 a
AVERAGE	25	12	3.9
		ANOVA	
P value (Pr > F)	0.8204^{ns}	0.5847^{ns}	0.4975^{ns}
CV	9.6	49.6	29.6

ns: not significant
cv. Mundo Novo - 3.7 x 0.7 m spacing.

4.4. Discussion

In this study, we compared four methods of coffee fertilization, three already existing and used by growers and one developed based on our previous research that considers the nutrient demand of the two simultaneous sinks - fruit load and active vegetative growth. Although fertilization methods differed in rates, there was no significant effect on coffee production among the treatments in the three research sites (Tables 15, 17 and 19). Furthermore, the productivity was high in all areas, considering the national average is ~30 bags per hectare (CONAB, 2022). Also, we highlight that the productivity was higher than expected (Table 14), which was estimated according to the production history of the orchards. On the overall average, 2019/2020 was a year of high productivity in the country (CONAB, 2022).

In Jacuí-MG, N rates ranged from 200 to 260 kg ha^{-1}, P_2O_5 rates ranged from 27 to 60 kg ha^{-1} and K_2O rates ranged from 140 to 260 kg ha^{-1} (Table 14). There was also no significant difference in the N nutritional status of coffee and P and K content in the soil at this site at harvest time (Table 16). In December 2019, the leaf N content was, on average, 34 g kg^{-1} (Table 13); at harvest, the average was 25 g kg^{-1} (Table 16). The range considered adequate is 25 to 30 g kg^{-1} (Quaggio et al., 2022), showing that the foliar N concentration in December was slightly above the ideal for all treatments. The concentration remained in the ideal range at harvest time, indicating that the plant had been well nourished with N after production and that the rates applied were sufficient. P and K content in the soil were adequate before the installation of the experiments according to Quaggio et al., (2022), which were 24 mg dm^{-3} P and 1.6 mmol dm^{-3} K (Table 12), since the ideal is 16 to 40 mg dm^{-3} P and 1.6 to 3.0 mmol dm^{-3} K. After harvest the P content in the soil remained at an average of 24 mg dm^{-3} P indicating that the rates met the plant's demand and the K content increased to an average of 2.3 mmol dm^{-3} indicating that the rates also met the plant's demand and increased the K soil content (Table 16).

In Pedregulho-SP, N rates ranged from 200 to 278 kg ha^{-1}, P_2O_5 rates ranged from 30 to 60 kg ha^{-1} and K_2O rates ranged from 80 to 217 kg ha^{-1} (Table 14). There was also no significant difference in the N nutritional status of coffee and P content in the soil at this site at harvest time (Table 18). In December 2019, the leaf N concentration was, on average, 31 g kg^{-1} (Table 13), also slightly above the ideal. At harvest, the average was 23 g kg^{-1} (Table 18), a little below the ideal concentration. The P content in the soil was adequate before the installation of the experiments, 18 mg dm^{-3} (Table 12) and at the harvest time, the P content was 42 mg dm^{-3} (Table 18). The P rates of the treatments would not be enough to raise the P content of the soil to 42 mg dm^{-3}. Therefore, we believe that there was a sampling error for this variable. There was a difference in the K content in the soil at the harvest time in this site. Before the application of the treatments, the K content in the soil was above the ideal, 4.2 mmol dm^{-3} (Table 12). We observed that the EsalqCafé method maintained the soil content above the ideal, 3.8 mmol dm^{-3} and the rate of the SP-1 method provided the lowest K content in the soil, 1.6 mmol dm^{-3} (Table 18). Probably, the SP-1 method caused this decrease because it was the lowest K (80 kg ha^{-1} K_2O), demonstrating that the K rate of this method was insufficient for the needs of the plant, resulting in a significant decrease of soil K reserves. In general, there was a slight decrease in the K content of the soil for the other treatments, which may be a consequence of the sandy soil texture of the soil, which facilitates the leaching of K^+ in the soil profile. Sandy soils present low cation exchange capacity (CEC); therefore, few negative charges to hold K^+ or other cations (Rosolem and Steiner, 2017).

In São Sebastião do Paraíso-MG, N rates ranged from 160 to 220 kg ha^{-1}, P_2O_5 rates ranged from 24 to 60 kg ha^{-1} and K_2O rates ranged from 120 to 163 kg ha^{-1}. There was also no significant difference in the N nutritional status of coffee and P and K content in the soil at this site at harvest time. In December 2019, the leaf N concentration was 35 g kg^{-1} (Table 13); at harvest, the average was 25 g kg^{-1} (Table 20). The P content in the soil was low before the installation of the experiment, 7 mg dm^{-3} (Table 12). At the harvest time, the P content in the soil was 12 mg dm^{-3} (Table 20), indicating an increase but remaining suboptimal. On the other hand, the K content in the soil was above the ideal before the installation of the experiments, 4.4 mmol dm^{-3} (Table 12) and remained above ideal, 4 mmol dm^{-3} (Table 20).

N rates were sufficient in all areas to supply the plant's demand, even though productivity was higher than expected. Theoretically, the rates applied would not be enough to meet the plant's needs, as production was higher and, therefore, higher demand. However, after analyzing the nutritional status of the plants in December, the concentrations were just above the ideal range and we decided to consider the ideal range for rate adjustment. This decision kept the rates slightly higher than considering the N concentration above the adequate range. Therefore, the rates of N were sufficient to supply the demand for the productivity obtained. In the case of the EsalqCafé method, the rate applied for lower productivity was also enough to supply the demand. In this case, we must rethink the fertilizer recovery efficiency of 50%. We hypothesize that the efficiency is higher and we underestimated it in the calculations. P rates that should be applied for the productivity obtained are very similar to the rates used and, in some treatments, the same. Therefore, it was not a limiting factor for production. Generally, the K rates to supply the demand of the obtained productivity should be a little higher for all treatments. However, although the rates applied did not affect productivity, we observed a decrease in the K content of the soil in the studied areas, except for Jacuí-MG (Tables 16, 18 and 20). This finding can be seen in the comparative table of rates (Table 21) in Appendix G.

4.5. Conclusion

The fertilization method EsalqCafé for arabica coffee considers the nutrient demand of the two simultaneous sinks - fruit load and active vegetative growth. Moreover, it relies on a minimal number of inputs to allow easy use. Compared to existing fertilization methods, our results revealed the method was sufficient to supply the plant nutrient demand, maintaining the N concentration in the leaf and the P and K content in the soil in the ideal range after harvest. These results show that studies are advanced; however, further studies should be carried out to improve the method and be fully validated, mainly on the efficiency of nitrogen fertilizer recovery considered in the calculation and its use in recommendations with expected yield closer to the yield obtained.

References

Amaral, J.A.T., da Matta, F.M., Rena, A.B., 2001. Effects of fruiting on the growth of arabica coffee trees as related to carbohydrate and nitrogen status and to nitrate reductase activity. Brazilian Journal of Plant Physiology 13, 66–74. https://doi.org/10.1590/S0103-31312001000100008

Bote, A.D., Jan, V., 2016. Branch growth dynamics, photosynthesis, yield and bean size distribution in response to fruit load manipulation in coffee trees. Trees 30, 1275–1285. https://doi.org/10.1007/s00468-016-1365-x

Bremner, J.M., 1965. Total nitrogen, in: Methods of Soil Analysis. American society of agronomy, Madison, pp. 1149–1178.

Cannell, M.G.R., 1985. Coffee: botany, biochemistry and production of beans and beverage., in: Clifford, M., Wilson, K. (Eds.), Physiology of the Coffee Crop. Croom Helm Ltd, London, pp. 108–134.

CONAB, C.N. de A., 2022. Acompanhamento da safra brasileira de café. Brasília, DF.

Cornet, D., Sierra, J., Tournebize, R., 2015. Assessing allometric models to predict vegetative growth of yams in different environments. Agron J 107, 241–248. https://doi.org/10.2134/agronj14.0370

DaMatta, F.M., Ronchi, C.P., Maestri, M., Barros, R.S., 2010. Coffee: environment and crop physiology, in: Ecophysiology of Tropical Tree Crops. Nova Science Publishers, New York, pp. 181–216.

Fenilli, T.A.B., Reichardt, K., Favarin, J.L., Bacchi, O.S., Silva, A.L., Timm, L.C., 2008. Fertilizer 15N balance in a coffee cropping system: a case study in Brazil. Rev Bras Cienc Solo 32, 1459–1469.

Franck, N., Vaast, P., Génard, M., Dauzat, J., 2006. Soluble sugars mediate sink feedback down- regulation of leaf photosynthesis in field-grown Coffea arabica. Trees 26, 517–525. https://doi.org/10.1093/treephys/26.4.517

Guimarães, P.T.C., Garcia, A.W.R., Alvarez, V.H., Prezotti, L.C., Viana, A.S., Malavolta, E., Corrêa, J.B., Lopes, A.S., Nogueira, F.D., Monteiro, A.V.C., 1999. Coffee, in: Ribeiro, A.C., Guimarães, P.T.G., Alvarez, V.H. (Eds.), Recommendations for the Use of Correctives and Fertilizers in Minas Gerais State. Viçosa, pp. 289–302.

Jackson, M.L., 1958. Soil Chemical Analysis. Englewood Cliffs, New Jersey.

Kuyah, S., Sileshi, G.W., Rosenstock, T.S., 2016. Allometric models based on bayesian frameworks give better estimates of aboveground biomass in the miombo woodlands. Forests 7, 1–13. https://doi.org/10.3390/f7020013

Malavolta, E., Favarin, J.L., Malavolta, M., Cabral, C.P., Heinrichs, R., Machado Silveira, J.S., 2002. Nutrients repartition in the coffee branches, leaves and flowers. Pesqui Agropecu Bras 37, 1017–1022. https://doi.org/10.1590/S0100-204X2002000700016

Mills, H.A., Jones, J.B.Jr., 1996. Plant nutrition manual II. MicroMacro Publishing, Athens, GA.

Pedrosa, A.W., Favarin, J.L., 2013. Eficiência da adubação nitrogenada no consórcio entre cafeeiro e Brachiaria brizantha. Universidade de São Paulo, Piracicaba, SP.

Quaggio, J.A., Thomaziello, R.A., van Raij, B., Cantarella, H., 2022. Café, in: Cantarella, H., Quaggio, J.A., Mattos, D., Boaretto, R.M., van Raij, B. (Eds.), BOLETIM 100: Recomendações de Adubação e Calagem Para o Estado de São Paulo. Instituto Agronômico, Campinas, pp. 165–176.

Quaggio, José Antonio, Raij, B. van, 1996. Correção da acidez do solo, in: Raij, B. van, Cantarella, H., Quaggio, José Antônio, Furlani, Â.M.C. (Eds.), Boletim Técnico 100: Recomendações de Adubação e Calagem Para o Estado de São Paulo. Instituto Agronômico de Campinas, Campinas, p. 285.

Raij, B. van, Cantarella, H., Quaggio, J.A., 1996. Coffee, in: Technical Bulletin 100: Fertilization and Liming Recommendations for the São Paulo State. Campinas Agronomic Institute, Campinas, pp. 97–101.

Riaño-Herrera, N.M., Arcila-Pulgarín, J., Jaramillo-Robledo, Á., Chaves-Córdoba, B., 2004. Acumulación de materia seca y extracción de nutrimentos por *Coffea arabica* L. cv. Colombia en tres localidades de la zona cafetera central 55, 265–276.

Rosolem, C.A., Steiner, F., 2017. Effects of soil texture and rates of K input on potassium balance in tropical soil. Eur J Soil Sci 68, 658–666. https://doi.org/10.1111/ejss.12460

Souza, L.T. de, Favarin, J.L., 2018. Nutrient demand for vegetation and fruiting of *Coffea arabica* L. University of São Paulo, Piracicaba.

Taiz, L., Zeiger, E.F., 2013. Fisiologia Vegetal, 5th ed. Artemed, Porto Alegre.

Temesgen, H., Affleck, D., Poudel, K., Gray, A., Sessions, J., 2015. A review of the challenges and opportunities in estimating above ground forest biomass using tree-level models. Scand J For Res 30, 326–335. https://doi.org/10.1080/02827581.2015.1012114

Vaast, P., Angrand, J., Franck, N., Dauzat, J., Génard, M., 2005. Fruit load and branch ring-barking affect on carbon allocation and photosynthesis of leaf and fruit of *Coffea arabica* in the field. Tree Physiol 25, 753–760. https://doi.org/10.1093/treephys/25.6.753

Vaast, P., Bertrand, B., Perriot, J.J., Guyot, B., Génard, M., 2006. Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica* L.) under optimal conditions. J Sci Food Agric 86, 197–204. https://doi.org/10.1002/jsfa.2338

Vaast, P., Génard, M., Dauzat, J., 2002. Modeling the effects of fruit load, shade and plant water status on coffee berry growth and carbon partitioning at the branch level. Acta Hortic 584, 57–62. https://doi.org/10.17660/ActaHortic.2002.584.5

APPENDICES

Appendix A. Vegetation dry matter: stem, branches and leaves that grew from the indicator wire until harvest.

Appendix B. Fruit dry yield: whole fruit (with outer skin, parchment with pulp and bean with silver skin).

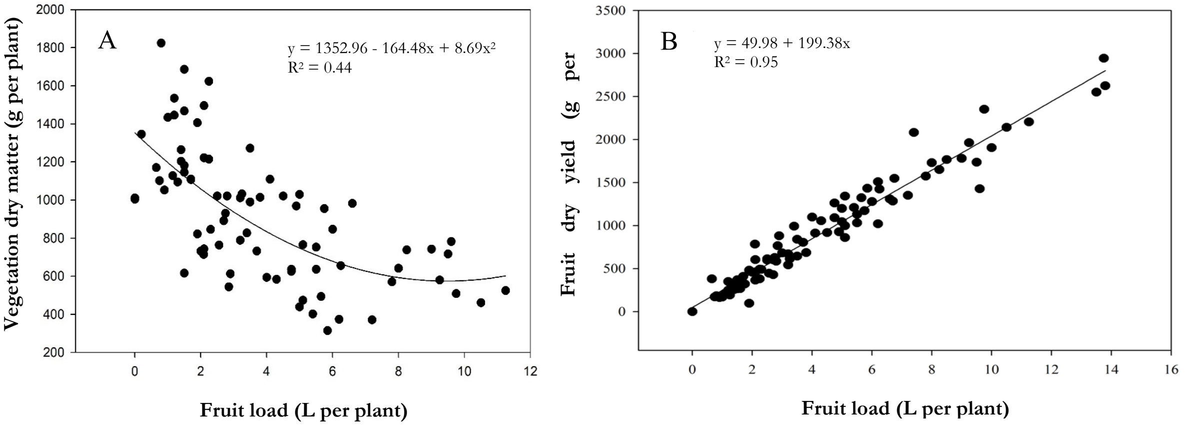
Appendix C. Green beans: coffee processed (without outer skin and parchment with pulp).

Appendix D. Bags: 60 kilograms of green beans processed (without outer skin and parchment with pulp).

Appendix E. Harvest index: ratio of the fruit dry yield to the total above-ground plant biomass produced over the growth cycle.

Appendix F.

Figure 11. Allometric model for vegetation dry matter (A) and fruit dry yield (B) regarding fruit load of arabica coffee, based on previous studies, used to calculate the fertilizer rates by EsalqCafé method in this study.



Appendix G.

Table 21. Fertilizer rates (N, P_2O_5 and K_2O) calculated according to each fertilization method, soil analysis, expected productivity and obtained for each experimental site.

Site	Expected productivity*		Obtained productivity*		Fertilization method	N			P_2O_5		K_2O	
						It should be applied considering the high N concentration in December	Applied	It should be applied considering the productivity obtained	Applied	It should be applied considering the productivity obtained	Applied	It should be applied considering the productivity obtained
	kg ha^{-1}	Bags** ha^{-1}	kg ha^{-1}	Bags** ha^{-1}		---------- kg ha^{-1} ----------						
Jacuí-MG	2700	45	3480	58	EsalqCafé	-	**220** (00)	260 (+40)	**27**	30 (+3)	**181**	210 (+29)
				≠13	SP-1	140	**200** (+60)	140 (-60)	**40**	40 (00)	**140**	140 (00)
					SP-2	180	**220** (+40)	200 (-20)	**60**	60 (00)	**180**	220 (+20)
					MG	170	**260** (+90)	200 (-60)	**0**	0 (00)	**260**	300 (+40)
Pedregulho-SP	3000	50	4080	68	EsalqCafé	-	**278** (00)	320 (+42)	**32**	37 (+5)	**217**	254 (+37)
				≠18	SP-1	140	**200** (+60)	170 (-30)	**40**	50 (+10)	**80**	100 (+20)
					SP-2	180	**220** (+40)	220 (00)	**60**	80 (+20)	**140**	220 (+80)
					MG	170	**260** (+90)	230 (-30)	**15**	20 (+5)	**175**	225 (+50)
S. S. Paraíso-MG	2100	35	3420	57	EsalqCafé	-	**210** (00)	260 (+50)	**24**	30 (+6)	**163**	208 (+45)
				≠22	SP-1	110	**160** (+50)	140 (-20)	**50**	60 (+10)	**135**	100
					SP-2	160	**200** (+40)	200 (00)	**60**	80 (+20)	**120**	180 (+60)
					MG	140	**220** (+80)	200 (-20)	**40**	55 (+15)	**150**	200 (+50)

* Green beans, ** bags = 60 kg