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Optimization of water use in *Coffea arabica* L. grown under different agronomic practices

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Abstract

Lower water availability due to climate change has dramatically affected coffee yields and quality. Characteristics related to plants and soil can be explored to obtain more productive and sustainable coffee production under adverse crop conditions. To this end, the objective of this study was to evaluate the potential for using different agronomic practices to optimize water use in coffee plants and to mitigate the effects of lower water availability to the crop. In the plots, three soil management systems (polyethylene film, brachiaria and bare soil) were used. In the subplots, two types of fertilizers were used (conventional and controlled-release fertilizer). Five soil conditioners (coffee husk, gypsum, water-retaining polymer, organic compost, and the control) were distributed throughout the sub-subplots. The plant growth, soil moisture, leaf physiology and anatomy, and soil chemical properties of coffee plants were analysed. The management of the soil cover using polyethylene film or brachiaria stood out as agronomic practices that can be combined with coffee husk applications to enable the better use of water by coffee plants and to favour soil conditioning. Controlled-release fertilizer and gypsum allowed for improvements in the anatomical and physiological characteristics of the plants. The use of organic compost favoured greater water availability; however, it caused losses in terms of coffee growth and physiological parameters due to nutritional imbalance. Therefore, based on results, the use of polyethylene film, brachiaria, controlled-release fertilizer, coffee husks, and gypsum are potential agronomic practices for optimizing water use and mitigating the effects of water deficit in coffee plants.

Keywords: water deficit; management; fertilizers; soil conditioners.

Introduction

According to climate change forecasts, which involve a temperature increase and reduced water availability scenario (Ipcc, 2014), the configuration of agricultural production could change significantly in the coming years. In coffee crops, water deficits already cause significant losses in coffee yield and quality (Conab, 2014). The global importance of coffee is notable, and it stands out as one of the most valuable of the primary products (Oic, 2017). Coffee is cultivated primarily in Brazil, the largest coffee producing and exporting country, and it is a driver of economic and social progress. High temperature and water deficits are the primary limiting climatic factors for coffee production across different coffee-growing regions (Da Matta and Ramalho, 2006). Characteristics related to plants and soil can be explored to optimize coffee production under adverse conditions. When considering studies on other plant species, soil cover management is an important tool for increasing the water use efficiency (Bizari et al., 2009; Souza et al., 2011). Promising results have been observed following the intercropping of coffee and brachiaria, which contributes to greater water storage in the soil, given that the presence of plant residues covering the soil allows for milder temperatures and consequently less water evaporation. Another alternative for soil cover is the use of polyethylene film, a widespread practice in the cultivation of vegetables (Branco et al., 2010). Additionally, soil fertility is undoubtedly an essential factor in the development and production of coffee. Technologies that optimize the use of nutrients and reduce their environmental impact are increasingly necessary (Guelfi, 2017). These technologies include slow- or controlled-release fertilizers with increased efficiency, which potentiate the supply of nutrients to plants by releasing them gradually and reduce losses by leaching and volatilization (Timilsena et al., 2014). Furthermore, soil conditioners can provide benefits to coffee cultivation. Gypsum and organic residues improve oil properties and favour the root system, providing greater access to the available water (Santos et al., 2014; Nogueira et al., 2016). In addition, under drought and/or irregular rainfall conditions, water-retaining polymers are able to increase the water retention in the soil and make it available to plants to a more satisfactory extent (Marques et al., 2013; Souza et al., 2016). However, there are few studies that show the combination of innovative technologies and traditional management systems to obtain more productive and sustainable coffee production in the face of the impacts of climate change and, more specifically, of water deficit. Therefore, the objective of this study was to evaluate the potential of different agronomic practices to mitigate the effects of decreased water availability in coffee plants.

Results and discussion

The presence of soil cover, either in the management system with brachiaria or with polyethylene film, resulted in higher plant growth (Fig 2A, C, F, H and I). Furthermore, these management systems were efficient at maintaining the soil moisture (Fig 3A and C) and the leaf water potential (Fig 4C) even during periods with low rainfall. All these findings optimizing the use of water by the coffee plants under the climatic conditions of the two study periods. Corroborating this study, Zhu et al. (2015) found lower soil water evaporation when using polyethylene film on a maize crop, which contributed to higher yields.

The brachiaria root system favours soil structuring, which, through significant increases in microporosity, considerably increases the water storage (Rocha et al., 2014). In addition, soil cover with brachiaria residues may favour the growth of coffee plants due to the supply of nutrients, especially nitrogen (Pedrosa et al., 2014).

The management of the coffee plants on bare soil decreases water infiltration, favours surface runoff, and increases the temperature, which can increase evapotranspiration, and, consequently, reduce the water storage in the soil (Martonaro et al., 2009).

Among the studied soil conditioners, the coffee husks and organic compost provided higher moisture contents (Fig 3B and D); however, among them, only the coffee husks promoted increases in plant growth (Fig 2B, D, E and G). This observation can be explained by the chemical nature of the compost used here, which, due to its origin, contained high levels of copper, iron, manganese, and zinc, which may have been toxic to the plants and caused nutritional imbalances, inducing the deficiency of other essential nutrients (Pavan and Bingham 1981).

When analysing the physiological characteristics of the coffee plants in bare soil, the coffee husks, gypsum and water-retaining polymer were associated with a higher chlorophyll A content than the organic compost and the control (Fig 4A), indicating the possible efficiency of these soil conditioners. The chlorophylls are directly related to the photosynthetic efficiency, affecting the growth and adaptation of plants to different growing environments. The chlorophyll content can be used as an indicator of the nutritional status of plants, especially nitrogen (Godoy et al., 2008). However, several other factors may affect this parameter, such as water stress, sunlight, and temperature (Streit et al., 2005).

The superior results obtained for the coffee husks were noteworthy, and they also resulted in higher chlorophyll B contents (Fig 4B), possibly due to the higher plant growth (Fig 2D and G) and soil moisture (Fig 3B) observed when using this conditioner. Chlorophyll B is considered an accessory pigment that assists in light absorption and energy transfer (Streit et al., 2005); therefore, higher chlorophyll B contents may enable greater plant adaptability to different environmental conditions.

Regarding gas exchange, controlled-release fertilizer provided higher photosynthetic rates in coffee plants under bare soil (Fig 4D) and greater stomatal conductance in plants without soil conditioners under polyethylene film or brachiaria (Fig 4E and F). Since increase in photosynthetic capacity could result in growth benefitis (Kirschbaum, 2011), the results obtained in this study indicating the superiority of the controlled-release fertilizer compared to the conventional fertilizer, especially in situations with lower water availability, as observed in 2017 (Fig 1B).

Regarding the leaf anatomy of the plants, the absence of soil cover, which resulted in lower water availability (Fig 3A and C), affected the development of the palisade parenchyma because the plants under bare soil and without soil conditioners (control) exhibited lower thickness in this tissue compared to those grown without conditioner but with polyethylene film or brachiaria (Fig 5A). A study developed by Grisi et al. (2008) showed greater palisade parenchyma thickness in irrigated coffee plants (cultivar "Catuaí") compared to non-irrigated coffee plants.

The palisade parenchyma is known to be directly related to the CO_2 fixation, and, consequently, to the photosynthetic efficiency of the plants. This parenchyma development may vary according to the environmental conditions (Castanheira et al., 2016).

In addition, the greater development of the spongy parenchyma contributes to increased CO_2 storage, favouring gas exchange (Terashima et al., 2011). The greater thickness of this tissue in the plants without soil conditioner grown with polyethylene film or brachiaria (Fig 5B) was observed. This result could have contributed in higher coffee growth when compared to those grown on bare soil without the conditioner (Fig 2A, C, F, H and I).

Coffee plants grown under brachiaria cover management and controlled-release fertilizer presented a greater number of xylem vessels (Fig 5C and D). The greater soil moisture provided by the brachiaria (Fig 3A and C) and the more efficient supply of N and K provided by the controlled-release fertilizers justifies investment in a greater number of xylem vessels observed in plants under the interaction of these factors.

The function of the xylem is related to the transport of the sap (Queiroz-Voltan et al., 2014; Castanheira et al., 2016; Hacke et al., 2017; Carvalho et al., 2018).

Decreasing the diameter and increasing the number of xylem vessels are considered an adaptation strategy of plants under water deficit, which can increase the efficiency of sap transport because it allows for a lower possibility of air embolism (Queiroz-Voltan et al., 2014; Hacke et al., 2017).

For the xylem vessel diameter in 2016, the lowest means were observed in the coffee plants grown in the bare soil treatment (Fig 5E), which may indicate the response of the plants to the lower water availability promoted by this management system. However, the plants did not respond in the same way in 2017, as characterized by the lack of rainfall and lower relative humidity compared to 2016 (Fig 1). At that time, the increase in the xylem vessel diameter in the coffee plants under bare soil (Fig 5F) might have occurred as a way to facilitate the water flow by the plant, which was required due to the climatic conditions observed during the period. However, the greater water use efficiency obtained with the increased diameter of these vessels may be due to their greater vulnerability to cavitation (Mcelrone et al., 2004). Plants seem to have different adaptation

Table 1. Chemical analysis (depths of 0-20 and 20-40 cm) and soil particle size distribution in the experimental area prior to the experiment.

Depth (cm)	pH	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	SB	t	CEC
	(H_2O)	(mg dm^{-3})		(cmol$_c$ dm^{-3})						
0-20	5.0	4.5	104	1.5	0.5	0.2	3.5	2.3	2.5	5.7
20-40	4.6	1.4	48	0.5	0.2	0.5	4.4	0.8	1.3	5.1
	V	m	OM	P-Rem	Zn	Fe	Mn	Cu	B	S
	(%)		(dag kg^{-1})	(mg L^{-1})	(mg dm^{-3})					
0-20	39.6	8.1	2.1	27.1	2.9	102.7	22.9	4.1	0.3	35.9
20-40	15.9	37.8	1.3	16.5	0.7	93.5	10.6	3.2	0.5	60.7
Soil classification		Clay			Silt			Sand		
		(dag kg^{-1})								
Clayey texture		44			9			47		

P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Al: aluminium; H + Al: potential soil acidity; SB: sum of exchangeable bases; t: effective cation exchange capacity; CEC: cation exchange capacity at pH 7.0; V: base saturation; m: aluminium saturation; OM: soil organic matter; P-Rem: remaining phosphorus; Zn: zinc; Fe: iron; Mn: manganese; Cu: copper; B: boron; and S: sulfur.

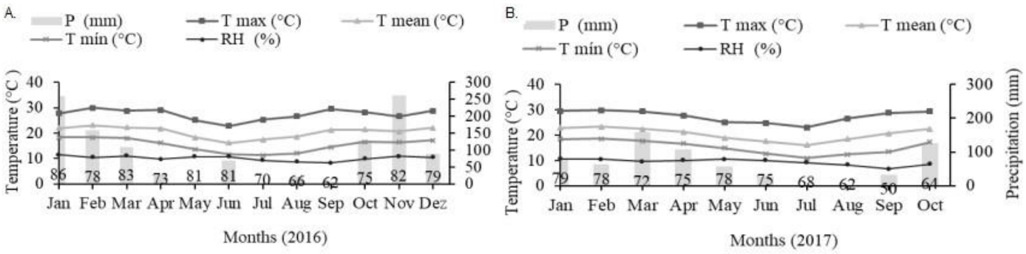

Fig 1. Climatological variables recorded monthly in 2016 (A) and 2017 (B).

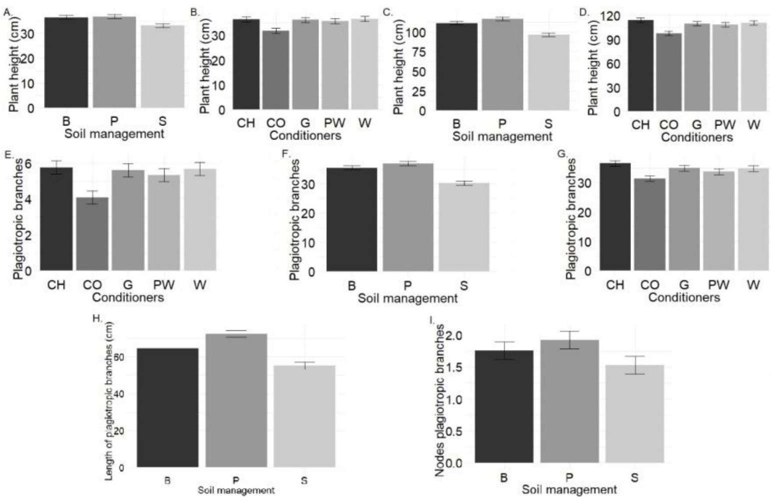

Fig 2. Growth of coffee plants under different soil cover management systems and conditioners: plant height in 2016 (A, B); plant height in 2017 (C, D); number of plagiotropic branches in 2016 (E); number of plagiotropic branches in 2017 (F, G); length of the first plagiotropic branch in 2017 (H); and number of nodes in the first plagiotropic branch in 2016 (I). The bars represent the means ± standard errors of the means. B: brachiaria; P: polyethylene film; S: bare soil; CH: coffee husk; CO: organic compost; G: gypsum; PW: water-retaining polymer; W: control.

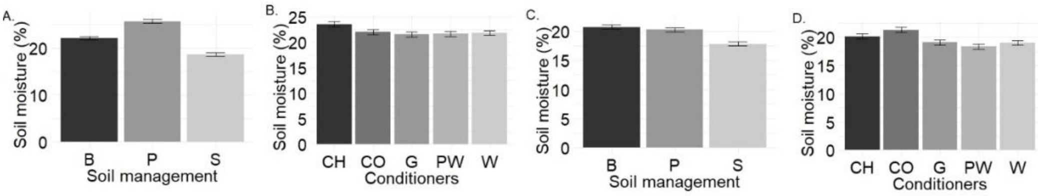

Fig 3. Soil moisture in coffee plants grown under different soil cover management systems and conditioners in 2016 (A, B) and 2017 (C, D). The bars represent the means ± standard errors of the means. B: brachiaria; P: polyethylene film; S: bare soil; CH: coffee husk; CO: organic compost; G: gypsum; PW: water-retaining polymer; W: control.

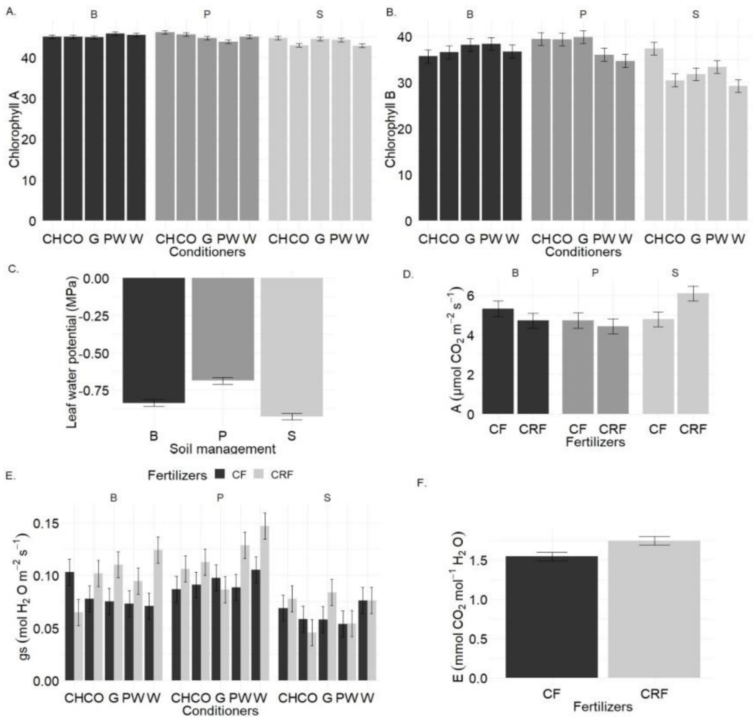

Fig 4. Physiological characteristics of coffee plants grown under different soil cover management systems, fertilizers and conditioners: chlorophyll A content in 2017 (a); chlorophyll B content in 2017 (b); leaf water potential in 2016 (c); photosynthetic rate in 2017 (d); stomatal conductance in 2016 (e); and transpiration rate (f) in 2016. The bars represent the means ± standard errors of the means. B: brachiaria; P: polyethylene film; S: bare soil; CH: coffee husk; CO: organic compost; G: gypsum; PW: water-retaining polymer; W: control; CRF: controlled-release fertilizer; CF: conventional fertilizer; A: net photosynthetic rate; gs: stomatal conductance; E: transpiration rate.

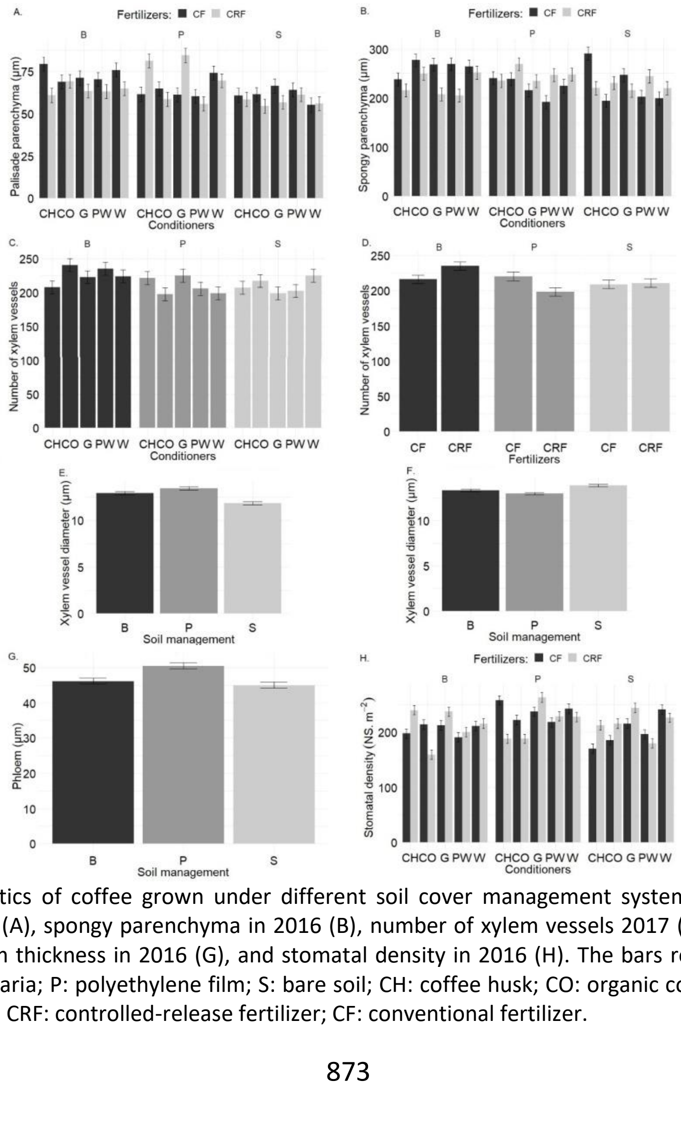

Fig 5. Anatomical characteristics of coffee grown under different soil cover management systems, fertilizers and conditioners: palisade parenchyma in 2016 (A), spongy parenchyma in 2016 (B), number of xylem vessels 2017 (C, D), xylem vessel diameter in 2016 (E) and 2017 (F), phloem thickness in 2016 (G), and stomatal density in 2016 (H). The bars represent the means ± standard errors of the means. B: brachiaria; P: polyethylene film; S: bare soil; CH: coffee husk; CO: organic compost; G: gypsum; PW: water-retaining polymer; W: control; CRF: controlled-release fertilizer; CF: conventional fertilizer.

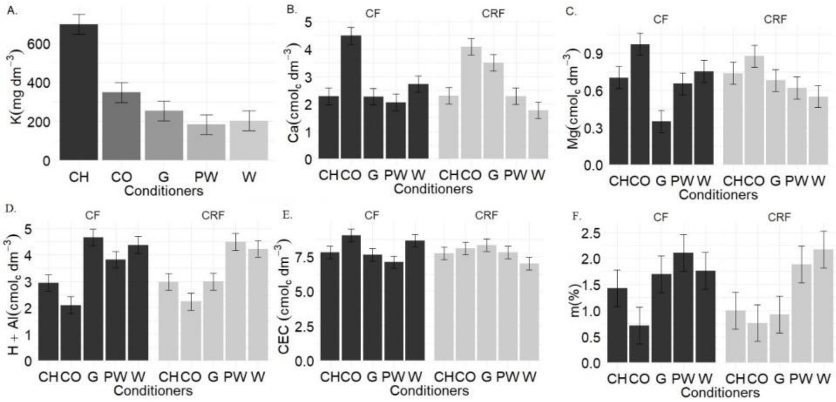

Fig 6. Soil chemical properties in coffee plants grown with different soil cover management systems, fertilizers, and conditioners: soil potassium (A), calcium (B), magnesium (C), potential acidity (D), cation exchange capacity at pH 7 (E), and aluminium saturation (F). The bars represent the means ± standard errors of the means. B: brachiaria; P: polyethylene film; S: bare soil; CH: coffee husk; CO: organic compost; G: gypsum; PW: water-retaining polymer; W: control; CRF: controlled-release fertilizer; CF: conventional fertilizer; K: potassium; Ca: calcium; Mg: magnesium; H+Al: potential soil acidity; CEC: cation exchange capacity; m: aluminium saturation.

mechanisms for increasing the efficiency of water and nutrient transport under stress conditions.

The greater phloem thickness was observed in the coffee plants under soil cover (polyethylene film or brachiaria) (Fig 5G). This might be related to the high plant growth supported by the use of these systems (Fig 2A, C, F, H and I). Plants engaged in intense growth have high metabolic activity, generating the demand for a greater amount of photoassimilates and thus requiring greater phloem development (Pereira et al., 2008; Sevanto et al., 2018).

Ribeiro et al. (2012) reported a positive relationship between greater phloem thickness and root system development in cassava genotypes grown under different environmental conditions. Given the above findings, the agronomic practices that enable greater phloem thickness may promote greater root system development due to the greater translocation of photoassimilates to this organ, increasing the tolerance of plants to lower water availability.

In general, in 2016, there was a higher mean stomatal density in coffee plants treated with polyethylene film when using gypsum combined with controlled-release fertilizer (Fig 5H). This positive relationship might have occurred due to the improved chemical properties of the soil provided by both factors, because the interaction between gypsum and controlled-release fertilizer enabled higher magnesium and calcium content in the soil than the interaction between gypsum and conventional fertilizer (Fig 6B and C). Gama et al. (2017) found increased stomatal density in the coffee plants as the fertilization levels (NPK) increased, demonstrating the possible correlation of this trait with the nutrient availability. It is also noteworthy that there was an increase in the stomatal density when controlled-release fertilizer was combined with other soil conditioners on bare soil (Fig 5H). This fact might have promoted the greater stomatal conductance observed in most treatments containing this fertilizer in 2016 (Fig 4E and F).

Among the conditioners, the coffee husks increased the potassium content by 73% compared to the control (Fig 6A), which may have contributed to the gains in the morpho-physiological aspects observed in the coffee plants that received this conditioner (Fig 4A and B, Fig 5A, B and H).

Due to the increased potassium content of the soil resulting from the application of the coffee husks, the use of this conditioner has been recommended as a supplementary nutrient source for coffee fertilization (Fernandes et al., 2014). Potassium is the second-most needed nutrient by this crop, and for various reasons, it plays a key role in the plant-water relationship because plants that are well-supplied with K increase the osmotic pressure of the guard cells, allowing the entry of water, which increases the turgor pressure and results in the opening of the stomata (Hawkesford et al., 2012). Accordingly, an adequate supply of K can be used as an important practice to mitigate the negative effects of water deficits on crop development (Grzebisz et al., 2013). Improving the physiological processes of plants through the use of coffee husks, which increased the level of K in the soil, promoted the optimization of water use in coffee plants.

The greater nutrient availability (Fig 6A, B and C), the reduction of aluminium saturation (Fig 6F), and the potential acidity of the soil (Fig 6D) due to the use of coffee husks, organic compost, and gypsum combined with controlled-release fertilizer indicate that these agronomic practices are capable of improving the soil conditioning.

It is known that gypsum promotes the correction of aluminium toxicity and provides calcium and thus enables the greater growth of the root system (Ramos et al., 2013). For all these gypsum proprieties, Silva et al. (2016) indicate their use in conjunction with organic residues in coffee plants to mitigate water stress during drier periods.

Soils containing low levels of calcium and excess aluminium seriously limit the growth of the root system (Santos et al., 2014). Furthermore, the lower magnesium content may impair plant metabolism because this element is the primary component of the chlorophyll molecule, and it effectively participates in the photosynthetic process of plants (Hawkesford et al., 2012).

In general, the organic compost promoted increased levels of potassium, calcium, and magnesium (Fig 6A, B and C), higher CEC mean (Fig 6F) and enabling the reduction of potential acidity (Fig 6D) and of aluminium saturation (Fig 6F) in the soil. This conditioner might have allowed for the greater input of organic matter, favouring improvements in the chemical properties of the soil analysed in this study. Similarly, organic residues contributed to the decrease in soil exchangeable acidity, in addition to being efficient sources of Ca, Mg and K, and S and B in coffee plants under organic and conventional management (Theodoro et al., 2009).

Higher values were observed for aluminium saturation when using the water-retaining polymer and no conditioners (control) (Fig 6F), which may have negatively affected the coffee plants. One of the primary soil limitations is the presence of aluminium, which is toxic to plants and primarily affects root growth. This element significantly reduces the stomatal conductance and the photosynthetic rate of the coffee plants, causing damage at the stomatal and biochemical levels (Konrad et al., 2005).

Materials and methods

Plant material and experimental setup and conditions

The plant species used was *Coffea arabica* L. "Mundo Mundo 379-19" cultivar. The experiment was conducted in the field, in the municipality of Lavras, state of Minas Gerais, Brazil, from January 2016 to October 2017. The geographical coordinates of the site are latitude 21°13'36.47" South and longitude 44°57'40.35 West, with an average altitude of 975 metres. According to the Koppen classification, the climate of the region is classified as Cwa, mesothermal, with mild summers and dry winters (Sá Júnior et al., 2012).

The coffee was planted in January 2016 using seedlings, with a spacing of 3.6 metres between planting rows and 0.75 metres between plants. Soil from the experimental area was classified as clayey dystrophic Yellow Red Latosol (Oxisol) (Table 1). Soil correction and phosphorus fertilization were performed according to the results of the soil analysis (Table 1), in accordance with the recommendations of Guimarães et al. (1999).

Experimental design and treatments

The factors under study were arranged in a 3x2x5 factorial design, with a total of 30 treatments spread over the experimental area in a split-split plot design. A randomized complete block design with three replications was used. In the plots, three soil management systems (polyethylene film (P), brachiaria (B) and bare soil (S)) were used. In the subplots, two types of fertilizers were used (conventional (CF) and controlled-release fertilizer(CRF)). Five soil conditioners (coffee husk (CH), gypsum (G), water-retaining polymer (PW), organic compost (CO), and the control (W)) were distributed throughout the sub-subplots. Each experimental unit consisted of six plants, and the four central plants were used.

For soil management with polyethylene film, a double-sided black-and-white product with a 1.60 m width was used. The film was laid on the planting row immediately after planting the coffee, with the white side up and the black side down. The brachiaria trial was established with the intercropping of coffee and brachiaria. The brachiaria (*Urochloa decumbens*) was cultivated in the inter-row of the coffee plots, while the planting rows were always kept covered by the plant residues from the harvest. Management on bare soil was performed by maintaining a 1.00 m strip on each side of the planting row that was always cleaned by weeding and herbicide applications.

The fertilizer factor consisted of two different practices for the supply of nitrogen (N) and potassium (K) to the plants. The conventional fertilizer consisted of the 20-00-20 formulation that was supplemented, when necessary, with conventional urea (45% N). The controlled-release fertilizer consisted of a commercial product (37% N) with urea coated with a layer of elemental sulfur that was, in turn, coated with one layer of organic polymer and another commercial product (52% K_2O) with potassium chloride, which was also coated with a layer of elemental sulfur coated with one layer of organic polymer. Fertilization was performed according to the results of the soil analysis (Table 1) and the nutritional requirements of coffee plants as described by Guimarães et al. (1999).

Regarding the soil conditioner factor, the coffee husks, gypsum, water-retaining polymer, organic compost, and a control, which did not receive any of the soil conditioners and was influenced only by the management and fertilizer factors, were used for the study.

The coffee husks, agricultural gypsum, and organic compost were applied by top-dressing, with projection over the coffee canopy immediately after planting (Guimarães et al., 1999). The coffee husks and compost were applied at a dose of 10 L per plant and evenly distributed over their respective sub-subplots. The organic compost used here was a commercial product containing waste from farms and food industries. In the treatments containing gypsum, 300 $g.m^{-2}$ was applied; this recommendation was based on the results of a 20-40 cm soil layer analysis (Table 1), and the dose was calculated based on the soil texture. The water-retaining polymer was applied at the time of planting, and the solution was prepared at a ratio of 1.5 kg of the product to 400 litres of water; it remained at rest for 30 minutes for full hydration. Subsequently, 1.5 litres of the solution were applied to each planting furrow, by incorporating the polymer into the soil (Pieve et al., 2014).

Climatic data monitoring

The climatic data were monitored using an automatic weather station installed near the experimental area. Data such as the rainfall volume (precipitation) (mm), maximum, mean and minimum temperatures (ºC), and relative humidity (%) were obtained (Fig 1).

Measurements of plant characteristics

Measurements of the plant growth, soil moisture, leaf physiology and anatomy were performed for two years during two specific times, July 2016 and July 2017, which represented the periods 6 and 18 months after the experiment was set up. To achieve the objective proposed in the study, the evaluation periods were determined by the lower water availability to the coffee plants because during these months, a low volume of precipitation is observed (Fig 1). The growth traits evaluated here were the plant height in cm, stem diameter in mm, number of plagiotropic branches, length of the first plagiotropic branch in cm, and the number of nodes in the first plagiotropic branch.

The soil moisture was determined by standard method by collecting a disturbed soil sample from the 0 to 20 cm layer of each experimental unit. The wet weight was measured on a precision scale, and the samples were kept in an oven at 105 °C for 24 hours to determine the dry weight. The gravimetric soil water content was subsequently calculated as a percentage, by taking the difference between the wet weight and dry weight and dividing it by the dry weight.

To evaluate the gas exchange, a portable infrared gas analyser (IRGA LICOR - 6400XT) was used. The net photosynthetic rate (A, µmol CO_2 m^{-2} s^{-1}), stomatal conductance (gs, mol H_2O m^{-2} s^{-1}), and transpiration rate (E, nmol H_2O m^{-2} s^{-1}) were evaluated. To calculate the water use efficiency (WUE, µmol CO_2 mol^{-1} H_2O), the ratio between the photosynthetic rate and the transpiration rate was calculated (Silva et al., 2010). The evaluations were performed between 8 and 11 a.m. under artificial light (1000 μmol m^{-2} s^{-1}) using fully expanded leaves located at the third node as counted from the apex of the plagiotropic branch.

The chlorophyll a, b and total chlorophyll contents were determined using a ClorofiLOG chlorophyll content meter (model CFL 1030). This meter expresses the contents as a proportion of the absorbance of the chlorophylls. The readings were performed on the same leaves as those used for assessing the gas exchange.

The leaf water potential (MPa) was determined during the predawn period using a pressure chamber (model 1000, PMS Instrument Company). The collected leaves were fully expanded and free of pests and diseases. They were evaluated in the chamber by applying pressure until exudation occurred through a cut made in the leaf petiole.

For the anatomical evaluations, fully expanded leaves were collected from the second or third node of the plagiotropic branch, in the middle third of the plants. The stomatal characterization was performed by making an impression of the leaf abaxial surface on a glass slide using a universal instant adhesive (cyanoacrylate ester) (Schmidt et al., 2017).

To study the leaf tissues and vascular bundles, the dehydration process was performed using a graded ethanol series. The plant material was embedded in methacrylate (according to the manufacturer's instructions) and cut into 0.8-μm-thick sections using a rotary microtome. The resulting sections were stained with toluidine blue (O'brien et al., 1964), and the slides were mounted using Entellan as the mounting medium. The resulting slides were observed and photographed under a Kasvi RED 200 model optical microscope coupled to a 5.0MP Motic moticam digital camera. To obtain the data, the images were subsequently analysed using UTHSCSA-ImageTool software. The following characteristics were evaluated: the stomatal density as the number of stomata per mm^2, the ratio between the polar diameter and equatorial diameter of the stomata, the adaxial epidermis thickness in μm, the abaxial epidermis thickness in μm, the palisade parenchyma thickness in μm, the spongy parenchyma thickness in μm, the mesophyll thickness in μm, the phloem thickness in μm, the xylem vessel diameter in μm, and the number of xylem vessels.

In October of 2017, the soil fertility (in the 0 to 20 cm layer) was sampled with a screw auger from the projection of the coffee canopy to evaluate the chemical properties of the soil. For each experimental unit, a composite sample of approximately 300 g was obtained from two single samples. After their collection, the samples were placed in plastic bags and sent for laboratory analysis. The following properties were determined: the pH in water (pH), the phosphorus content (P, mg dm^{-3} by Mehlich-1 extractor), potassium content (K, mg dm^{-3} by Mehlich-1 extractor), calcium content (Ca, $cmol_c$ dm^{-3} with a 1 mol L^{-1} KCl extractor), magnesium content (Mg, $cmol_c$ dm^{-3} by 1 mol L^{-1} KCl extractor), aluminium content (Al, $cmol_c$ dm^{-3} by 1 mol L^{-1} KCl extractor), potential acidity (H + Al, $cmol_c$ dm^{-3} with a 0.5 mol L^{-1} calcium acetate extractor at pH 7.0), effective soil cation exchange capacity (CEC pH 7, cmolc dm^{-3}), base saturation (V, %), and aluminium saturation (m, %).

Statistical analysis

The data were tested for ANOVA assumptions by assessing the normality of the data using the Shapiro-Wilk test.

Due to the large number of characteristics evaluated here, a variable selection was performed by Procrustes analysis method. The backward elimination algorithm proposed by Krzanowski (1987) was used in which the M^2 statistic is used for discarding variables, enabling the selection of a subset of variables that represents the structure of the original variable set. The analysis was performed using "GENES" software (Cruz, 2006).

Subsequently, an analysis of variance was performed, with the significance of the sources of variation assessed by F test at a 5% probability level. When significant, the results were compared by overlapping the standard error of the mean to study the effects of the interactions and the effects of the primary factors. These statistical procedures were performed using R software (R Core Team, 2016). The presentation and discussion of the results were performed based on the variables that were significant ($p < 0.05$).

Conclusions

The use of polyethylene film, brachiaria, controlled-release fertilizer, coffee husks, and gypsum are potential agronomic practices for optimizing water use and mitigating the effects of water deficit in coffee plants.

Despite not providing significant gains in plant growth, controlled-release fertilizers and gypsum led to improvements in plant anatomical and physiological characteristics. The use of organic compost favoured greater water availability; however, it caused damage to the coffee plants due to nutritional imbalance.

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References

Bizari DR, Matsura EE, Roque MW, Souza AL (2009) Consumo de água e produção de grãos do feijoeiro irrigado em sistemas plantio direto e convencional. Cienc Rural. 39(1): 2073-2079.

Branco RB, Santos LG, Goto R, Ishimura I, Schlickmann S, Chiarati CS (2010) Cultivo orgânico sequencial de hortaliças com dois sistemas de irrigação e duas coberturas de solo. Hortic Bras. 28(1): 75-80.

Carvalho MR, Losada JM, Niklas KJ (2018) Ploem networks in leaves. Current Opinion Plant Biol. 43(1): 29-35.

Castanheira DT, Rezende TT, Baliza DP, Guedes JM, de Carvalho SP, Guimarães RJ, Viana MT (2016) Potential use of anatomical and physiological characteristics in the selection of coffee progenies. Coffee Sci., 11(3): 375 – 386.

Compania Nacional de Abastecimento - Conab (2014) Acompanhamento da safra brasileira de café, Safra 2014, Quarto Levantamento, Observatório Agrícola, Brasília, 1(3).

Cruz CD (2006) Programa Genes: biometria. Viçosa, MG, 382p.

Da Matta FM, Ramalho JDC (2006) Impacts of drought and temperature stress on coffee physiology and production: a review. Braz J Plant Physiol. 18(1): 55-81.

Fernandes AL, Santinato F, Ticle R, Santinato R (2014) Reduction of mineral fertilization of arabic coffee using coffee straw. Coffee Sci. 8(3): 324-336.

Gama TC, Sales Junior JC, Castanheira DT, Silveira HR, Azevedo HP (2017) Anatomia foliar, fisiologia e produtividade de cafeeiros em diferentes níveis de adubação. Coffee Sci. 12(1): 42-48.

Godoy LJ, Santos TD, Villas Bôas RL, Leite Júnior JB (2008) Índice relativo de clorofila e o estado nutricional em nitrogênio durante o ciclo do cafeeiro fertirrigado. Rev Bras Cienc Solo. 32(1): 217-226.

Grisi FA, Alves JD, Castro EM, Oliveira CD, Biagiotti G, Melo LA (2008) Avaliações anatômicas foliares em mudas de café 'Catuaí' e 'Siriema' submetidas ao estresse hídrico. Cienc Agrotec. 32(6): 1730-1736.

Grzebisz W, Gransee A, Szczepaniak W, Diatta J (2013) The effects of potassium fertilization on water-use efficiency in crop plants. J Plant Nutr Soil Sci. 176(1): 355–374.

Guelfi DR (2017) Fertilizantes nitrogenados estabilizados, de liberação lenta ou controlada. Informações Agronômicas. 157: 1-14.

Guimarães PTG, Garcia AWR, Alvarez VH, Prezotti LC, Viana AS, Miguel AE, Malavolta E, Correa JB, Lopes AS, Nogueira FD, Monteiro AVC, Oliveira JA (1999) Cafeeiro. In: Ribeiro, A. C.; Guimarães, P. T. G.; Alvares, V. H. (Ed). Recomendação para o uso de corretivos e fertilizantes em Minas Gerais: 5ª aproximação. Viçosa, MG, 289p.

Hacke UG, Spicer R, Schreiber SG, Plavcová L (2017) An ecophysiological and developmental perspective on variation in vessel diameter. Plant Cell Environ. 40(1): 831–845.

Hawkesford M, Horst W, Kichey T, Lambers H, Schjoerring J, Møller IS, White P (2012) Functions of macronutrients. In Marschner's Mineral Nutrition of Higher Plants, Third Edition, San Diego, Academic Press, 135p.

Intergovernmental Panel on Climate Change – Ipcc (2014) Climate Change 2014: Impacts, Adaptation and Vulnerability. Summary for Policymakers. WG II. Genebra: IPCC.

Kirschbaum MUF (2011) Does enhanced photosynthesis enhance growth? lessons learned from CO_2 enrichment studies. Plant Physiol. 155(1): 117-124.

Konrad ML, Silva JA, Furlani PR, Machado EC (2005) Trocas gasosas e fluorescência da clorofila em seis cultivares de cafeeiro sob estresse de alumínio. Bragantia. 64(3): 339-347.

Krzanowski WJ (1987) Selection of variables to preserve multivariate data structure,using principal components. J Appl Stat. 36(1): 22-33.

Marques PA, Cripa MA, Martinez EH (2013) Hidrogel como substituto da irrigação complementar em viveiro telado de mudas de cafeeiro. Cienc Rural. 43(1): 1-7.

Martonaro LG, Bergamaschi H, Dalmago GA, Faria RT, Mielniczuk J, Comiran F (2009) Indicadores da condição hídrica do solo com soja em plantio direto e preparo convencional. Rev Bras Eng Agr. 13(1):397-405.

McElrone AJ, Pockman WT, Martínez-Vilalta J, Jackson RB (2004) Variation in xylem structure and function in stems and roots of trees to 20 m depth. New Phytol. 163(1): 507–517.

Nogueira KB, Roque CG, Borges MC, Troleis MJ, Barreto RF, Oliveira MP (2016) Atributos físicos do solo e matéria orgânica sob dois manejos e efeito residual da aplicação de calcário e gesso agrícola. Rev Fac de Agron. 115(1): 45-54.

O'brien TP, Feder N, Mccully MiE (1964) Polychromatic staining of plant cell walls by toluidine blue. O Protoplasma. 59(2): 368-373.

Organização Internacional do Café – Oic (2017). Relatório sobre o mercado de café.

Pavan MA, Bingham FT (1981) Toxidez de metais em plantas. I. Caracterização de toxidez de manganês em cafeeiros. Pesqui Agropecu Bras. 16(1): 815-821.

Pedrosa AW, Favarin JL, Vasconcelos AL, Carvalho BV, Oliveira FB, Neves GB (2014) Brachiaria residues fertilized with nitrogen in coffee fertilization. Coffee Sci. 9(3): 366-373.

Pereira FJ, Castro EM, Souza TC, Magalhães PC (2008) Evolução da anatomia radicular do milho 'Saracura' em ciclos de seleção sucessivos. Pesqui Agropecu Bras. 43(12): 1649-1656;

Pieve LM, Guimarães RJ, Assis GA, Amato GA, Corrêa JM (2014) Use of water retention polymers during implementation of coffee plantations. Coffee Sci. 8(3):314-323.

Queiroz-Voltan RB, Nardin CF, Fazuoli LC, Braghini MT (2014) Caracterização da anatomia foliar de cafeeiros arábica em diferentes períodos sazonais. Biotemas. 27(4): 1-10.

R Development Core Team (2016) R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing.

Ramos BZ, Toledo JP, Lima JM, Serafim ME, Bastos AR, Guimarães PT, Coscione AR (2013) Gypsum applications to coffe: influence on calcium, magnesium and potassium contents and pH of the solution of a dystrophic red latosol. Rev Bras Cienc Solo. 37(4): 1018-1026.

Ribeiro MD, Carvalho SP, Pereira FJ, Castro EM (2012) Anatomia foliar de mandioca em função do potencial para tolerância à diferentes condições ambientais. Rev Cienc Agron. 43(2): 354-361.

Rocha OC, Guerra AF, Ramos ML, Oliveira AD, Bartholo GF (2014) Qualidade físico-hídrica de um latossolo sob irrigação e braquiária em lavoura de café no cerrado. Coffee Sci. 9(4): 516-526.

Sá Júnior A, Carvalho LG, Silva FF, Carvalho Alves M (2012) Application of the Koppen classification for climatic zoning in the state of Minas Gerais, Brazil. Theor Appl Climatol. 108(1): 1-7.

Santos WJ, Silva BM, Oliveira GC, Volpato MM, Lima JM, Curi N, Marques JJ (2014) Soil moisture in the root zone and its relation to plant vigor assessed by remote sensing at management scale. Geoderma. 221(1): 91-95.

Schmidt D, Caron BO, Pilau J, Nardino M, Elli E F (2017) Leaf morphoanatomy of ryegrass in the tree species understory in agroforestry systems. Rev Ceres. 64(4): 368-375.

Sevanto S, Ryan M, Dickman LT, Derome D, Patera A, Defraeye T, Pangle RE, Hudson PJ, Pockman WT (2018) Is desiccation tolerance and avoidance reflected in xylem and phloem anatomy of two coexisting aridzone coniferous trees? Plant Cell Environ. 41(1): 1551-1564.

Silva VA, Antunes WC, Guimarães BL, Paiva RM, Silva VD, Ferrão MA, DaMatta FM, Loureiro ME (2010) Resposta fisiológica de clone de café Conilon sensível à deficiência hídrica enxertado em porta-enxerto tolerante. Pesqui Agropecu Bras. 45(5): 457-464.

Silva EA, Silva SH, Oliveira GC, Carducci CE (2016) Root spatial distribution in coffee plants of different ages under conservation management system. Afr J Agric Res. 11(49): 4970-4978.

Souza, A. J. D. J. et al. Quantitative analysis of growth in coffee plants cultivated with a water-retaining polymer in an irrigated system. Rev Cienc Agron. 47(1): 162-171, 2016.

Souza AJ, Guimarães RJ, Colombo A, Sant'Ana JA, Castanheira DT (2011) Evapotranspiração, coeficientes de cultivo e eficiência do uso da água da cultura do pimentão em diferentes sistemas de cultivo. Acta Sci Agron. 33(1): 15-22.

Streit NM, Canterle LP, Canto MW, Hecktheuer LH (2005) As clorofilas. Cienc Rural. 35 (1): 748-755.

Terashima I, Hanba YT, Tholen D, Niinemets Ü (2011) Leaf functional anatomy in relation to photosynthesis. Plant Physiol. 155(1):108-116.

Theodoro VC, Mendes AN, Guimarães RJ (2009) Resposta de lavouras cafeeiras em transição agroecológica a diferentes manejos de solo. Coffee Sci. 4(1): 56-66.

Timilsena YP, Adhikari R, Casey P, Muster T, Gill H, Adhikari B (2014) Enhanced efficiency fertilisers: a review of formulation and nutrient release patterns. J Sci Food Agr. 95(6): 1131-1142.

Zhu L, Liu JL, Luo SS, Bu LD, Chen XP, Li SQ (2015) Soil mulching can mitigate soil water deficiency impacts on rainfed maize production in semiarid environments. J Integr Agric. 14(1): 58-66.