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Intercropping of coffee with the palm tree, *macauba,* can mitigate climate change effects

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ABSTRACT

Global climate changes can affect coffee production in Brazil, and in other coffee producing countries. We examined the potential for an agroforestry system with the native species, macauba (*Acrocomia aculeata*), to mitigate impacts on coffee production by reducing maximal air temperature and photosynthetic active radiation. The objective of this study was to investigate the influence of an agroforestry system with *macauba* on productivity, microclimatic characteristics and soil physical quality on a coffee plantation in the Atlantic Rainforest biome, in Southern Brazil. We measured soil attributes (moisture, temperature, and physical properties), microclimate conditions (air temperature, photosynthetic active radiation) and coffee production parameters (productivity and yield). Macauba palm trees were planted at different planting densities on the rows and distances from the coffee rows. Planting density of *macauba* and their distance from the coffee rows affected soil thermal-water regime. Compared with the traditional unshaded sole coffee planting, the intercropped cultivation provided more coffee yield on both macauba density planting and distance evaluated. On the other hand, coffee productivity was increased by agroforestry systems just for 4.2 m distance between palm trees and coffee rows. Planting density of *macaubas* did not affect coffee yield and productivity. Best coffee harvest in agroforestry systems with *macauba* was related to higher soil moisture at the depth of 20–40 cm, higher photosynthetic active radiation, and maximum air temperatures lower than 30 °C. Agroforestry with coffee and *macauba* trees can be an adaptation strategy under future climatic variability and change related to high temperatures and low rainfall.

1. Introduction

Climate variability is the main factor responsible for variations in coffee harvest from year-to-year in Brazil (Camargo, 2010). Given the projected global climate change scenarios, there is considerable interest in the potential impact on coffee production in traditional areas of coffee plantation in Brazil.

Among the climatic variables that affect the growth and production of *Coffea arabica*, temperature, light and water availability stand out as the most relevant (Camargo, 2010). According to the Fifth Report of the Intergovernmental Panel on Climate Change (IPCC et al., 2013), coincidentally these variables probably will change in the future, raising the risk for the coffee farmers and the coffee industry of Brazil and other parts of world, as pointed for Nicaragua (Läderach et al., 2017), Nepal (Ranjitkar et al., 2016), Mexico and Vietnam (Eakin et al., 2009) and Ethiopian (De Beenhouwer et al., 2016).

While macroclimate changes are not manageable by coffee producers, there may be agronomic strategies available for reduction the expected consequences of climate change in the medium term by altering in the microclimate. Agroforestry systems are a possible strategy to minimize the effects of climate change on coffee crops (Fazuoli et al., 2007; Lin, 2010; Venturini et al., 2013) by reduction of solar radiation (Pezzopane et al., 2010; Siles et al., 2010) and air temperature (Morais et al., 2006; Pezzopane et al., 2010; Siles et al., 2010; Valentini et al., 2010), leading to the stabilization of microclimate and a decrease in soil carbon dioxide (CO_2) efflux variability (Gomes et al., 2016), as well as a better water use efficiency (Lin, 2010). In addition, agroforestry systems can contribute to the improvement of soil physical quality (Aguiar, 2008) and to provide environmental services and more products to the farms.

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Coffee production under agroforestry systems was common in northern and northeastern regions in Brazil until the 1960s (Jaramillo-Botero et al., 2006). However, these systems used high-density tree planting and often had low coffee productivity (Caramori et al., 2004). Negative effects on production are associated with competition for water, nutrients, and light between tree species and coffee plants. Nevertheless, in the 1970s, through coffee afforestation programmes, agroforestry was re-emphasized because of the benefits of moderate shade to the coffee plants (Caramori et al., 2004). After that, further studies are been required considering different tree species and different spacing aiming to maximize the benefits of agroforestry systems on coffee plantation in diverse regional peculiarities.

Among the tree species suitable for agroforestry, *macauba* (*Acrocomia aculeata*) has gained recent prominence, primarily because it is a palm tree widely distributed throughout Brazil. This palm tree is found in open and relatively dry areas (Mota et al., 2011), has monopodial growth, can reach the height of 20 m, and fruit harvesting concentrates between September and January (Lorenzi, 2006), differently of coffee plants that concentrate production from April to July. A major potential use of *macauba* fruit is for biofuel production since pulp and beans are rich in lipids. In addition, these two fruit components can be used by food industries, and for detergent and cosmetics production (Azevedo-Filho et al., 2012). A National Program for Production and Use of Biodiesel (PNPB), launched in 2004 by the Brazilian Government, has promoted the purchase of those raw materials directly from farmers.

Hence intercropping *macauba* trees with coffee plants could be a profitable venture for farmers. However, there is limited understanding of the interactions between these two species and how they are influenced by tree spacing and planting density, in order to achieve a balance between environmental and economic gains.

Therefore, this study objective to investigate the influence of agroforestry systems with *macauba* on microclimatic characteristics, soil physical quality, and yield of a coffee plantation in the Minas Gerais State, located at Atlantic Rainforest biome in Southern Brazil.

2. Materials and methods

2.1. Site characterization

The experiment was carried out in Viçosa, located in the Atlantic Rainforest Brazilian biome, in Minas Gerais State, Brazil. The agroforestry experiment could not be structured in such a way as to control the heterogeneity of the site and was composed of a single experimental block in a real farm situation. The site was at around 675 m a.s.l. on a Red Yellow Latosol (Hapludox) with clayed texture. It was uniform in terms of soil attributes (Table 1) and slope (northwest, 17%). Additionally, at the start of the experiment, the total area was prepared on the same day, using the same mechanical procedures and received the equal amounts of fertilizes and liming. Since then, all management practices were performed following the same procedures and according to standard techniques used by coffee farmers.

The agroforestry treatments were established in November 2007 with *Coffea arabica* (cv. Oeiras) intercropped or not with macauba: coffee grown 1.4 m (T1) or 4.2 m (T2) away from *macaubas* planted at high row density (318 palm trees ha^{-1}); coffee grown 1.4 m (T3) and 4.2 m (T4) away from *macaubas* planted at low row density (203 palm trees ha^{-1}); and a control treatment, corresponding to the full-sun coffee cultivation (T5) (Fig. 1).

Macauba trees had been planted in two densities: 11.20 m × 2.80 m (high) and 11.20 m × 4.40 m (low). Since distances between rows were the same for both treatments, high and low density refer to narrower and wider spacing of trees within a row, respectively. In both densities, the trees grew to around 6 m height. In all treatments, coffee plants spacing was 2.80 × 0.75, corresponding to 4.762 plants ha^{-1} (Fig. 1).

The experiment was carried out considering four replicates (plots) per treatment, excepting when sensors were used (soil moisture and temperature, and air temperature). Variables recorded by sensors were evaluated considering two replicates, and sensors were installed in the center of two plots. The size of each plot was 8.4 m^2, corresponding to 4 coffee plants. Plots of T2 and T4 are contiguous, but plots of T1 and T3 were divided in two equal parts and management close do macauba plants of two different palm lines.

Table 1
Soil chemical and physical characterization of the experimental area in Viçosa, MG, Brazil.

Chemical attributes		Physical attributes		
	0–20 cm		0–20 cm	20–40 cm
pH (H_2O)	5.98			
P (mg dm^{-3})	2.60	Sandy (%)	44	39
K (mg dm^{-3})	103.7	Silt (%)	13	12
OM (dag kg^{-1})	1.91	Clay (%)	43	49
Ca ($cmol_c$ dm^{-3})	1.95			
Mg ($cmol_c$ dm^{-3})	0.66	θFC (m^3/m^3)	0.44	0.44
Al ($cmol_c$ dm^{-3})	0.20	θPWP(m^3/m^3)	0.20	0.22
H + Al ($cmol_c$ dm^{-3})	4.41			
CEC (t) ($cmol_c$ dm^{-3})	3.07			
CEC (T) ($cmol_c$ dm^{-3})	7.28			

Chemical characterization according Embrapa (2011).
θFC: moisture at field capacity.
θPWP: moisture at permanent wilting point.

Since the experiment started, all plots received the same management. Only coffee plants received annual mineral fertilization, corresponding to doses recommended by Guimarães et al., (1999), which is distributed in three applications during the rainy season. In 2013 and 2014, 100 and 150 g of 20-5-20 fertilizer (N – P_2O_5 –K_2O) were used, respectively, per application. The control of weeds was performed periodically in all treatments without pesticides use, just by manual and mechanical weeding, and residues are left on the soil surface.

2.2. Evaluation of soil physical quality and soil moisture and temperature

Soil moisture and temperature were monitored from April to August 2014, coinciding with the dry season in the southeast region of Brazil. Rainfall during 2014 was below average than previous years. While 2014 presented 825 mm the average of 2011–2013 was 1349 ± 75 mm.

Soil moisture and temperature were monitored by sensors (Decagon EM50) placed in the center of two layers, in the top (0–20 cm) and deep (20–40 cm) positions, with two replications per treatment (Fig. 1). Soil layers selected represent the soil portion with the highest concentration of absorbing roots of coffee plants (Rena and Guimarães, 2000). The sensors were coupled to a datalogger (Decagon ECH_2O Logger) which set to take readings at intervals of 60 min. Moisture sensors were calibrated using with gravimetric soil water values.

Rainfall was monitored on the experimental area using two rain gauges. The volume collected was measured daily at around 4:30 pm to get the accumulated rainfall data.

For soil physical quality evaluation, four undisturbed soil cores (5 cm height and diameter) were sampled in the coffee rows at the center of 0–10, 10–20, 20–30 and 30–40 cm depth layers in each treatment (one soil core per plot). These samples were used for the determination of soil bulk density (Bd) and soil microporosity (Mi). Density of particles (Dp), total soil porosity (TP) and macroporosity (Ma) were also evaluated. All soil physical analyzes were conducted according to Embrapa (2011).

2.3. Microclimatic characterization

Maximum and minimum air temperatures were monitored by

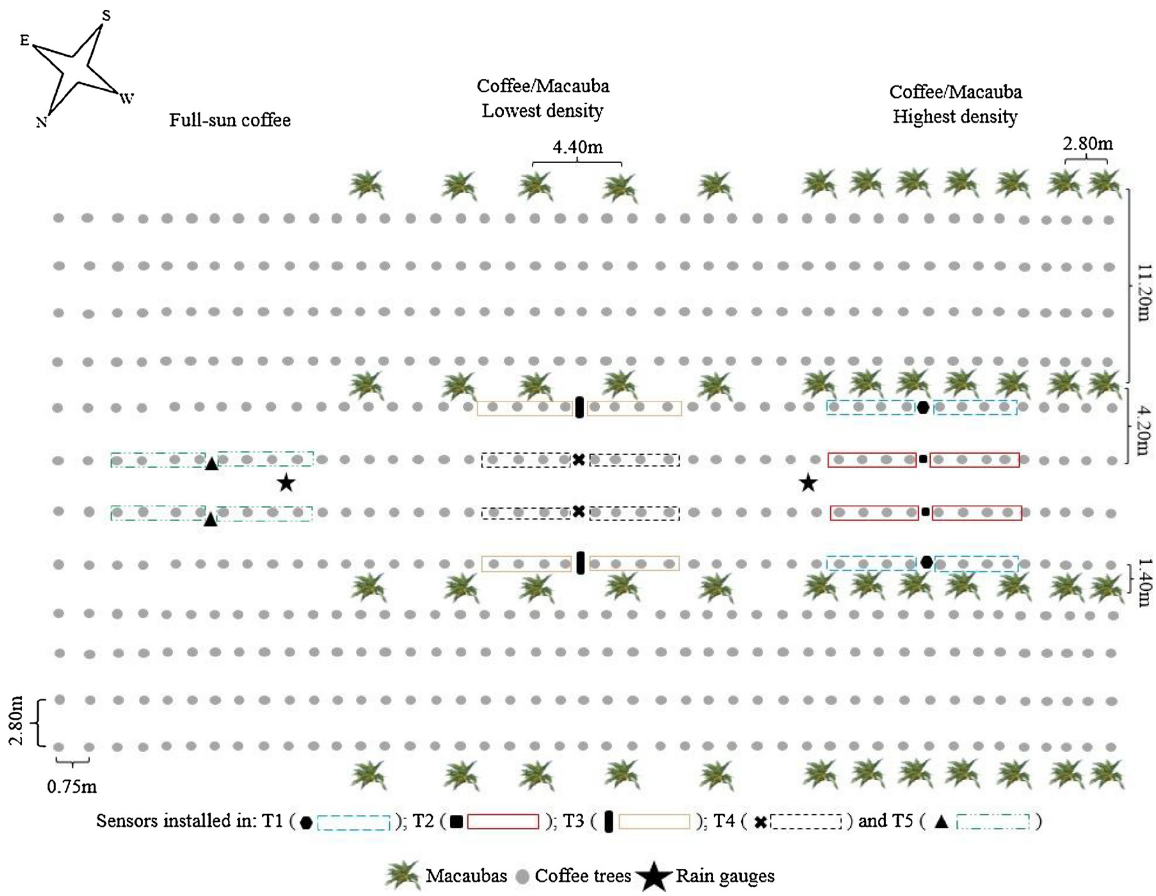


Fig. 1. Distribution of soil water and temperature sensors and rain gauges on experimental area in the coffee plants rows, 1.4 m and 4.2 m away from *macaubas* planted in the highest and the lowest density. Soil water and temperature sensors were at two depths (0–20 and 20–40 cm).

traditional min/max analog thermometers. They were installed at 1.5 m height in coffee plants near the moisture and temperature soil sensors among the tree crown in order to avoid direct solar incidence. Readings were taken every day in the afternoon (4:30 p.m.) from April to August 2014.

The photosynthetically active radiation (PAR) above the coffee canopy were evaluated using an AccuPar Ceptometer®. Readings were performed in triplicate in each treatment, in two seasons; on April 9th, 2014 (fall) and September, 2nd 2014 (winter), from 11.00 a.m. to 12.00 p.m. The percentage of available PAR was calculated by the ratio between PAR values from above coffee plants in agroforestry systems and on the unshaded area (Pezzopane et al., 2010). Shadow percentage was estimated in quintuplicate in rows of each treatment, above the coffee canopy, in February 2014 using hemispherical photographs (Schleppi et al., 2007). A camera coupled with a fisheye lens mounted on a tripod with bubble level and facing north was used. Images were obtained before sunrise with diffused light conditions to obtain the maximum contrast between leaves and the sky (Whitford et al., 1995). After that, pictures were processed in a computer using GLS software (Gap Light Analyzer© 2.0) to estimate the average shade percentage in the period from February to August 2014 in each treatment.

2.4. Evaluation of coffee yield

Coffee yield was assessed in 2013 and 2014, from the fruit produced by 16 coffee plants per treatment obtained from four replicates composed of four plants each one. After harvesting, fruits production was recorded and subsamples were dried until reaching moisture between 12 and 13%. These subsamples were processed to obtain productivity in kg of processed grains per plant. Additionally, we evaluated the production efficiency, a parameter related to crop costs and revenues evaluation (Silva et al., 2008). Production efficiency was obtained by the dry ratio between processed grains mass and fruits production after drying.

2.5. Statistical analysis

Descriptive statistics was used initially for data evaluation. After the relationship evaluation of soil physical, soil water, soil temperature variables, and attributes of microclimate with coffee productivity on presence, planting density and distance to coffee plants of *macauba* was performed using Boosted Regression Trees (BRT) modeling technique according to Schapire et al. (2003) and Elith et al. (2008). For BRT analysis, we considered only 2014, when variables and attributes were measured. For BRT procedures, the GBM package in Software R, version 3.0.1 was used, as recommended by Elith et al. (2008).

3. Results

3.1. Soil moisture

Higher soil water in the 0–20 cm depth layer was identified when coffee grown 4.2 m away from *macaubas* during most of the evaluation period (April–August 2014), regardless of palm density (Fig. 2a). The coffee rows closest to *macaubas* planted at higher density had the lowest soil moisture content. The soil from unshaded coffee crop initially had an intermediate water content between that for the longer and shorter distances to palm trees. After, in the period from July to August, full sun coffee exhibited the highest soil water content.

In the deeper soil layer (20–40 cm), soil moisture was higher during

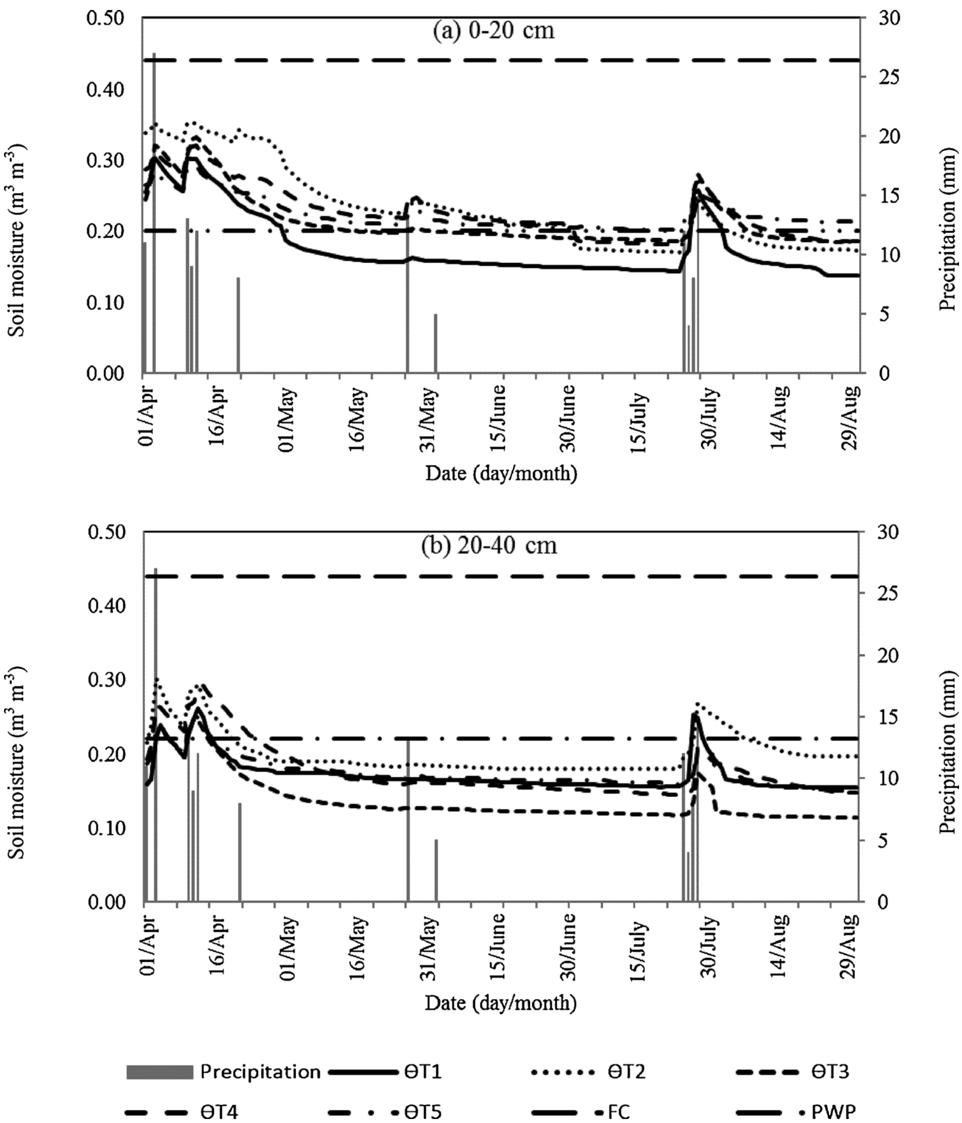


Fig. 2. Soil moisture (m^3/m^3) from 0 to 20 cm (a) and 20–40 cm (b) depths, expressed in terms of daily average, and accumulated daily rainfall (mm) under coffee plants grown 1.4 m (T1) or 4.2 m (T2) away from *macaubas* in the high and low planting densities, and under coffee as an unshaded crop (T5). Horizontal lines represented soil water content remaining at field capacity (FC) and at the permanent wilting point (PWP).

most of the experimental period in the coffee rows placed further from the *macaubas* planted at higher density (Fig. 2b). The lowest soil water in this subsurface layer was found in the coffee rows 1.4 m away from *macaubas* planted in lower planting density in almost all the monitoring period.

The soil water content never reached field capacity (FC) at either depths evaluated in the monitored period. On the other hand, soil moisture was lower than the permanent wilting point at 0–20 cm depth under coffee plants planted close to *macaubas* at the high row density treatment (T1), between May and August 2014, and in the 20–40 cm depth layer in all treatments, between April and August 2014 (Fig. 2a, b).

3.2. Soil temperature

The soil temperature between April and August followed the expected trend of autumn and winter in the southeast region of Brazil (Fig. 3). Over the days, the soil temperature decreased gradually until the middle of August, when started to increase. The cultivation of unshaded coffee plants (T5) presented the lowest soil temperature at the two evaluated depths, especially when soil temperature reduced from the end of April.

3.3. Soil physical properties

In general, no treatments affected soil physical quality (Table 2).

3.4. Microclimatic characterization

3.4.1. Air temperature

The unshaded system of coffee (T5) showed the highest daily temperature range, with both higher maximum and lower minimum temperatures compared to the other treatments. From August 22–27, when the highest temperatures were registered, the unshaded coffee had air temperature maximum of 39.8 °C and minimum of 4.5 °C, while in the other treatments the maximum reached 35.3 °C (T4), and a minimum was 5.8 °C (T2) (Fig. 4).

The highest mean maximum air temperature (31.3 °C) was recorded in the unshaded coffee plants, surpassing the maximum temperature observed in the shaded coffee crops by 1.3–2.9 °C (Table 3). Variation among treatments in minimum air temperature was minor, but unshaded area temperatures were 0.9–1.1 °C lower than in shaded coffee

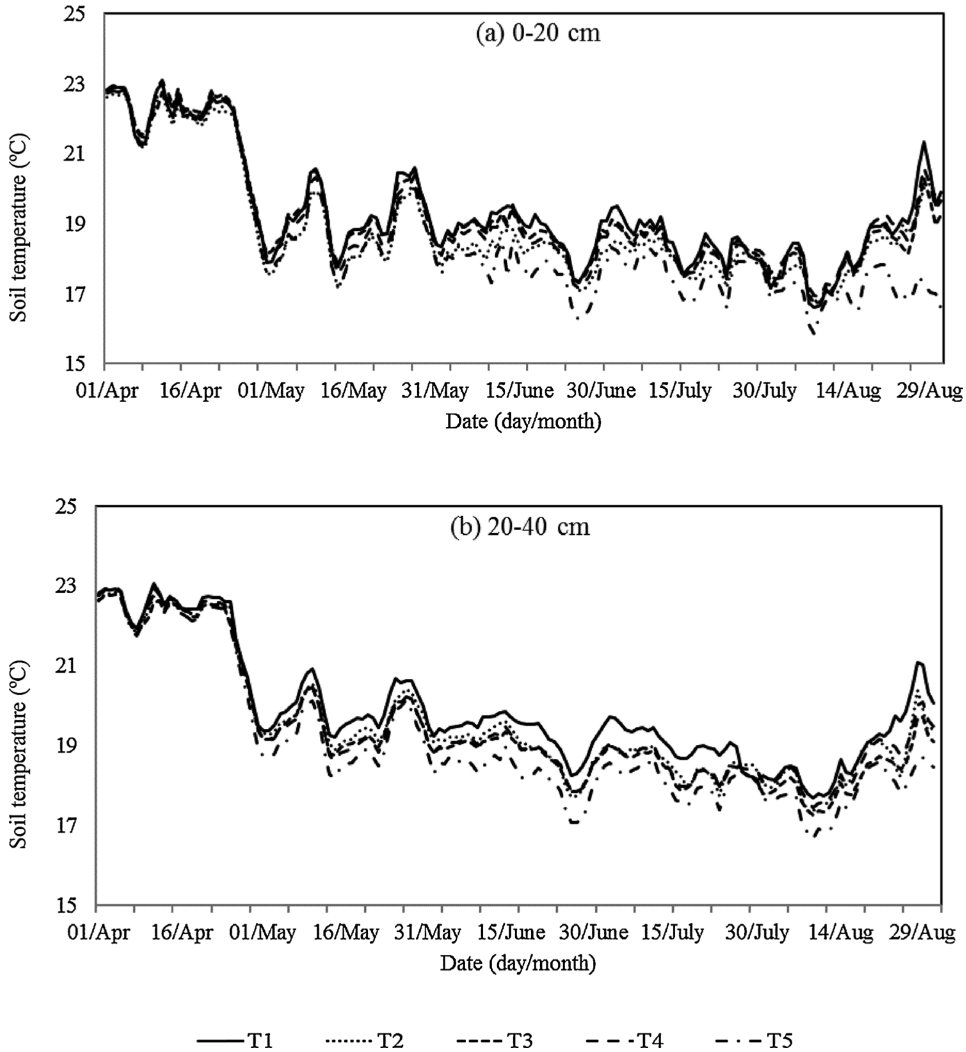


Fig. 3. Soil temperature (°C) from 0 to 20 cm (a) and 20–40 cm (b) depths, expressed in terms of daily average, under coffee plants grown 1.4 m (T1) or 4.2 m (T2) away from *macaubas* in the high and low planting density, or under coffee grown as an unshaded crop (T5).

crops. Mean air temperatures in all treatments varied between 20.2–21.2 °C (Table 3).

3.4.2. Shading evaluation

Hemispherical photographs indicated higher shading in coffee rows grown closer (1.4 m) to *macaubas*, both in low (51.8% shading) and in high (47.4% shading) palm trees density planting (Table 4). Coffee rows (4.2 m) further from *macaubas* were less shaded, with the same percentage (30.1%) in the two planting densities of palm trees. In the unshaded treatment (T5), the 2.1% of shading was associated with self-shading provided by the coffee canopy.

The available PAR reaching the coffee plants was affected by treatments. Coffee rows 1.4 m away from *macaubas* (T1 and T3) were the most affected, and the highest palm tree planting density (T1) presented the lowest PRA availability (Table 5). The highest global PRA rate above the canopy of coffee plants was verified in the unshaded treatment (T5).

Regardless of the *macauba* planting density, at the greater distance between rows of coffee plants and palm trees (4.2 m), available PAR values were higher than with the shorter distance (1.4 m) (Table 5). Availability of PAR was little affected by palm tree density at the greater distance between coffee plants to *macaubas* (T2 and T4), with values close to 100%. However, when the distance was reduced, the percentage of radiation that reaches the crown of coffee plants was reduced to almost half (T3) or less than half (T1).

3.5. Yield and production efficiency of coffee plants

Yields results represent the biennial pattern of coffee production in Brazil, where a year of high yield is followed by a year of low yield. In 2013, the cultivation in full sun system (T5) presented similar productivity (0.232 kg of processed coffee per plant) than shaded coffee treatments (Fig. 5) and similar production efficiency (Table 6).

In 2014, coffee plants grown further from the *macaubas* had the highest productivity, with 0.720 kg (T2) and 0.681 kg (T4) of processed coffee per plant. In the unshaded system (T5), the productivity of 0.230 kg was similar to the previous year (Fig. 5), but production efficiency was the lowest (Table 6). Coffee planted close to *macaubas* (T1 and T3) were more affected in terms of productivity in both palm trees planting densities in 2014, but providing yields similar to that of the unshaded treatment (T5) (Fig. 5).

Considering the average yield for the two assessed years, which represent the biennial pattern of Brazilian coffee production, higher productivity were related to coffee plants grown 4.2 m away from *macauba*, both in the higher (T2, 0.522 kg/plant) and in the lower (T4, 0.487 kg/plant) row density (Fig. 5). The other treatments, which include coffee plants grow closer to *macaubas* and in the unshaded system, presented similar lower yields.

Table 2
Soil physical attributes under coffee plants grown under different treatments.

Treatments	Bd	Dp	Ma	Mi	TP
	kg/dm^3		m^3/m^3		
0–10 cm depth					
T1	1.3 ± 0.06	2.5 ± 0.15	0.08 ± 0.03	0.39 ± 0.02	0.47 ± 0.04
T2	1.4 ± 0.10	2.6 ± 0.04	0.06 ± 0.03	0.39 ± 0.02	0.45 ± 0.04
T3	1.4 ± 0.13	2.7 ± 0.12	0.13 ± 0.04	0.36 ± 0.01	0.49 ± 0.03
T4	1.4 ± 0.05	2.6 ± 0.13	0.07 ± 0.04	0.38 ± 0.01	0.45 ± 0.05
T5	1.4 ± 0.07	2.6 ± 0.04	0.14 ± 0.04	0.34 ± 0.03	0.48 ± 0.03
20–30 cm depth					
T1	1.3 ± 0.08	2.4 ± 0.21	0.09 ± 0.06	0.36 ± 0.02	0.45 ± 0.06
T2	1.3 ± 0.09	2.6 ± 0.11	0.11 ± 0.04	0.37 ± 0.02	0.48 ± 0.05
T3	1.5 ± 0.08	2.7 ± 0.10	0.07 ± 0.05	0.37 ± 0.02	0.44 ± 0.04
T4	1.4 ± 0.01	2.5 ± 0.15	0.08 ± 0.04	0.37 ± 0.04	0.45 ± 0.03
T5	1,3 ± 0.09	2.6 ± 0.12	0.17 ± 0.05	0.33 ± 0.02	0.50 ± 0.04
20–30 cm depth					
T1	1.3 ± 0.13	2.7 ± 0.05	0.13 ± 0.08	0.38 ± 0.03	0.51 ± 0.05
T2	1.4 ± 0.07	2.6 ± 0.12	0.10 ± 0.03	0.39 ± 0.02	0.49 ± 0.02
T3	1.5 ± 0.05	2.7 ± 0.06	0.05 ± 0.03	0.41 ± 0.02	0.46 ± 0.03
T4	1.4 ± 0.15	2.7 ± 0.10	0.10 ± 0.08	0.38 ± 0.10	0.48 ± 0.05
T5	1.4 ± 0.12	2.6 ± 0.02	0.10 ± 0.07	0.35 ± 0.02	0.45 ± 0.05
30–40 cm depth					
T1	1.3 ± 0.04	2.6 ± 0.04	0.09 ± 0.06	0.39 ± 0.04	0.48 ± 0.02
T2	1.4 ± 0.02	2.6 ± 0.10	0.06 ± 0.07	0.40 ± 0.07	0.46 ± 0.02
T3	1.4 ± 0.06	2.7 ± 0.08	0.05 ± 0.01	0.42 ± 0.01	0.47 ± 0.01
T4	1.4 ± 0.09	2.5 ± 0.14	0.06 ± 0.05	0.39 ± 0.02	0.45 ± 0.03
T5	1.5 ± 0.14	2.6 ± 0.08	0.08 ± 0.06	0.35 ± 0.03	0.43 ± 0.06

Data are means ± standard deviation. Bd: soil bulk density, Dp: density of particles, Ma: macroporosity, Mi: microporosity, TP: soil total porosity.
Treatments: coffee plants grown 1.4 m (T1) and 4.2 m (T2) away from *macaubas* in the high (T3 and T4, respectively) and low plant density, or grown as an unshaded crop (T5).

Attributes related to the productivity and production efficiency of coffee plants

The attributes most related to the increase in coffee productivity in 2014 were soil moisture higher than 0.18 m^3/m^3 in the 20–40 cm depth layer (Fig. 6a), PAR values higher than 1000 μol m^{-2} s^{-1} (Fig. 6b), and maximum air temperatures lower than 30 °C (Fig. 6c). These three variables, among all microclimate and soil physical and soil water attributes, together accounted for 93.5% of the relative influence on coffee productivity. In turn, the minimum air temperature (Fig. 6d), soil moisture at 0–20 cm depth layer (Fig. 6e), soil temperature in the 20–40 cm depth layer (Fig. 6f), soil temperature at 0–20 cm depth layer (Fig. 6g) and average air temperature (Fig. 6h) had little influence on coffee productivity, accounting together for only 6.5% of the relative influence.

The BRT analysis also indicated the influence of planting density and the distance of *macaubas* from coffee trees on yield for 2014, considering the three variables previously selected as the most important (soil moisture at 20–40 cm; PAR and maximum air temperature). The highest coffee productivity was associated with coffee plants planted 4.2 m away (Fig. 7b) of higher density (Fig. 7a) of *macaubas* trees.

Soil moisture in the 20–40 cm depth layer was related to the planting density of *macauba*. The high relative influence (71.9%) of the planting density in the soil moisture indicated that higher plant density of *macauba* maintained higher soil moisture content in that layer (Fig. 7c). The distance between coffee plants and *macauba* did not affect soil moisture at this layer (Fig. 7d). This suggests that shading effect is more important than the water competition between the coffee and *macauba* trees.

The distance of the coffee plants to *macaubas* was crucial in the PAR contribution to productivity, while palm trees planting density presented little influence on that variable (Fig. 7e and f). Thus, the greater distance between coffee and *macauba* plants (relative influence of 98.6%) provided higher PAR for coffee plants comparable to that in the unshaded coffee.

M*acaubas* planting density, as well as the distance of the *palm* trees to the coffee trees, influenced the maximum air temperature. Lower maximum temperatures were associated with coffee grown closer to *macaubas* planted at higher row density (Fig. 7g, h). Both situations indicate greater interception of sunlight by the canopy of *macaubas* and consequent attenuation of the air temperature.

4. Discussion

4.1. Soil moisture

The greatest coffee-*macauba* distance (4.2 m) provided less shading, but still enough to reduce losses of soil water, as demonstrated by higher soil moisture at 0–20 cm depth layer at T2 and T4. The lower soil moisture verified at the shortest distance from coffee rows to *macaubas* (1.4 m) in the higher planting density (T1) may be related to the water uptake by the palm tree, reducing water availability for coffee plants.

The higher soil moisture recorded at 0–20 cm depth of the unshaded coffee treatment (T5) from July to August, which coincides with the regional lowest rainfall period, is interesting. Similar results were found by Neves et al. (2007) in Viçosa, MG, Brazil, who observed at the beginning of the dry period an increase in soil moisture in the shaded coffee crop in the 10–20 cm depth layer, but with the advance of the dry season, the higher soil moisture became higher in the unshaded treatment. In southwestern Bahia, Coelho et al. (2010) verified no differences in soil moisture at 0–20 cm depth layer between the shaded and unshaded coffee systems in March (rainy season). However, in August, the region's driest month, the soil in the unshaded treatment had higher moisture, which can be related to the water competition in shaded systems between tree species and coffee plants. However, this tendency may be different in high rainfall areas, as verified by Lin (2010), in Chiapas, Mexico. This author found lower soil moisture in the 0–30 cm depth layer in the lowest shadow treatment (10–30%) compared to the other two one more shadowed (30–50% and 60–80%), both in the rainy as well as in the dry seasons. These results can be due to the high

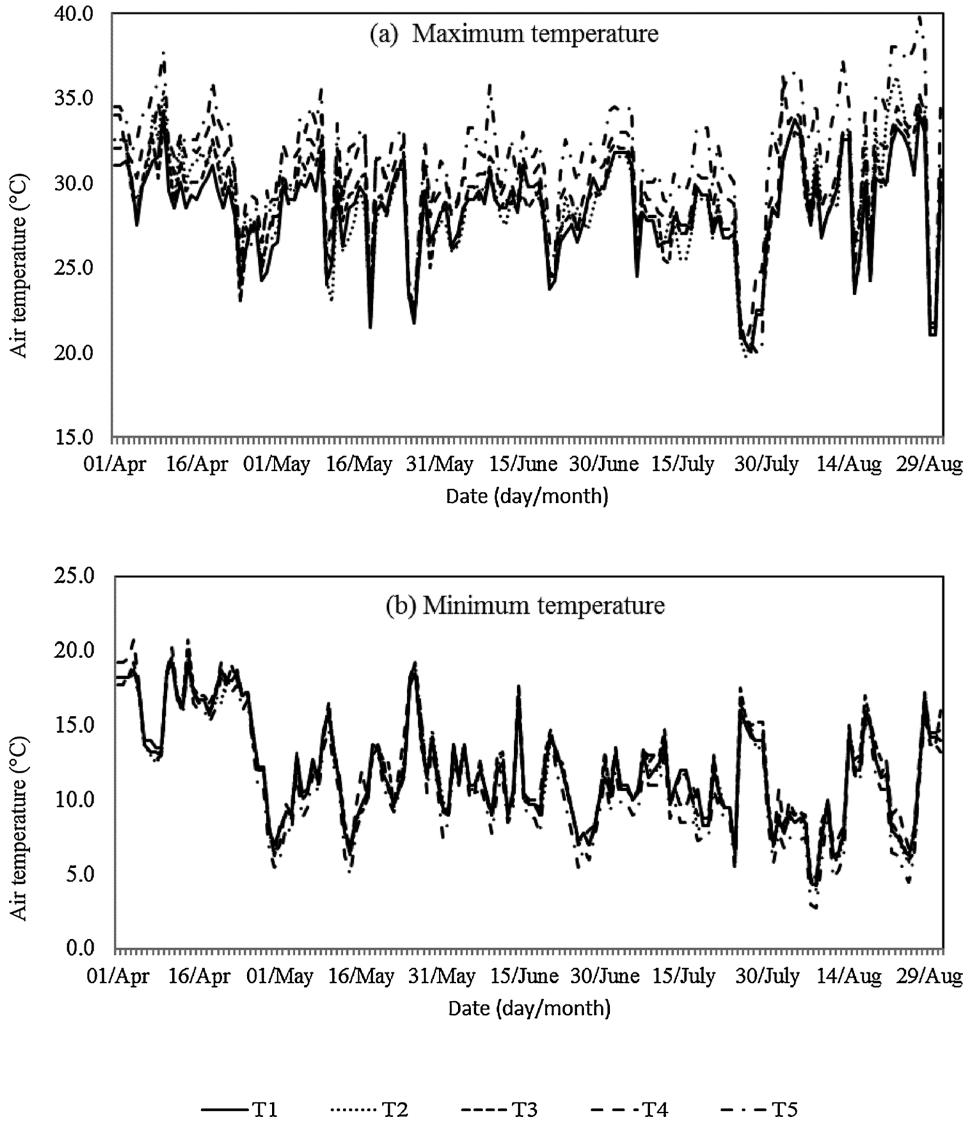


Fig. 4. Daily maximum (a) and minimum (b) air temperatures (°C) in the experimental area where coffee plants were grown 1.4 m (T1) and 4.2 m (T2) away from macaubas in the high and low density planting density (T3) and T4, respectively), or grown as an unshaded crop (T5).

rainfall of study area (> 3000 mm, concentrated from May to October) combined with the shading effect, both reducing losses by evaporation and transpiration in areas with larger vegetation cover.

The fact that soil moisture contents in all treatments did not reach field capacity at the two depths is a consequence of sampling in the dry season. Soil moisture below to the permanent wilting point did not cause the death of plants, as also reported by Neves et al. (2007) in Viçosa, MG, Brazil, who concluded that water uptake by the roots was continuing in deeper and not in the monitored soil layers. Finally, it is interesting to consider that the period evaluated in this study coincides with the period when coffee plants require less soil moisture, because is the harvest phase and reduced growth stage.

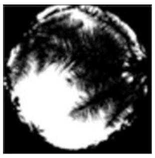
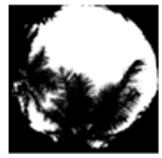
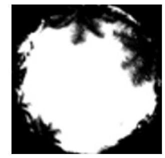
The water requirement of coffee plants is higher during the vegetative and reproductive growth stages (Camargo, 1985), coinciding in the region studied to the period between September and March. In this period, low soil water availability causes remarkable effect on coffee productivity. Lower soil water contents from October to December delay fruits expansion, leading to a reduction of coffee grain sizes and, consequently, loss of productivity (Silva et al., 2008). From January to March, low soil water availability affects fruit formation phase

Table 3
Air temperature average from April to August in the experimental area.

Temperature	T1 °C	T2	T3	T4	T5
Maximum	28.4 ± 2.8	28.8 ± 3.1	28.7 ± 3.0	30.0 ± 3.0	31.3 ± 3.9
Minimum	11.9 ± 3.5	11.9 ± 3.6	12.1 ± 3.6	12.2 ± 3.5	11.0 ± 3.8
Mean	20.2 ± 2.0	20.3 ± 2.3	20.4 ± 2.1	21.1 ± 2.2	21.2 ± 2.4

Data in daily means ± standard deviation.
Treatments: coffee plants grown 1.4 m (T1) and 4.2 m (T2) away from *macaubas* in the high (T3 and T4, respectively) and low plant density, or grown as an unshaded crop (T5).

Table 4
Estimate percentage of shading of coffee at different distances from macaubas planted at high and low density (n = 5). Representative hemispherical photos are shown.

T1	T2	T3	T4	T5
Shading (%)				
51.8	30.1	47.4	30.1	2.1
				

Treatments: coffee plants grown 1.4 m (T1) and 4.2 m (T2) away from *macaubas* in the high (T3 and T4, respectively) and low plant density, or grown as an unshaded crop (T5).

Table 5
Photosynthetically active radiation (PAR) and available PAR in the experimental area for different treatments.

Treatments	Sampling date		Mean
	09/04/2014	02/09/2014	
PAR (μmol $m^{-2} s^{-1}$)			
T1	667 ± 23.6	705 ± 109.9	686 ± 73.5
T2	1.772 ± 25.1	1.715 ± 16.2	1.743 ± 7.0
T3	1.116 ± 29.5	1.005 ± 40.3	1.061 ± 26.6
T4	1.763 ± 51.2	1 724 ± 75.4	1.744 ± 46.0
T5	1.864 ± 13.4	1.760 ± 36.4	1.812 ± 24.9
Mean	1.436 ± 452.7	1.382 ± 454.9	
Available PAR (%)			
Treatments			Mean
T1	35.8 ± 1.2	40.0 ± 6.2	37.9 ± 4.9
T2	95.0 ± 1.3	97.4 ± 9.3	96.2 ± 4.5
T3	59.9 ± 1.5	57.1 ± 2.2	58.5 ± 1.3
T4	94.6 ± 2.7	97.9 ± 4.2	96.2 ± 2.5
Mean	71.3 ± 24.7	73.1 ± 26.2	

Available PAR: ratio between the global PAR measured in shaded coffee and in unshaded coffee (T5). Treatments: coffee plants grown 1.4 m (T1) and 4.2 m (T2) away from *macaubas* in the high (T3 and T4, respectively) and low plant density, or grown as an unshaded crop (T5).
Data in mean ± standard deviation.

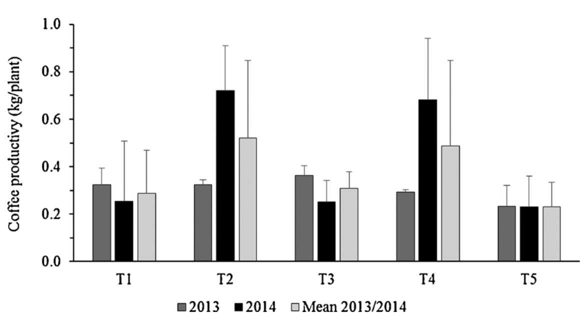


Fig. 5. Productivity (kg of processed grains per plant) of coffee plants in the different treatments: coffee plants grown 1.4 m (T1) and 4.2 m (T2) away from *macaubas* in the highest planting density, grown 1.4 m (T3) and 4.2 m (T4) away from palm trees planted in the lowest density, and grown as unshaded crop (T5). Bars represent standard deviation.

providing low yield and poor fruit quality. However, between April to June, period associated to the ripening of the coffee fruits, a moderate water deficit can be beneficial to the product quality (Camargo and Camargo, 2001), because provided uniform grains maturation and floral differentiation of buds, and contributed to the roots growth and development of branches formed in the rainy season (Sediyama et al., 2001). However, at this stage, most pronounced water deficit could affect the formation of floral buds, flowering and fruiting in the

Table 6
Production efficiency of coffee crop planted in different treatments.

Production efficiency (%)			
Treatments	Harvest 2013	Harvest 2014	Mean
T1	55.2 ± 0.05	55.7 ± 0.02	55.4 ± 0.04
T2	54.9 ± 0.02	55.7 ± 0.02	55.3 ± 0.02
T3	53.8 ± 0.04	57.9 ± 0.02	55.8 ± 0.04
T4	54.2 ± 0.01	55.2 ± 0.02	54.7 ± 0.01
T5	54.6 ± 0.02	46.4 ± 0.03	50.5 ± 0.05

Treatments: coffee plants grown 1.4 m (T1) and 4.2 m (T2) away from *macaubas* in the high (T3 and T4, respectively) and low plant density, or grown as an unshaded crop (T5).
Production efficiency represent the ratio between processed grains mass and fruits production after drying.
Data in mean ± standard deviation.

following year. Therefore, the period evaluated in this study (April–August), water stress is not critical, and soil moisture can approach the permanent wilting point, with no damages on the coffee.

4.2. Soil temperature

The lowest soil temperature at the both evaluated depths in unshaded coffee plants (T5) differ from results reported by Morais et al. (2006), who studied coffee grown under *guandu* (*Cajanus cajan*) shade in Londrina, Paraná State, and from those by Bote and Struik (2011), who evaluated coffee under shade of different tree species in Ethiopia. Both studies showed lower temperature in shaded coffee in relation to the unshaded treatment. Reduction of soil temperature on shaded treatments are expected and related to shading effect. Morais et al. (2006) consider also the effect of the mass of roots, stems and leaves accumulated in agroforestry system contribute to a reduction in the flow of heat in the soil.

In our study, we did not find any accumulated litter in any of the treatments, not even in the shaded ones, since *macaubas* did not significantly produce litter. The studied period may also explain soil temperature results, since data was recorded in autumn and winter, therefore, more cold seasons. The presence of palm trees seems to allow, on the one hand, solar radiation to reach the soil surface in the shaded treatment during the day and, at night, promote a buffering effect, reducing losses of long-wave radiation, and thus creating a hotter microclimate in the shaded systems. In the summer season, high air temperatures supplant this buffering effect, and low temperatures are expected on shaded treatments in comparison to unshaded ones. The effect of palm trees as windbreakers cannot be discarded, since the winds are most common and strong during the dry and cold season in the region. The presence of palm trees can provide greater resistance to air flow near the soil surface, thus reducing heat losses from the soil.

Our results show the presence of tree component may contribute to

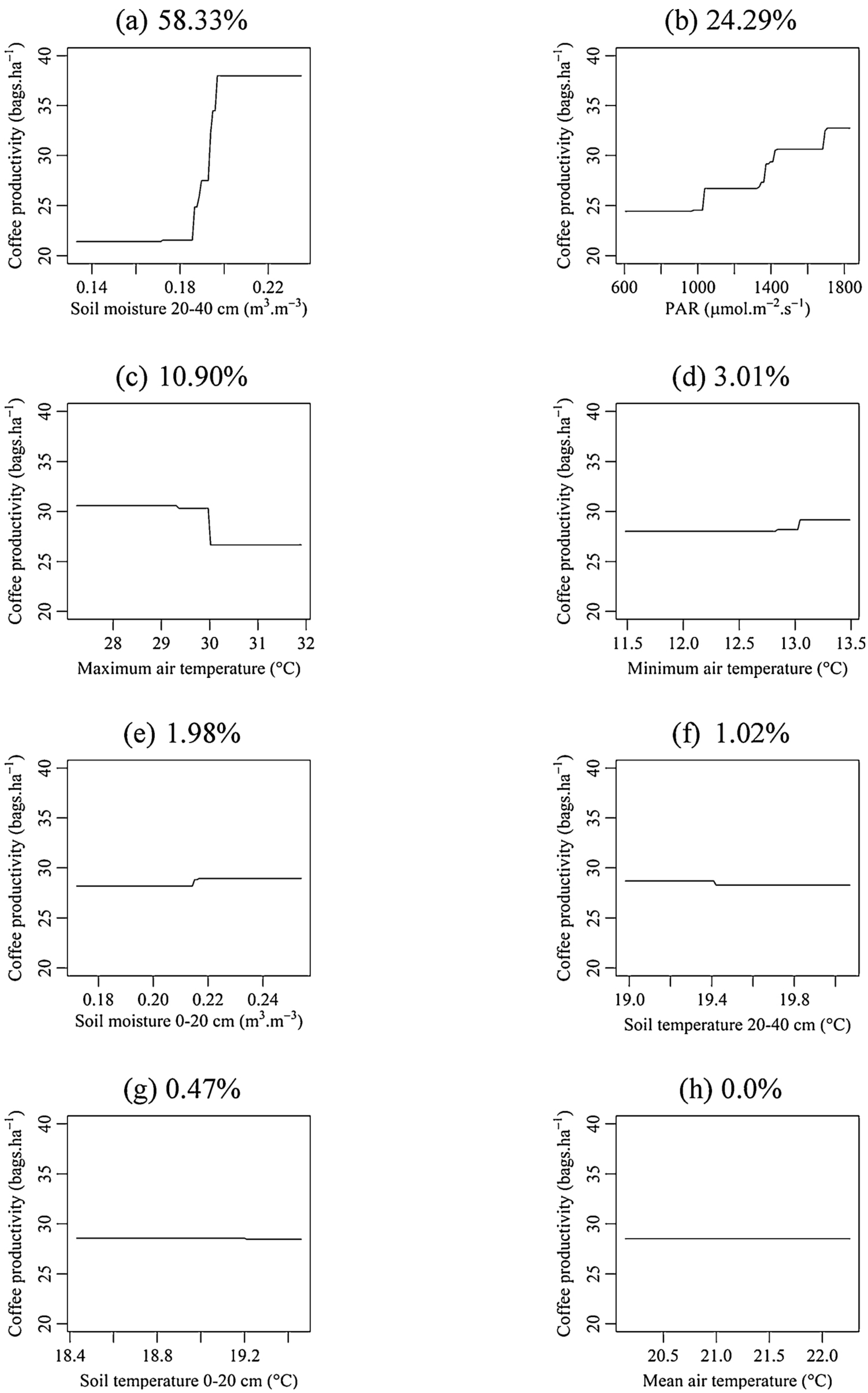


Fig. 6. Relationship of microclimate attributes and soil physical, soil temperature and soil water variables on coffee yield(bags/ha) in 2014 and their relative influence (%) after Boosted Regression Trees (BRT) analysis.

the increase in soil temperature in agro-ecosystem in the cold periods, an important characteristic to be considered in regions affected by cold-weather damage (frosts) which causes major damage in coffee plants (Camargo, 2010).

4.3. Soil physical quality

Positive effects of agroforestry systems on the soil physical quality have been studied by Aguiar (2008) after 13 years of coffee intercropped with *ingá* trees in Araponga, Minas Gerais State. Aguiar (2008) verified lower soil bulk density and microporosity and higher soil porosity in soil under shaded coffee plants in comparison to unshaded

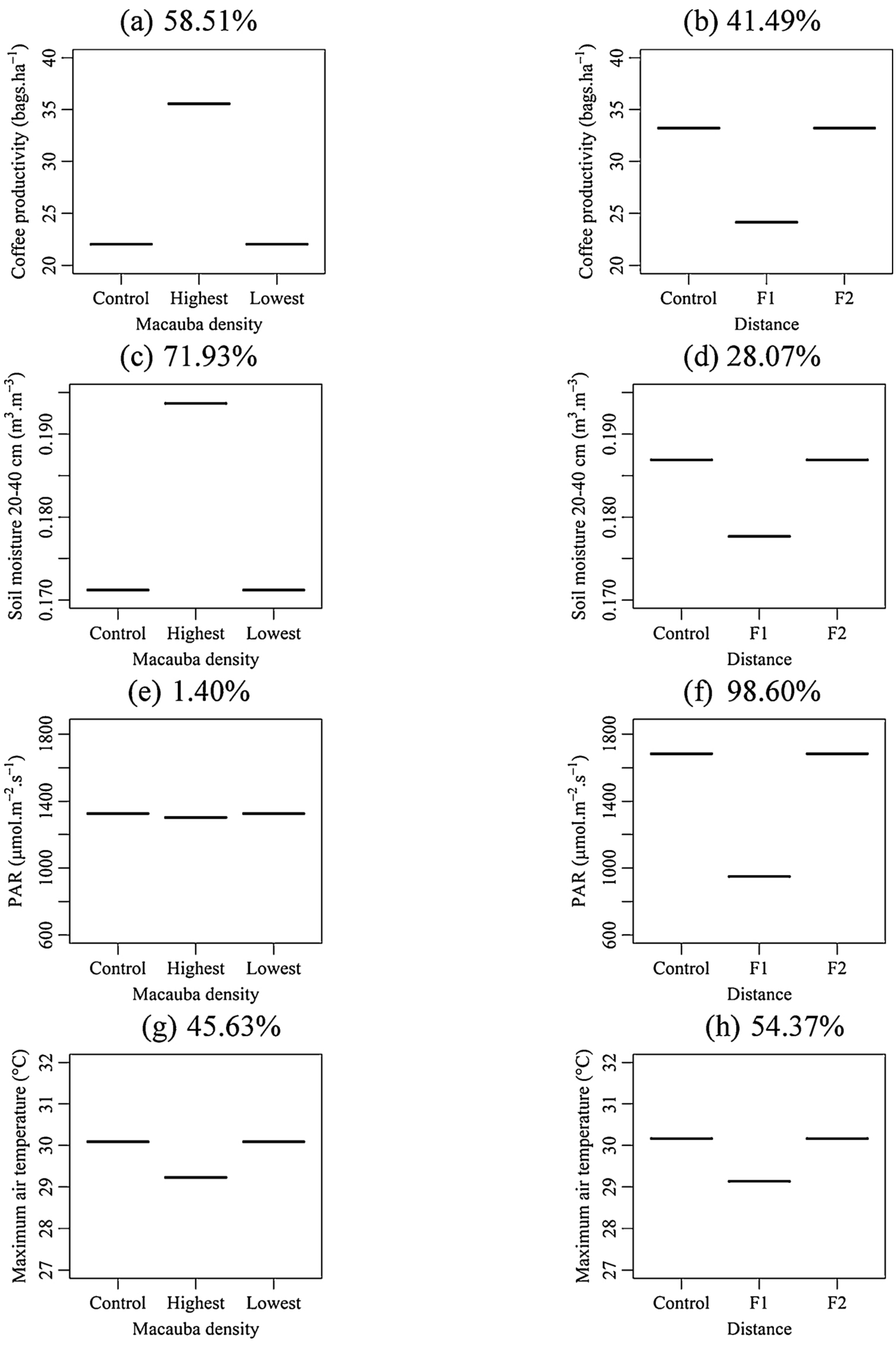


Fig. 7. Relationship among variables recorded in coffee crop grown in shaded and unshaded system. Shaded system is composed by *macaubas* trees planted at high (318 plants/ha) and low density (203 plants/h) and at distances of 1.4 m (F1) and 4.2 m (F2) from coffee rows. Values represent the level of influence on coffee productivity from the Boosted Regression Trees (BRT) analysis.

treatment. That no shading effect on soil physical quality was observed in our study may be associated with the shorter time of management (seven years), little litter fall from the aerial part of *macauba*, and expected roots vertical conformation of the palm trees. Since most part of the soil physical effects attributed to the trees component in agroforestry systems are associated with root turnover, the vertical root system of *macauba* is expected be make a smaller contribution to soil physical properties. Further studies are required to assess whether a longer time under the *macauba* intercrop could affect soil physical properties.

4.4. Microclimatic characterization

4.4.1. Air temperature

Treatments affected microclimatic dynamics, and data obtained suggest the effect of afforestation to mitigate air temperature extremes. All shaded treatments reduced the thermal amplitude of air temperature, increasing average minimum temperature and reducing maximum one in comparison to unshaded treatment.

The average of air temperature recorded in unshaded coffee treatment was the higher, however, did not exceed the ideal range for *Coffea* *arabica*, which is 18–22 °C (Assad et al., 2004). This can be due the air temperature monitoring was carried out in the autumn and winter. In the spring and summer season, we can expected higher air temperature and a greater difference between shaded and unshaded treatments. This tendency has been observed by other authors in Brazilian states of Minas Gerais (Campanha et al., 2004), Paraná (Morais et al., 2006), São Paulo (Valentini et al., 2010; Pezzopane et al., 2011), Rio de Janeiro (Cocheto-Junior et al., 2011), and Costa Rica (Siles et al., 2010). Campanha et al., (2004) observed during one year a reduction of 2.6 °C in maximum air temperature in agroforestry systems with coffee in comparison to the unshaded one.

The increase in the air temperature may cause severe damage to the coffee plants, and as a consequence, loss of crop yield (Camargo, 1985). Average annual temperatures higher than 23 °C accelerate fruit maturation and cause lower product quality (Camargo, 2010); above 30 °C, there is yellowing of leaves and reduced growth (DaMatta and Ramalho, 2006); and at or above 34 °C, abortion of flowers is common (Sediyama et al., 2001). Some peaks of air temperature bigger than 34 °C were observed in unshaded treatment, not being noted in other shaded treatments. In spring and summer, these peaks are expected more frequently, causing more damage to coffee plants. In addition, damages are especially harmful when high temperatures are associated with a prolonged dry season (Camargo, 2010).

The results indicate the potential for the agroforestry system to buffer air temperature with a two-fold positive effect for coffee crops. Firstly, in the face of rising temperature expected with global climate change the agroforestry planting may be somewhat protected against extreme temperatures at least in the medium term. On the other hand, protection of coffee crops in regions subject to frost, which despite being sporadic, further support the success of shaded coffee crops (Camargo, 2010).

4.4.2. Shadowing

Part of the effects of tree components in an agroforestry system is due to the shade provided which is dependent on the distance of the main crop from the trees (Siles et al., 2010). Thus, it was expected the largest shade percentages would be provided by *macaubas* when the rows were closest to coffee plants. Even at the farthest distance, the shade percentage exceeds the recommended by DaMatta (2004) for tropical regions, who indicated 20% of shade as a superior limit to avoid losses in coffee crop yield.

The proximity of the coffee rows and planting density of *macaubas* also affected the PAR that reaches the trees in the two sampling periods. Similar effects were found by Pezzopane et al. (2010) in an experiment carried out in São Mateus, state of Espírito Santo, where coffee crop was intercropped with macadamia trees. The authors verified lower availability of PAR above the crown in coffee rows 2.5 m away from macadamias in relation to the rows at 5.0 m.

Solar radiation is an important factor in coffee flowering and yield (Queiroz-Voltan et al., 2011). However, exposure of coffee plants to high levels of solar radiation, combined with high temperatures, as observed in T5, leads to rapid decrease in photosynthesis (Morais et al., 2003), in addition of causing photoxidative damage to coffee leaves, the situation often seen in unshaded systems (DaMatta, 2004). Thus, the use of the tree component may be a strategy to attenuate the entry of light under the trees, but the interception by trees should be moderate, since excessive shade may lead to severe reductions in crop yield.

4.5. Intercropping coffee with macauba facing climate change and variability effects

The crop productivity is related to a set of biotic and abiotic factors affecting the plant during its growth. Thus, production is the result of how such factors affected the plant, and how it responds to different management techniques.

The lower yields associated with the proximity to *macaubas* may be related to low solar radiation reaching the coffee plants due to higher shade, as indicated by the highest percentage of shading and lower values of PAR and availability of PAR. Another factor that may have contributed to the reduction of productivity in these treatments was the lowest soil moisture found in the vicinity of coffee plants closer to *macaubas*.

The production efficiency of coffee crop in 2014 indicates that the effect of the distance of *macaubas* is not crucial to distinguish shaded treatments, because all of them presented similar performance. On the other hand, coffee plants intercropped with *macauba* provided higher production efficiency than the unshaded coffee plants, which is an important factor for the income revenue of the farmer and indicate the vulnerability of the unshaded coffee crop in extreme weather events. In addition, shaded systems still provide the production of *macauba* fruits, which was not valued and should be considered in further studies on the productivity and profitability of the agroforestry system.

Despite the severe drought that hit the region in 2014, the presence of *macaubas* at a greater distance from the coffee plant rows contributed to the achievement of higher productivity. Again, the explanation may be associated to the maintenance of a greater soil moisture in these treatments provided by shading and due to the lower competition for water, guaranteed by the greater distance of trees from the coffee rows.

For coffee crop in the intercropped system, the association with trees plays an important role on productivity. Both lack of effect and increase in the productivity of coffee plants under moderate shading in relation to unshaded coffee are common (Soto-Pinto et al., 2000; Ricci et al., 2006; Cocheto-Junior et al., 2011). However, when there is excessive shading, productivity losses are considerable (Campanha et al., 2004; Morais et al., 2006; Jaramillo-Botero et al., 2010; Siles et al., 2010). In a study carried out by Jaramillo-Botero et al. (2010) in Viçosa, MG, Brazil, coffee productivity decreased related to shade increasing, especially in years of high productivity. Those reports support our results of lower productivity in coffee rows closer to *macaubas* trees. While these coffee plants were submitted to shade of 51.8% (T1) and 47.4% (T3), the more distant coffee plants presented 30.1% of shade. The greatest coffee-*macauba* distance resulted in less shading, which was still sufficient to reduce water losses from the system, as indicated by the highest soil moisture obtained from these treatments.

The use of boosted regression tree analysis (BRT) aimed to investigate the influence of physical and water attributes of soil and of microclimatic variables on coffee productivity in 2014, which was the monitored year. Higher soil moisture in the 20–40 cm depth layer, greater photosynthetically active radiation and maximum air temperatures lower than 30 °C best explained the increase in coffee productivity. Coincidentally, those variables are the main factors involved in affect the growth and productivity of *Coffea arabica* according to Camargo (2010).

This study indicates that use of Macaubas trees intercropped with the coffee crop in agroforestry systems can provide changes in microclimate to face consequences of climate change. However, a limitation of this study concerns that the experiment could not be ideally structured to control site heterogeneity. Thereby further studies would be useful to fully establish the benefits of intercropping. On the other hand, we have evidence of the homogeneity of the area, and we consider the results relevant for advanced studies mainly considering the data scarcity about the intercropping association between palms and crops.

5. Conclusions

Macaubas trees modified the microclimate of the coffee crop in the agroforestry system, providing reduction of the maximum air temperatures and the intensity and availability of photosynthetically active radiation.

The agroforestry system of coffee intercropped with *macauba* trees provides advantages in coffee productivity and production efficiency when compared to unshaded crops, and may be a mitigation strategy against future climatic variability and change related to high temperatures and low rainfall.

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