




Microclimate and soil and water loss in shaded and unshaded agroforestry coffee systems

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Abstract The agroforestry systems are a potential pathway to improve soil quality and protect against extreme temperatures that negatively impact coffee growth. However, more studies about the effects of inclusion of tree elements in coffee systems soil and water loss dynamics are needed. This study aimed to understand how the inclusion of trees influences the microclimate and soil and water loss in shaded compared with unshaded coffee systems. Two pluviometers, one in shaded and the other in unshaded area, were installed to record hourly data from August 2009 to June 2010. Soil temperature and moisture were monitored by a system of sensors: air temperature, soil temperature at 10 cm depth, and soil moisture at 10, 30 and 100 cm depths, recording data at hourly intervals from August 2009 to June 2010. The surface water runoff and soil mass lost by laminar erosion were measured using collectors. Air temperature under shaded conditions had less variation than under unshaded conditions and lower maximum temperatures. Soil and water loss of both systems were small due to the high soil cover. Our results indicate that the water loss was higher in the unshaded area (338 L ha^{-1}) during the study period compared

with the shaded system (150 L ha^{-1}). Soil temperature was lower under shaded conditions and there was water absorption complementarity between coffee and trees in shaded area. Soil moisture of shaded area was lower than unshaded area for all depths in all monitored period. Therefore, the shaded agroforestry coffee systems improve microclimate conditions and deep water drainage compared with unshaded coffee systems.

Keywords Brazilian soils · Climate change · Coffee plantations · Tropical conditions · Soil water availability · Soil conservation · Tropical conditions

Introduction

Climate change represents an immediate and unprecedented threat to agriculture (Jaramillo et al. 2009). The future crop production in certain regions is at risk due to increasing competition for water and more frequent of temperature extremes (Rosenzweig et al. 2004). Although intensive agricultural activities at large scales increased the food production in the last decades, it also promoted a depletion of natural resources (Hurni et al. 2015), increasing the risk of severe consequences for the global climate regulation. The conversion from natural vegetation to agricultural systems, as coffee crop, has largely contributed to the intensive use of local natural resources. However,

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conservative practices can contribute to reduce the negative impacts of agriculture on environment (Meier et al. 2015), improving the soil quality and efficiency of use of sunlight and rainfall. This is especially important for family smallholders, which depend on crops production for their subsistence (Donatti et al. 2019). In Brazil, family smallholders represent 84% of rural enterprises (Graeub et al. 2016), and the coffee crop is one of the most important in the country. Yet, the majority of coffee produced in Brazil is cultivated in unshaded systems, which can be affected negatively by climate extremes and increase the vulnerability of family smallholders under future projections of climate change.

Conventional coffee management practices are generally associated with intensive crop cultivation and unsustainable agricultural practices, leading to soil erosion (Gómez-Delgado et al. 2011) and decline in soil quality (Lin 2010). This is directly related to low crop productivity and a decrease in the smallholder's livelihoods. In this sense, agroforestry systems are a potential pathway to improve soil quality and protect against extreme temperatures that negatively impact coffee growth, and possibly to improve livelihoods simultaneously (Gomes et al. 2016). In the Brazilian Atlantic Forest biome, the Zona da Mata region is an important area of coffee production, but the historic management of the unshaded coffee systems has resulted in soil degradation (Cardoso et al. 2001). Aiming to restore the soil quality, the family farmers implemented agroforestry systems 1990, in a joint cooperation between Rural Workers Unions, the NGO Centre for Alternative Technologies of the Zona da Mata (CTA-ZM) and several researchers from the Federal University of Viçosa (Cardoso et al. 2001; Souza et al. 2010).

Agroforestry is an agroecological scheme that uses trees between crops (Tscharntke et

al. 2011). This scheme is based on the principle that trees increase benefit to the cropping system into which they are integrated (Cannell et al. 1996). However, there is a concern on the part of farmers about the possibility that tree species may absorb water from the topsoil competing with coffee (Souza et al. 2010). This observation is supported by comments of (DaMatta 2004) that species choice and proper management are decisive in the efficiency of water use in regions or seasons where this resource reaches limiting levels. The studies already carried out

on water economy and temperature in agroforestry systems in the Zona da Mata of Minas Gerais recorded specific information and did not follow up with detail the evolution of these factors in the critical phases of the crop (Aguar 2008). Therefore, the objective of the present study was to understand how the inclusion of tree elements influences the microclimate and soil and water loss in shaded and unshaded coffee systems.

Material and methods

Study area characterization

The study units are located in the municipality of Araponga, Zona da Mata de Minas Gerais, Brazil (Fig. 1). The region is a mosaic composed mainly by pasture and coffee areas intercalated with forest fragments (Gomes et al. 2020a). The mean annual air temperature is 18 °C and the long-term precipitation varies between 1200 and 1800 mm, with a dry period of 2–4 months. This climate is ideal for *Coffea Arabica* cultivation, which has optimal development and production between 18–21°C (Alègre 1959), with this region representing one of the largest areas of coffee production in Brazil. The relief is mountainous with a slope ranging from 20 to 45% (Lamberto 1975) and the predominant soil class is red-yellow Oxisol, which is weathered, deep, well-drained, acidic, and with low nutrient content (Souza et al. 2012).

We selected the study area based in the farm's history, experience of farmer with the management of agroforestry systems and the presence of shaded and unshaded coffee systems cultivated with similar management practices. The studied coffee area has a total area of 5053 m², with a south-southwest sun exposure (Fig. 2) at 918 m altitude, and positioned in the middle third of a convex elevation. The hilltop of the farm is covered by a secondary forest fragment and below the coffee area there is a small pasture area. The coffee fields were implemented in 1995 using *Coffea arabica* vs Catuaí with plant density of 3 × 1 m, and in the same year 25 trees were planted between the coffee rows. We selected the shaded and unshaded areas that presented the same management practices and were located in the same position in the relief, differing only by the presence or absence of tree species (Fig. 2). Although there are sparse trees in the unshaded area, the sampling was performed at an

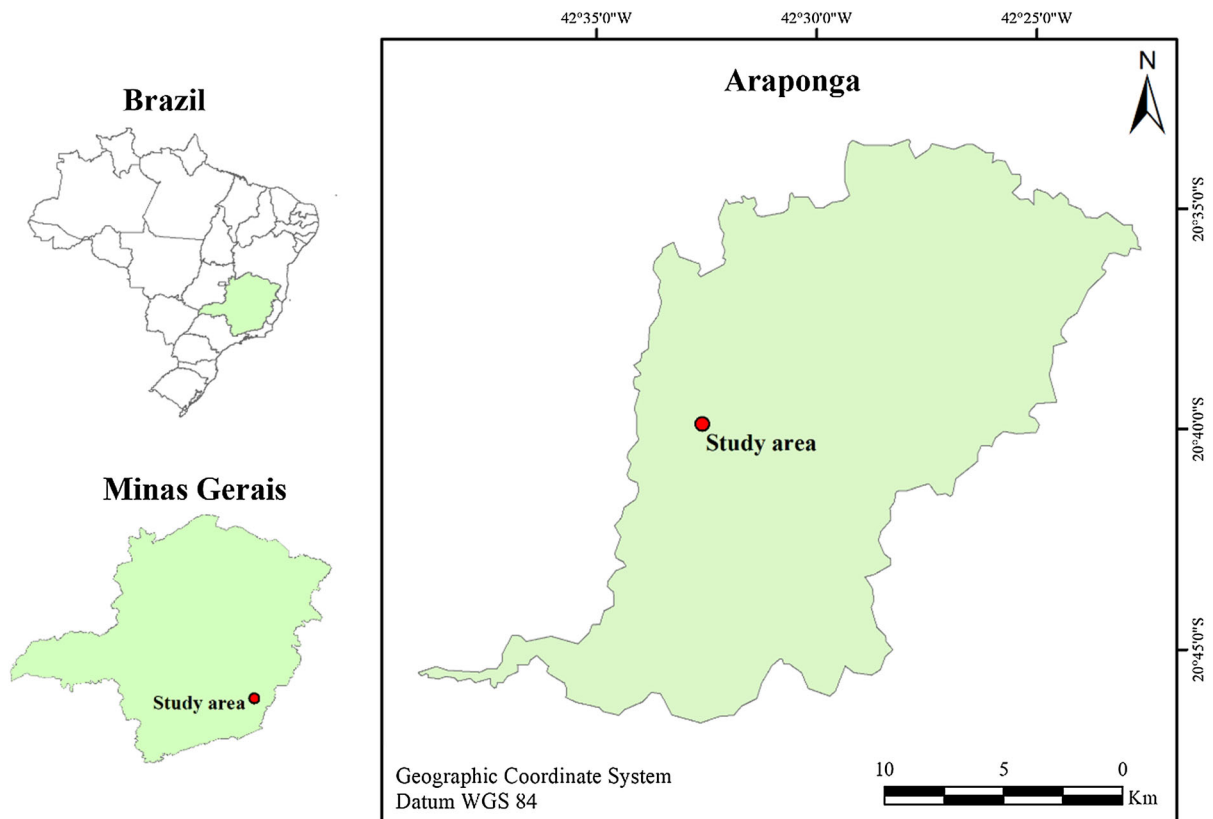


Fig. 1 Location of the study area, in the municipality of Araponga, Zona da Mata de Minas Gerais, Brazil

unshaded point without the influence of trees (see the area of canopies cover, Fig. 2).

The coffee fields were implemented in 1995 using *Coffea arabica* L. cv. Red and Yellow Catuaí with plant density of 3×1 m, and in the same year the farmer planted 25 trees, and the Elephant grass (*Pennisetum purpureum* Schum cv. Napier), Calopogonium (*Calopogonium mucunoides* Desv.), and perennial soybean (*Glycine wightii* (W. and A.) Verdc.) between the coffee lines. Based on outputs from interview with the family farm, we identify the main conservative practices applied on shaded and unshaded coffee systems: (i) manual control of invasive plants without full soil exposure; (ii) legume planting in the herbaceous stratum; (iii) chemical fertilization and liming in small amounts and; (iv) suppression of use of pesticides. In 1998 a selective cut of the trees was made, obeying the empirical criterion of positive association with coffee and the criterion observed by the farmer of deciduous leaves in late autumn and early winter (Duarte et al. 2013).

According to the farmer, the species *Erythrina verna* Vell. was the one that best met this criterion, since it favored the light availability and reduced the labor force due to unnecessary needs of pruning. Also in 1998 the elephant grass plants that had dominated the shrub stratum, competing strongly with coffee, were eradicated using the Roundup herbicide applied with a single jet. The crop received liming (100 g/pit dolomitic limestone) every three years and annual fertilization of 100 g/pit of formulation NPK 20–05–20. The management of spontaneous plants was done by mechanical control. The trees received annual pruning of conduction, especially of the inferior branches, facilitating the entrance of light in the places in which the density of the canopies was high.

Physical and soil organic carbon analysis

Soil samples were collected at 0–10, 20–30 and 90–100 cm soil depth in shaded and unshaded areas during the dry season. The granulometric analysis of

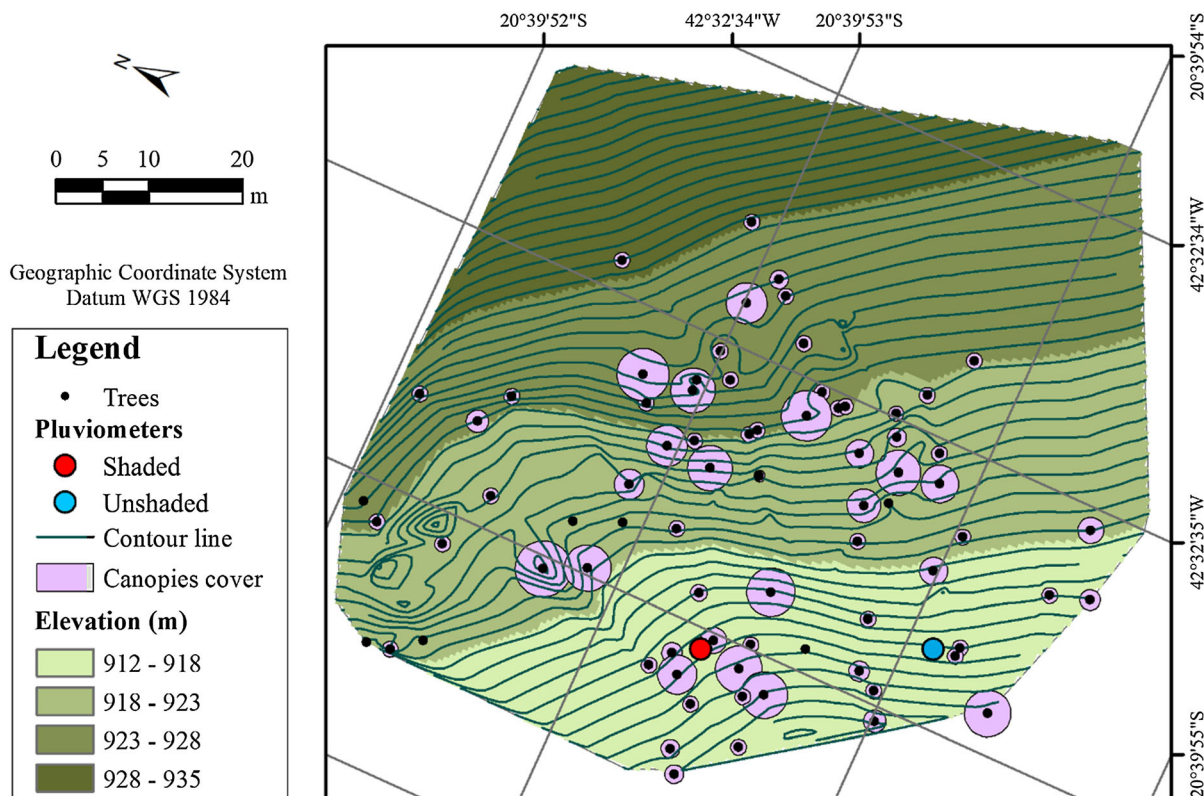


Fig. 2 Planialtimetric map of agroforestry coffee systems managed under shaded and unshaded conditions with the position of the trees and canopies cover and the position of pluviometers

the soil was performed by the method proposed by Ruiz (2005). The following analysis were done according to EMPRAPA (2017): clay dispersed in water (CDW); soil bulk density (D_s); particle density (D_p); total porosity (P_t), determined by the relationship between D_s and D_p ; microporosity (Microp) in undisturbed soil samples; macroporosity (Macrop), calculated by the difference between P_t and Microp; and saturated hydraulic conductivity. The determination of water retention at -10 kPa (field capacity—FC) and -1500 kPa (permanent wilting point—PWP) were determined, according to Richards (1954). The soil organic carbon (SOC) was determined by wet combustion method, according to Yeomans and Bremner (1988).

Assessment of soil and water loss and soil cover

The surface water runoff and soil mass lost by laminar erosion were measured during four times during the rainy season (2009/2010) using the Gerlach model

collector, adapted to the conditions of the smallholders by Franco et al. (2002). The collector is composed of a metal table with 20 cm of opening, which is fixed to the ground and coupled to a movable metal drawer. Plastic bags, with sufficient volume to store the soil and water, are affixed to the moving drawer. Plastic bags are removed to measure water and soil-stored after rain events. The collectors were installed in two 10×10 m areas, one managed under shaded and another under unshaded conditions. The upper limit of the collection area was isolated to prevent the entry of external surface water runoff. Five equidistant collectors were installed along a contour line at each shading point. Soil cover was estimated using visual evaluation of the area covered in a 1 m^2 template, randomly placed on the ground at nine points of each system, covering the three coffee rows inside the 10×10 m areas.

Assessment of rainfall, temperature and soil moisture

Two pluviometers recorded data at hourly intervals from August 2009 to June 2010 (resolution: 0.33 mm, measuring range: 0–2400 mm h⁻¹ and a capture area of 346 cm²). Aiming to identify the effect of tress on the precipitation interception, we installed one pluviometer in a shaded and another one in the unshaded area, both located at 2 m high from soil and above the coffee plant canopy (Fig. 2). To monitor the soil and air temperature, and moisture, we installed in August 2009 one system of sensors in each coffee area: (i) a soil temperature probe (Campbell L107E thermocouple, accuracy of ± 0.2 °C) arranged under the projection of the coffee plant canopy at 10 cm depth; (ii) a air temperature thermistor (accuracy of ± 0.1 °C) installed at 100 cm above the soil surface, in the planting line and between coffee plants; (iii) three soil moisture probes (Campbell CS616, accuracy of ± 2.5%) were arranged in a vertical array at 10, 30 and 100 cm depths, under the projection of the coffee plant canopies. All probes were connected to a Campbell Scientific CR 1000 data logger recording data at hourly intervals from August 2009 to June 2010.

To calibrate the sensors, we collected disturbed soil samples in cylinders (35 cm height and 10 cm diameter) in the three soil depth to measure the gravimetric moisture, which was further converted to volumetric moisture using the soil bulk density as the specified procedure in the operating manual of the equipment. In this way, the data recorded by the sensors were transformed into gravimetric moisture content. Volumetric moisture data collected at depths of 10, 30 and 100 cm were taken as moisture means for three soil layers: (i) superficial layer I: 0 to 20 cm; (ii) subsurface layer II: 20 to 40 cm; and (iii) subsurface layer III: 40 to 160 cm.

Calculation of available water capacity index (AWCI)

Soils with the same water content may have different amounts of water available to the plants, and it is not useful to compared the availability of water between different soil types. To allow this comparison, we used the available water capacity index (AWCI), which is the available water retained in soil between -10 kPa (Field Capacity—FC) and -1500 kPa (permanent

wilting point – PWP). We calculated the AWCI for each measure of gravimetric moisture of each depth using the equation (Eq. 1):

$$AWCI = BW/RAW, \quad (1)$$

where BW is the balance of water and RAW is the range of available water, both calculated by the equations (Eq. 2 and 3):

$$BW = \text{gravimetric moisture} - PWP \quad (2)$$

$$RAW = FC - PWP \quad (3)$$

AWCI values < 0 indicate moisture below PWP, therefore unavailable to plants; AWCI values > 1 indicate moisture above FC, in this case, subject to percolation to below the evaluated depth; 0 < AWCI < 1 values indicate available moisture for the plants. This calculation allows the moisture range between the FC and the PWP assume the value of a unit, and allow the comparison of available water between different soils or different depths of the same soil. Pereira (1957) assumes that the minimum moisture threshold to avoid the water stress of the Arabica coffee crop corresponds to half of the range of available water in the soil. Thus, we have AWCI equal to 0.5 as a reference parameter for the maintenance of the physiological activity of the culture.

Results and discussion

The soil texture under shaded and unshaded conditions is clayey (Table 1). The low CDW values can be explained by the mean and high levels of SOC in the superficial layers of soils (Table 1), as well as by the practice of liming, in small doses, adopted in these systems. The Pt presented lower values for all depths in shaded conditions. The water retention at -10 kPa and -1500 kPa was slightly higher in the area under shaded than in the area under unshaded (Table 1).

The hydraulic conductivity in saturated conditions of the soils under shaded and unshaded conditions is within the upper class, according to the USDA (2017). The hydraulic conductivity values observed are in agreement with those obtained by Aguiar (2008) when evaluating the physical properties of shaded area managed similarly, in the same region. For this author, the high soil cover, aggregation index and hydraulic conductivity of shaded and unshaded areas are directly

Table 1 Granulometric analysis, clay dispersed in water (CDW), soil organic carbon (SOC), soil density (Ds), particle density (Dp), total porosity (Pt), microporosity (Microp), macroporosity (Macrop), saturated hydraulic conductivity, and water retention of soils of coffee crop managed under shaded and unshaded agroforestry systems

Depth cm	Granulometric analysis				SOC		Soil density		Soil porosity			Saturated hydraulic conductivity		Water retention	
	Coarse sand	Fine sand	Silt	Clay	CDW %	Ds g kg ⁻¹	Dp g dm ⁻³	Ds	Dp	Pt	Microp	Macrop	FC -10 kPa kg kg ⁻¹	PWP - 1500 kPa kg kg ⁻¹	
<i>Shaded</i>															
0–10	290	180	90	440	11	475	1048.6	2560.0	059	036	023	023	2911	0327	0191
20–30	200	150	100	550	21	454	961.0	2580.0	063	035	028	028	3124	0338	0210
90–100	180	160	100	560	4	165	907.9	2590.0	065	037	028	028	1483	0370	0213
<i>Unshaded</i>															
0–10	300	180	100	420	12	507	1195.0	2580.0	054	032	022	022	3304	0303	0161
20–30	200	140	100	560	13	359	1180.8	2570.0	054	032	022	022	2089	0303	0173
90–100	190	130	90	590	2	147	981.7	2590.0	062	034	028	028	1429	0332	0197

related to the water infiltration capacity and inversely with the water runoff indicated by the soil and water loss values.

Lower losses of soil and water were measured in the shaded area during the rainy season, corresponding to 26 and 44% of accumulated losses in the unshaded area, respectively (Table 2). The values for soil losses are in agreement with those found by Franco et al. (2002), for the same region and management systems. The percentage of soil cover in both systems was about 80% during the rainy season (Table 2). The values of water loss are similar to those reported for systems where the soil is kept covered with vegetation (Silva et al. 2005), however, are much smaller than those reported by Bertolani and Vieira (2001) and Carvalho et al. (2002) for conventional management systems with removal of spontaneous plants from the soil surface. These data are important, as they corroborate the results obtained by Franco et al. (2002), and confirm that both shaded and unshaded conditions protect against soil and water losses more efficient than conventional systems that adopt mechanical control of spontaneous plants.

The rainfall measured in the area under unshaded area was 1238.9 mm, while in the shaded area was 825.0 mm, which represented 66.6% of the first one (Table 3). The interception by canopies is considered to be responsible for the lower internal rainfall of tree vegetation. The percentage values of water drained by the trunk in similar plant formations are low. Arcova et al. (2003) found only 0.2% of rainfall drained by trunks and 81.4% of internal rainfall; Oliveira Júnior and Dias (2005) reported 81.7% of internal rainfall in a regeneration area of the secondary forest in Viçosa region, Minas Gerais State. Diniz et al. (2013) recorded values of internal rainfall of secondary forest in Pinheiral, Rio de Janeiro State, corresponding to approximately 77% of external rainfall. Scheer (2009)

reported 87% of internal rainfall in the dense ombrophilous forest on the coast of Paraná State and the value obtained is higher than those recorded in the literature, ranging from 64 to 82%. Although less relevant, low internal rainfall in shaded area may also be a consequence of the option of using only a pluviometer, while the literature data cited above were obtained with multiple pluviometers.

The mean temperature, the mean maximum and minimum, and the amplitude between the maximum and minimum temperatures of the soil, at 10 cm depth, under shaded area was always lower than under unshaded area (Table 3). The protection provided by canopies cover reduces the incidence of direct radiation and the emission of indirect radiation from the air that reaches the soil. This observation suggests that evaporation/evapotranspiration may be lower in shaded area.

The amplitude of variation between the soil temperatures in the areas under shaded and unshaded conditions was higher during the summer than in the winter (Fig. 3), in the winter periods, temperatures approached. This seasonal variation in temperature is important for the organic matter decomposition. If the remaining conditions are maintained, the organic matter decomposition can be faster in the shaded area (Drewnik 2006).

Table 4 shows the mean air temperatures, maximum mean and daily minimum, for day and night shifts from September 2009 to March 2010 and April to August 2010. These periods are described by Camargo and Camargo (2001), respectively, as the phenological phases of axillary bud/maturation and flowering for shaded and unshaded conditions. Camargo and Camargo (2001) studied the phenological cycle of Arabica coffee in two years, justifying the reproductive bi-annually of the crop. In the first year are produced the leaf buds that turn into floral buds; in

Table 2 Soil and water loss and soil cover of coffee crop managed under shaded and unshaded agroforestry systems

Date of collection	Soil loss		Water loss		Soil cover	
	Shaded kg ha ⁻¹	Unshaded	Shaded L ha ⁻¹	Unshaded	Shaded %	Unshaded
12/14/2009	0.6	5.1	50.0	206.0	88.0	79.0
01/28/2010	1.4	5.2	80.0	102.0	84.0	76.0
02/04/2010	0.0	1.6	20.0	24.0	86.0	78.0
03/19/2010	1.6	7.0	0.0	6.0	83.0	74.0
Period acumulated ¹	3.6	13.8	150.0	338.0	85.0	77.0

¹For soil cover: average

Table 3 Rainfall precipitation (Pr), mean (T_{mea}), maximum (T_{max}) and minimum (T_{min}) temperatures and the amplitude (Δ) at 2 m above ground and above the coffee plant canopy under shaded and unshaded agroforestry systems, between August 2009 and June 2010

System	Pr mm	T _{mea} °C	T _{max}	T _{min}	ΔT max—min
Shaded	825.0	19.3	24.7	13.8	10.9
Unshaded	1238.9	20.3	26.8	14.1	12.7
Δ Unshaded—Shaded	413.9	0.95	2.1	0.3	1.8

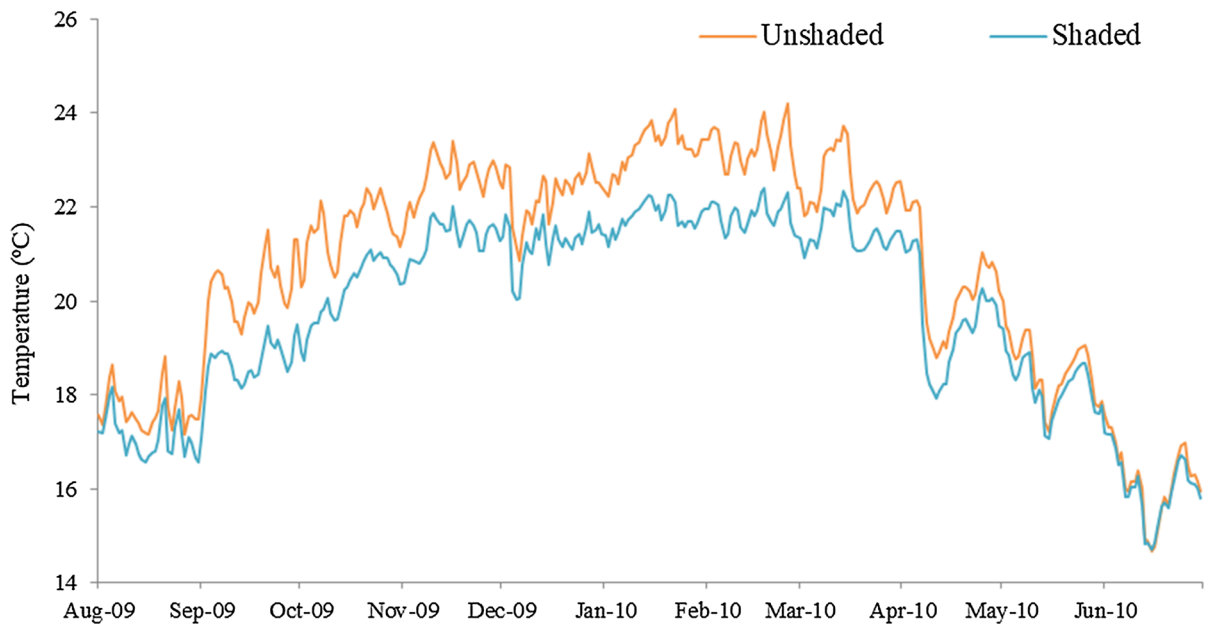


Fig. 3 Mean daily soil temperature (at 10 cm depth) of agroforestry coffee systems managed under shaded and unshaded conditions, between August 2009 and June 2010

Table 4 Mean maximum, mean and minimum daily temperature during night and day under shaded and unshaded agroforestry systems, between September 2009 to March 2010 and April to August 2010

	September—March				April—August			
	Day		Night		Day		Night	
	°C							
Maximum	Shaded	Unshaded	Shaded	Unshaded	Shaded	Unshaded	Shaded	Unshaded
	28.6	29.3	21.4	21.4	22.8	23.5	17.1	17.1
Mean	23.6	24.1	19.5	19.4	18.8	19.0	15.6	15.5
Minimum	18.7	18.9	17.6	17.5	14.7	14.6	14.0	13.9

the second year, there was flowering and grain expansion. The temperature is a significant factor in the first phenological year because it influences the

production, maturation, and opening of floral buds (DaMatta 2004; Silva et al. 2004). Drinnan and Menzel (1994) studied the influence of air temperature

on floral initiation and vegetative growth and concluded that the diurnal-nocturnal binomial determines the success of the production. Temperatures higher than 33–28°C prevent floral initiation (Drinnan and Menzel 1994; Silva et al. 2004). Mean temperatures of 28–23 °C induce the production of a large number of buds, however, leading to poor formation of flower buds (Camargo 1985; Pinto et al. 2001; Sedyama 2001). The best reproductive performance in the phenological phases of production and floral maturation is attributed to the binomial 23–18°C (Drinnan and Menzel 1994).

Both shaded and unshaded areas are oriented to south-southwest (Fig. 2). Considering that the exposure side has an azimuth of 240°, therefore very close to the direct exposure to the west, and that the unit is located in convex elevation (Fig. 2), during the summer the direct radiation reaches the area until the sun reaches the west, without obstacles. The air temperature differences between shaded and unshaded conditions (Table 4) follow the same trend of soil temperature; but, with lower amplitudes (Fig. 4). However, the mean of the minimums has an inverse behavior, being lower in unshaded area, probably due to the energy losses due to irradiation of this system, which is exposed directly to the atmosphere.

Under shaded condition, the trees favor the reflection of the energy emitted within the system (Caramori et al. 2004). This effect was striking in the late spring of 2009 when the amplitude in unshaded area was higher than in unshaded and reached higher values during the day and lower values at night (Fig. 5). One of the objectives of agroecology is to include the perspective of the farmer to evaluate and improve the production systems. Thermal comfort is pointed out by farmers as a necessity for much of the day when handling work is done in the production areas. Thus, shaded area provide the reduction of direct sunlight and ambient temperature, contributing to the quality of life of farmers. Moreover, climate change scenarios for the Zona da Mata predict that temperature conditions will make large parts unsuitable for coffee growing by 2050 (Assad et al. 2004; Gomes et al. 2020b). In this sense, shaded condition makes coffee production more resistant to temperature rise resulting from climate change.

It is verified that both systems are within the range considered favorable to the production and reproduction of the coffee tree (Table 4), taking the parameter 18–23 °C of the diurnal-nocturnal binomial. The nighttime temperatures were very similar in both areas. The highest temperature amplitudes promoted by shading occurred in the daytime maximums

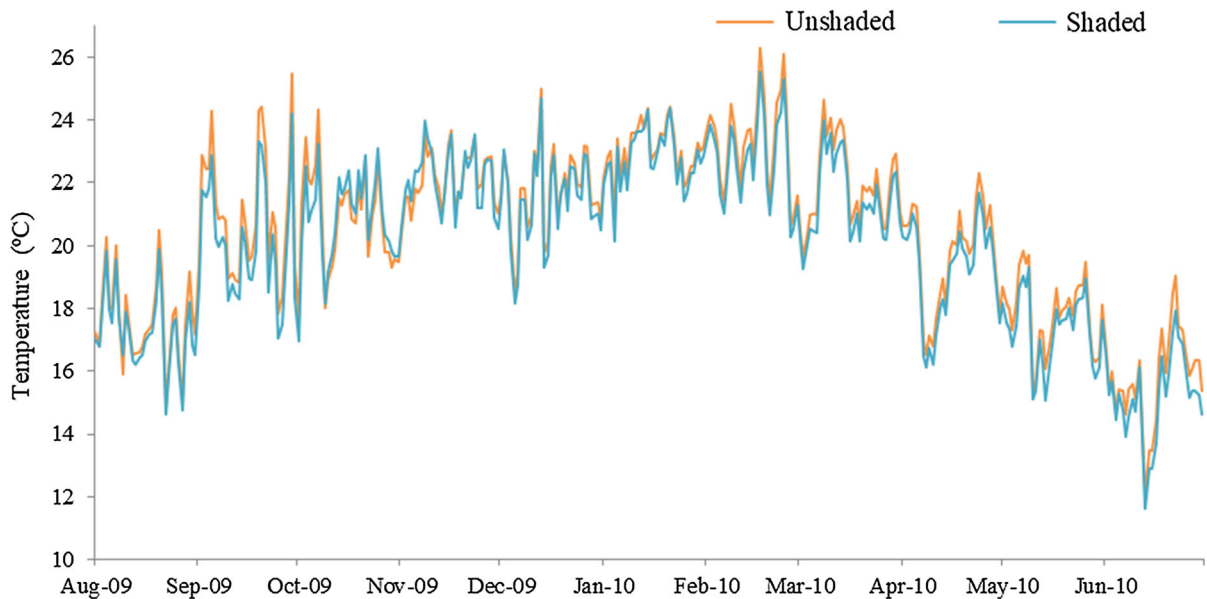


Fig. 4 Air temperature (at 100 cm above the soil surface) of agroforestry coffee systems managed under shaded and unshaded conditions, between August 2009 and June 2010

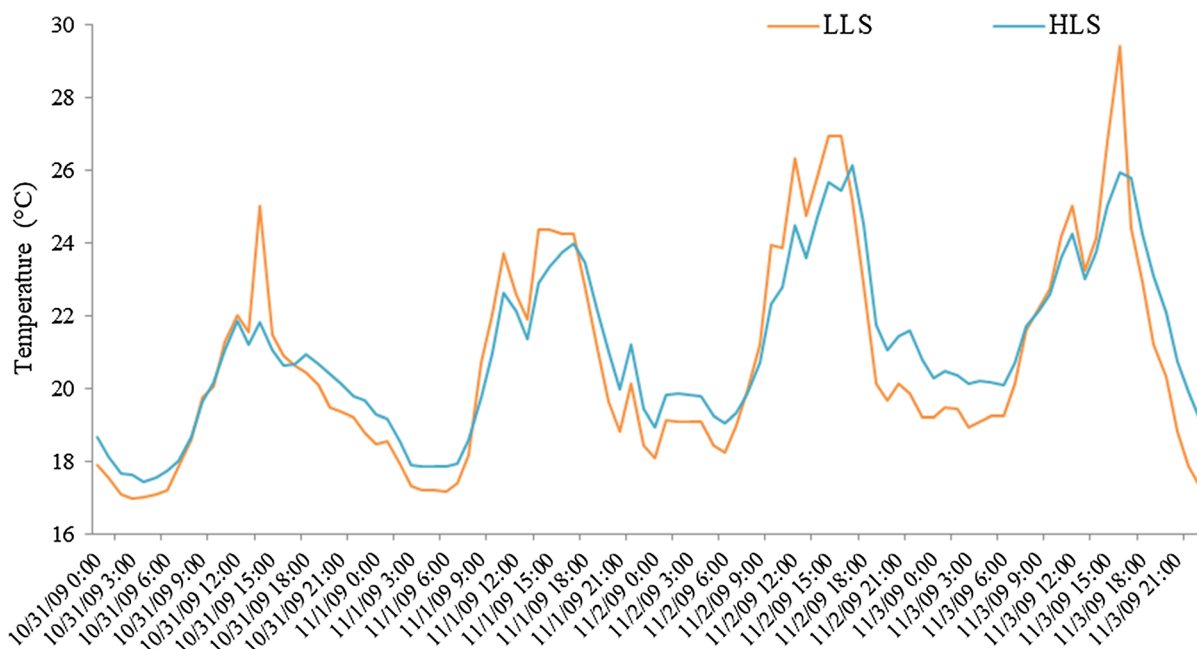


Fig. 5 Air temperature (at 100 cm above the soil surface) of agroforestry coffee systems managed under shaded and unshaded conditions, between 10/31/2009 and 11/03/2009

(0.7 °C) in the September 2009 to March 2010. The open architecture of the canopies and the conduction of pruning determined the wide circulation of air in both areas, justifying this behavior.

The rainfall records between August 2009 to June 2010, in shaded and unshaded areas, indicate a direct relation with the increase of soil moisture in the three depths (Fig. 6 (a)). However, the intensity of the response is lower at the greater depths, as a function of the time the water takes to infiltrate and the greater initial moisture soon after the rainfall event.

The volumetric moisture of layer I (0–20 cm), II (20–40 cm) and III (40–160 cm) of shaded and unshaded soils was recorded between August 2009 to June 2010, totaling 501 days and converted to the AWCI (Fig. 6 b, c and d; Table 5). In layer I, both shaded and unshaded conditions showed a very similar AWCI variation throughout the year ($r = 0.9079$). However, the mean of the AWCI in the unshaded soil in this layer is 1.55 times higher than in the shaded area (Table 5). This fact can be attributed to the lower effective internal rainfall in the unshaded area, since part of the rainfall is intercepted by the canopy and evaporates directly back to the atmosphere.

The total rainfall registered in the shaded area was 823.3 mm of precipitation and in the unshaded area of

1274.6 mm, that is, a 1.55-fold increase in unshaded condition. The variation of the superficial moisture soon after the rainfall events presents two behaviors depending on the system. Under shaded condition, the moisture reduction is more abrupt than under unshaded condition. After this immediate fall, the inclination of the curves reduces, and these assume a parallel behavior. In both shaded and unshaded areas, the mean daily moisture did not exceed the total AWCI (> 1.0). Even in the hourly intervals, the moisture in this layer did not exceed the FC. However, this does not mean that, momentarily, the moisture does not reach saturation, because the sensor recorded only the reading of the last instant of each period of an hour.

The saturated hydraulic conductivity for layer I is 291.1 mm h^{-1} under shaded condition and 330.4 mm h^{-1} under unshaded condition (Table 2). This indicates that the superficial layer allows the infiltration of intense rains. Also, to collect the rings with samples to determine the saturated hydraulic conductivity, the process avoids points where there are thick roots or channels produced by the fauna. This procedure ensures the integrity of the collected volume; however, it does not express the infiltration variability at those points where the bioturbation

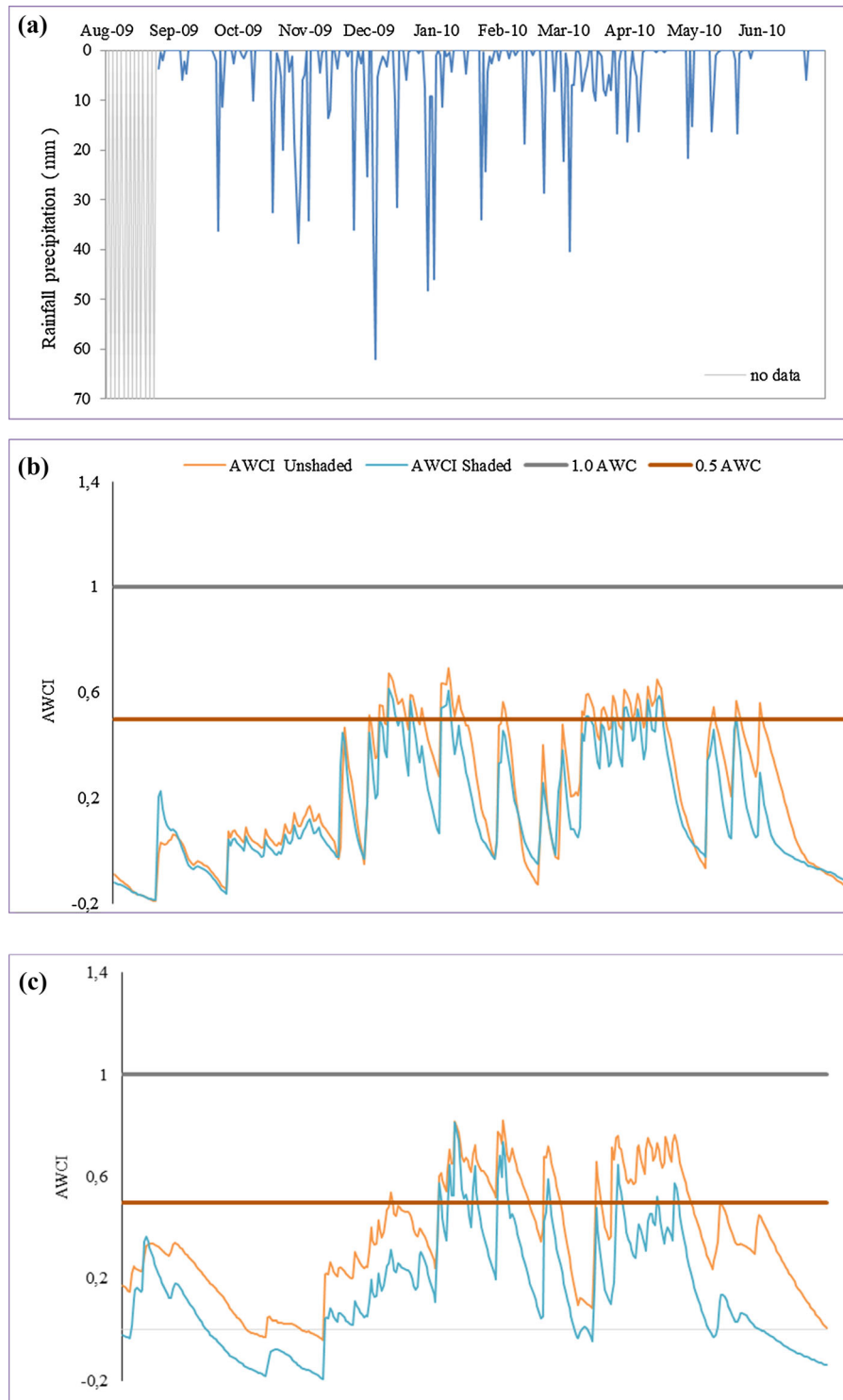


Fig. 6 a Rainfall precipitation between August 2009 until June 2010; and b available water capacity index (AWCI) at 10, c 30 and d 100 cm soils depths of agroforestry coffee systems

managed under shaded and unshaded conditions, between August 2009 until June 2010

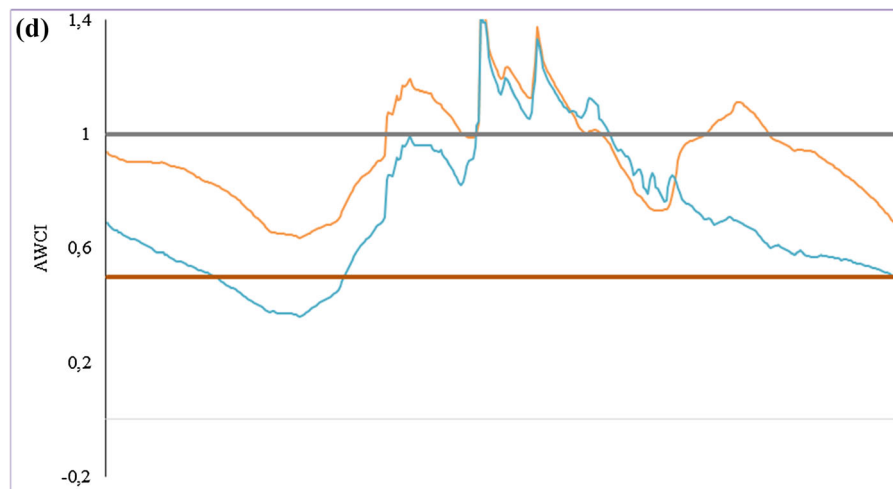


Fig. 6 continued

Table 5 Number of days with available water capacity index (AWCI) of three soil layers of soils managed under shaded and unshaded, between February 2009 until June 2010

Layer ¹	AWCI ²	Unshaded	Shaded	AWCI Unshaded/Shaded
I	\bar{x}	0.24	0.16	1.55
	number days < 0	110	145	
	number days > 0.5	110	41	
	number days > 1	0	0	
II	\bar{x}	0.39	0.19	2.11
	number days < 0	28	128	
	number days > 0.5	179	61	
III	\bar{x}	0.97	0.78	1.25
	number days < 0	0	0	
	number days > 0.5	501	427	
	number days > 1	225	126	

¹Depth of layers: I-0.0 to 20 cm, II-20 to 40 cm and III-40 to 160 cm;

²AWCI = 0 moisture at the permanent wilting point; AWCI = 1 humidity at the field capacity

increases the porosity. Saturation is a condition for surface runoff. There was no significant record of surface water losses, as discussed later. Therefore, soil and water losses should not occur significantly under shaded and unshaded conditions.

From this evidence, we infer that a large part of the water reaching the surface of the shaded and unshaded areas infiltrates rapidly, making the surface layer a place where water stress can limit full root growth. Resende et al. (2014) said that these first centimeters of the soil surface can be an inhospitable environment for root development. During the rainy season, the exploitation of this layer by the coffee roots should increase and contribute to the depletion of water. Van Kanten et al. (2005) observed that the density of the

fine roots of coffee up to the depth of 20 cm was greater than the tree species *Eucalyptus deglupta* Blume and *Terminalia ivorensis* A. Chev. in the rainy season. Another important aspect to consider for this layer is the rate of decomposition of organic matter. It is expected that the organic matter decomposition incorporated in these first centimeters of soils will be higher in unshaded than in shaded area, considering only moisture. Under shaded condition the moisture reaches the water deficit status (AWCI < 0) in 110 days, in the period evaluated (Table 5).

In layer II, the behavior of the AWCI curve for the two systems resemble shape and intensity. The ratio of AWCI unshaded/shaded in this layer is higher than in layer I (Table 5). The moisture in layer II is influenced

directly by root absorption, mainly coffee. The effective depth of the irrigated coffee root system was evaluated by Barreto et al. (2006) and reached 63 cm in a clayey eutrophic red Oxisols. Motta et al. (2006) observed in a dystrophic red Oxisol, clay-silty texture class that 86.7% of the total length and 88.5% of the dry matter of the roots were up to the depth of 40 cm. Therefore, layer II may have contributed to a large amount of water absorbed by the coffee trees in both systems. Considering that roots of coffee may be active at this depth in drier periods, the layer II of shaded soil may contribute significantly to the water absorbed by coffee in shaded conditions, although in smaller amounts and for longer periods than in the unshaded.

Under unshaded, besides the presence of coffee, the spontaneous plants that cover the soil must also absorb water from layer II. However, unshaded area presented more moisture in layer II ($\bar{x} = 0.39$) than shaded area ($\bar{x} = 0.19$) (Table 5). One of the reasons for this behavior may be the lower amount of internal rainfall in the shaded area, as already discussed for a depth of 10 cm. Although the presence of roots at great depths (up to 4.5 m) has been reported, most of the records emphasize that the roots that fulfill the functions of water absorption and nutrients occur in the superficial layers of the soil, both in crops with tree species and in full-sun (Ritchie 1998).

Rena and Guimarães (2000) reported that about 80% of the absorbing roots of coffee are superficial and occur in the first 40 cm of depth and approximately 90% under the canopy. Soares et al. (2007) reported that, in clayey Oxisols, under soil moisture deficit, 70% of the coffee roots were distributed to a depth of 60 cm. Water supplementation to reach 70% of the available water range in the soil modified the root distribution to 50 cm. In this way, the smaller amount of water in the superficial layer of the shaded soil can promote greater root growth in layer II, which contributes to this layer presenting smaller amounts of water. Another reason for the lower water content in shaded soil may be the lower contribution of rising water, in the periods in which the moisture reaches the PWP (Table 5).

In layer III, the relative difference between the shaded and unshaded soil moisture is reduced; the ratio of AWCI unshaded/shaded is 1.25 (Table 5). Among the reasons for this reduction, one can consider the difference in the contact of this layer with the

deeper water flow along the slope, attenuating the effects of direct infiltration of the local surface layers. In the wetter periods, the values are close, as in February/2010; however, in the drier periods, the water depletion in the shaded area is much higher. Soon after the rain events, the reduction of soil moisture in the shaded area is much more intense than in the unshaded. This effect was mainly observed in 2010 when the rains of January were lower than the historical average for the period and compromised the supply of the water table.

Considering that a significant part of water depletion at greater depths is due to root uptake, the presence of trees in the shaded area could explain the marked difference of AWCI at 100 cm depth. Lott et al. (2003) identified that shaded area of *Grevillea robusta* A. Cunn and corn transpired 25% of the total annual water during the dry season, both species took advantage of the water accumulated in the profile. During the maize crop period, the shaded area transpired 85% of the precipitated water, compared to less than 50% in the case of the isolated maize crop, resulting in lower water supply to the water table (Lott et al. 2003). Thus, shaded condition was more efficient at using total rainwater than maize monoculture.

The same trend was recorded by Jackson et al. (2000) and by Lehmann et al. (1998) studied root length, soil water depletion and water stress of the roots of a consortium of *Acacia saligna* (Labill.) H. L. Wendi and *Sorghum bicolor* (L.) Moench, and evaluated the systems with isolated Acacia, a consortium of Acacia and sorghum and isolated sorghum. The root length was always higher at the surface, regardless of the season and cropping system. In the dry season, the amount of roots in the isolated Acacia system was higher than in the consortium of Acacia and sorghum, and this higher than in the isolated sorghum system. The same sequence was found for the ratio between the amount of sub-surface and shallow roots. That is, the consortium favored the occupation of the soils by the roots and promoted the spatial separation of the root systems of the species. The sorghum produced more roots on the surface and Acacia more roots on the sub-surface in the consortium system. The water depletion was higher in the Acacia system than in the consortium of Acacia and sorghum, and this was higher than in the isolated sorghum. The consortium promoted water competition between Acacia and sorghum. Although isolated

sorghum absorbed surface water more efficiently, the consortium was able to utilize the total water more deeply and sooner after irrigation. In this way, the consortium took advantage of a larger volume of water than monoculture systems.

Considering the total volumes of water absorbed by the plants in the three layers during the year, there was complementarity between the trees and the coffee. During dry periods, both trees and coffee significantly reduce the total water demand, so that the available volumes were sufficient to maintain the physiological activities of the plants of the system until, in the next rainy season, they again absorbed water and grow.

Conclusions

This study provides evidence that the type of coffee management can affect the microclimate conditions. The shaded agroforestry coffee systems promoted improvement of microclimate conditions, regarding unshaded area.

In the shaded area, there was attenuating the soil temperature and maximum air temperatures, and reducing the range of variation of the mean air temperature. Considering the future climate change scenarios, shaded condition makes coffee production more resistant to temperature rise. This further emphasizes the importance of trees in the agroforestry systems.

The trees in the agroforestry systems also decrease the superficial water losses. Although the water availability is lower during the dry season in the shaded system, it does not affect the coffee physiology since during this season the coffee plant has neglected physiological growth development (DaMatta, et al., 2007). These results show the great potential of agroforestry systems as a strategy for soil and water conservation when compared to conventional systems.

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