Revista Ciência Agronômica, v. 47, n. 4, p. 700-709, out-dez, 2016
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

Artigo Científico
ISSN 1806-6690

Microclimate, development and productivity of robusta coffee shaded by rubber trees and at full sun[1]

Microclima, desenvolvimento e produtividade do cafeeiro conilon arborizado com seringueira e a pleno sol

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ABSTRACT - There are few studies about the shading of Robusta coffee with rubber trees. The aim of this study was evaluate the microclimate, development and yield of Coffea canephora grown at full sun and shaded by rubber trees. The experiment consisted of a Robusta coffee crop (*Coffea canephora*) grown at under full sun and another coffee crop intercropped with rubber trees (*Hevea brasiliensis*). The rubber trees and coffee crop were planted in the East/West direction, in Jaguaré, Espírito Santo, Brazil. Was evaluated the luminosity, temperature and relative humidity, leaf nutrient concentrations; internodes of the plagiotropic and orthotropic branches, leaf area; relative chlorophyll index, and tree yield of the coffee crops. The shading directly influenced the microclimate by reducing the air temperature in the summer and winter, as well as by increasing relative humidity. Luminosity in the summer had an average decrease of 905 lumens ft^{-2} throughout the day, which was equivalent to 72.49%, and luminosity in the winter had an average decrease of 1665 lumens ft^{-2}, which was equivalent to 88.04%. The shading provided greater etiolation of the plagiotropic and orthotropic branches as well as greater leaf expansion as compared to the full sun. The leaf concentration of Fe and Mn were higher in the shaded coffee. Estimated chlorophyll *b* and total chlorophyll were greater in the coffee crop grown at under full sun. The dense shading produced by rubber trees provided losses in the coffee crop yield, however, there is the formation of the rubber tree.

Key words: *Coffea canephora*. *Hevea brasiliens*. Shading. Intercropping. Monoculture.

RESUMO - Existem poucos estudos sobre arborização de café conilon com seringueira. Objetivou-se avaliar o microclima, desenvolvimento e produtividade do cafeeiro conilon cultivado a pleno sol e sob sombreamento proporcionado pela seringueira. O experimento foi composto por uma lavoura de café conilon (*Coffea canephora*), cultivada a pleno sol e outra lavoura de café consorciada com seringueira (*Hevea brasiliensis*). A seringueira e o cafeeiro foram plantados no sentido Leste/Oeste, em Jaguaré, Espírito Santo, Brasil. Avaliou-se a luminosidade, temperatura e umidade relativa do ar, concentração foliar de nutrientes, medição dos internódios dos ramos plagiotrópicos e ortotrópicos, área foliar, índice relativo de clorofila, e a produtividade do cafeeiro. O sombreamento influenciou diretamente no microclima, reduzindo a temperatura do ar no verão e no inverno e aumentando a umidade relativa. A luminosidade no verão teve uma redução media de 905 lumens ft^{-2} ao longo de todo dia, equivalente a 72,49%, e no inverno de 1665 lumens ft^{-2}, equivalente a 88,04%. O sombreamento proporcionou maior estiolamento dos ramos plagiotrópicos e ortotrópicos, bem como maior expansão foliar. A concentração foliar de Fe e Mn foram maiores no cafeeiro arborizado. A clorofila *b* e total estimada foram maior no cafeeiro cultivado a pleno sol. O denso sombreamento oferecido pela seringueira nas condições estudadas proporcionou perdas na produtividade do cafeeiro, contudo, ocorre a formação da seringueira.

Palavras-chave: *Coffea canephora*. *Hevea brasiliensis*. Arborização. Consórcio. Monocultivo.

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[1]Recebido para publicação em 04/11/2013; aprovado em 07/03/2016
Parte de Dissertação de Mestrado apresentada ao curso de Pós-Graduação em Agricultura Tropical da Universidade Federal do Espírito Santo/ UFES, São Mateus
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INTRODUCTION

Coffee is a product of great importance worldwide; it is cultivated in more than 80 countries, with a 2014 production of 143 million bags (ICO, 2015). The rubber tree is the main source of natural rubber, which is used in the manufacture of various products with the tire industry being its most popular use. The rubber tree is cultivated in several regions of the world, and Southeast Asian countries are the greatest natural rubber producers.

It is a great challenge to achieve development that combines fully functional maintenance and a diversified environment, especially with the integrated sustainable development (ADAMS *et al*., 2004). However, shading for coffee production should address the diversification and recovery of the fields with a socially fair and ecologically sound environment (TEJEDA-CRUZ *et al*., 2010).

The shade-grown coffee crop is an example of a sustainable agricultural practice, as studies have indicated that coffee produced under shade has greater biodiversity, unlike crops exposed to under full sun. Moreover, for the last decade, shaded coffee has promoted a commercial activity compatible with conservation of forests and their related fauna (RAMAN, 2006; SALES *et al*., 2013).

Coffee crops grown under shade undergo less environmental pressure and have greater physiological potential for carbon sequestration and photosynthetic performance compared to coffee plants grown at full sun, thereby producing larger grains, which further improves the organoleptic quality of the grains and results in a lower incidence of Cercosporiosis (BALIZA *et al*., 2012; STEIMAN *et al*., 2011). Analysing the leaves of Arabica coffee, Ronquim *et al*. (2006) recorded an increase of net daily photosynthesis in three instances on cloudy days as compared to leaves exposed to full sun.

On average, agroforestry systems with 12 years of implantation have 43% greater production than at full sun despite having a higher cost of implantation, thereby offering environmental and economic mitigation (SOUZA; GRAAFF; PULLEMAN, 2012). Coffees grown in agroforestry systems associated with the Inga tree and Southern silky oak obtain superior yields to coffee grown at full sun (SALGADO *et al*., 2005). However, Ricci et al. (2006) reported decreased production at coffee shaded.

By studying the physiological and biochemical responses of photosynthesis to elevated atmospheric CO_2 concentration and/or temperature in several *Coffea arabica* and *C. canephora* genotypes, Rodrigues *et al*. (2016) demonstrated that predictions concerning the impacts of climate change and global warming should consider the role of CO_2 as a key player in coffee heat tolerance. They also demonstrated a relevant heat resilience of coffee species and showed that an elevated CO_2 concentration remarkably mitigated the impact of heat on coffee physiology.

There is a demand for agronomic and economic knowledge pertaining to forested coffee production systems, especially for Robusta coffee. Information about handling practices that allow favourable performance of these production systems with knowledge about the appropriate choice of tree species, their spacing, pruning frequency, coffee crop nutrition and selection of cultivars that are more adapted to these conditions is still not clear enough for the successful insertion of these production systems in agroecosystems and local production chains (JARAMILLO-BOTERO *et al*., 2006a, b).

The objective of this study was to evaluate the microclimate, development and yield of *Coffea canephora* grown at full sun and shaded by rubber trees.

MATERIALS AND METHODS

The research was conducted between January 2012 and May 2013 on a farm in the city of Jaguaré, Espírito Santo, Brazil (18º56' South and 39º58' West; altitude of 70 m). The climate is Aw, warm tropical, according to Köppen, and the average annual temperature is 23.3 ºC. The average annual rainfall ranges from 1,200 to 1,300 mm per year, with a predominance of rain in the months of October to January. The soil is classified as dystrophic red-yellow Latosol (oxisol) with loamy sandy texture (SILVA; JESUS; GIOVANELLI, 2011).

The experiment consisted of a coffee crop grown under full sun with 3.0 x 1.1 m spacing (3,030 plants ha^{-1}) and a coffee crop intercropped with rubber trees planted at 7.8 x 2.3 m (557 plants ha^{-1}) and coffee planted in double rows at 5.4 x 2.6 x 1.3 m (1,972 plants ha^{-1}). The coffee in both crops was planted in late 2006, and the rubber trees were planted in late 2007. Both crops were aligned in the East/West direction. Sampling at 0-20 cm for soil fertility was conducted in January 2012 with an auger probe for the canopy projection of the coffee crops and rubber trees (Table 1).

The microclimate characterisation involved the following variables: luminosity, temperature and relative humidity. Measurements were conducted with HOBO U12 Temp/RH/Light/External Data Logger devices, which were installed at 3 m above the coffee crop lines at full sun and in the crop intercropped with rubber trees. The devices were placed in the central portion of the crops to minimise external interference. Three devices were used in each row as three repetitions, and the devices were programmed to

Table 1 - Chemical characteristics of the soil at the 0-20 cm layer of the two evaluated crops. Jaguaré, Espírito Santo, Brazil

Treatment	mg dm^{-3}							
	P	K	S	Fe	Zn	Cu	Mn	B
Full sun	3.0	29	6	65	4.0	0.2	19	0.30
Shade-grown	2.4	42	5	55	11.9	0.7	17	0.43
Treatment	dag kg^{-1}			cmol$_c$ dm^{-3}				
	pH	MO	Na	Ca	Mg	Al	H+Al	
Full sun	5.9	1.7	11	1.3	0.3	0.0	2.2	
Shade-grown	5.4	1.7	17	0.9	0.3	0.3	2.9	

perform readings every 10 min. Microclimate data were collected on January 27 th and 28 th (summer) in 2012 and on September 12 th and 13 th (winter) in 2012 between 06:00 and 19:00 hours (local time). On these days, the sun had a solar declination of -18.55 and -18.30 (January 27th and 28th, respectively) in the summer and 2.62 and 3.22 (September 12th and 13th, respectively) in the winter.

The growth characteristics of the coffee crops were evaluated at the same time that the microclimate measurements were taken. The number of nodes was quantified, and the lengths of the orthotropic, fruit-bearing plagiotropic and fruitless young plagiotropic branches were measured. Twenty plants were evaluated per treatment by dividing the branch length by the number of nodes, thereby generating the average size of the internode (etiolation). In the old branches, the distances of the nodes with coffee berries and the branch tip without coffee were measured, and the entire branch was measured for young branches. Orthotropic branches were measured from the fruitless young branch to the tip.

In the two periods of the year, the chlorophyll *a*, chlorophyll *b* and total chlorophyll contents of the leaves were estimated. Twenty leaves located on the upper middle third of the plant in the third or fourth pair of leaves were sampled per treatment with the use of an electronic chlorophyll content metre (Falquer clorofila CFL 1030). Sixty leaves from each treatment were collected with the same collection pattern for nutrient concentration analysis and leaf area measurement. Leaf area was estimated according to Partelli *et al*. (2006), and leaf nutrient concentration was measured in the summer.

The coffee berry harvest was performed manually between May 2012 and May 2013, when approximately 80% of the berries were ripe. Three plants were collected per parcel in a total of four repetitions per treatment. The average coffee crop production of grains was quantified in litres per plant and extrapolated by kilogram per hectare using a ratio of 5.33 ripe litres per kilogram of processed coffee, which was the average achieved in the property.

Analysis of variance (ANOVA; at 5%) was conducted to test the hypothesis of equality for the analysed variables and data description.

RESULTS AND DISCUSSION

Microclimate Evaluation

Shading by rubber trees promoted a decrease of transitivity of the solar radiation in relation to the production at full sun for both measurement events (Figure 1) with higher incidence values occurring in the morning in both the summer and winter. In the summer at certain times of the morning, the shaded crop showed luminosity peaks that almost reached the values of the crop at full sun, and much lower values were observed for the crop at full sun in the afternoon (Figure 1A). In the winter, the shaded crop had much lower values compared to the crop at full sun virtually all day (Figure 1B), which may have been influenced by the solar declination on the day of the measurements. By totalling the luminosity values throughout the measurement day, it was observed that the light interception was 88.04% in the winter and 72.49% in the summer.

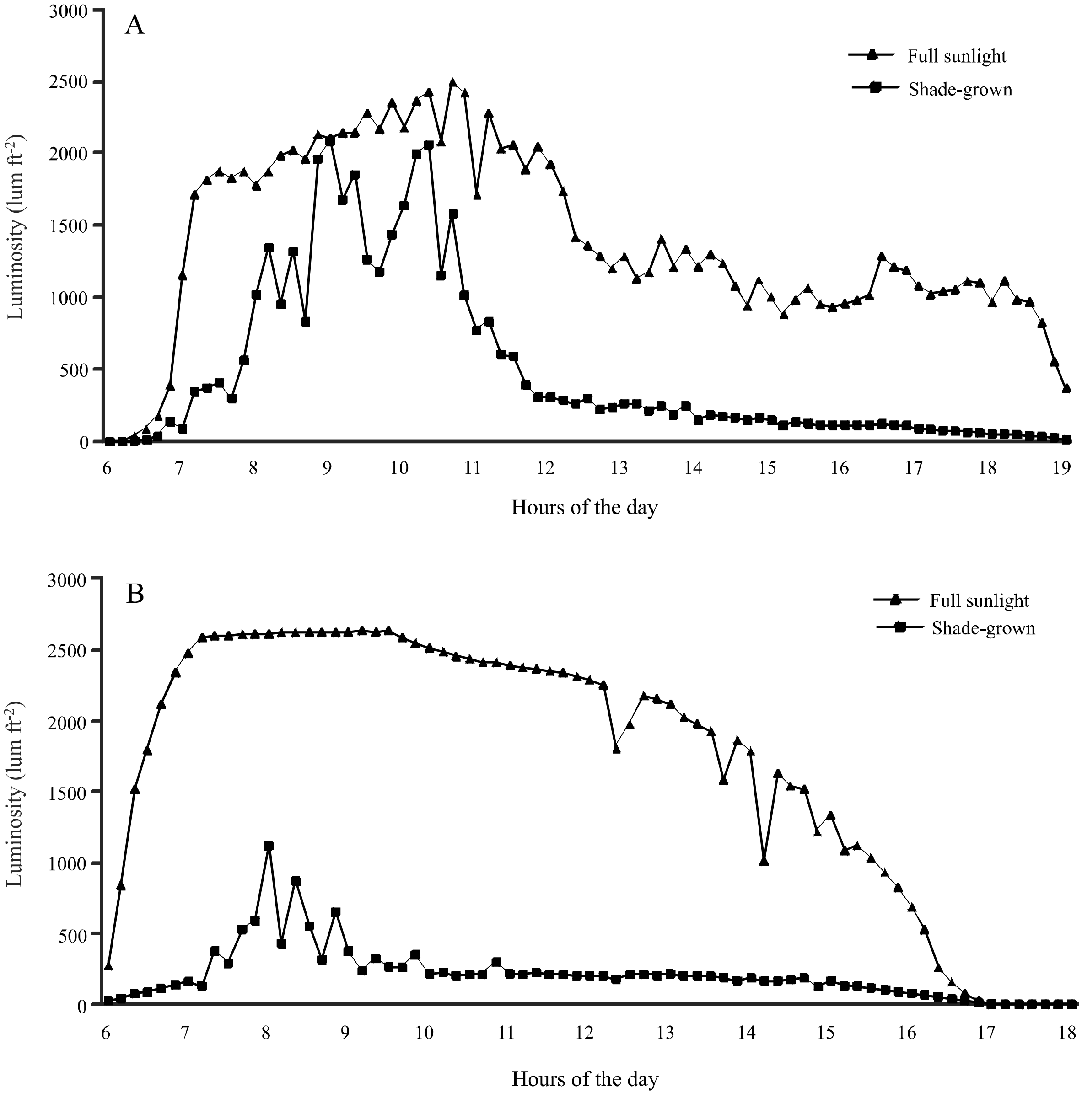
The greatest difference in luminosity in the summer occurred at 11:50 hours with 2041 lumens.ft^{-2} at full sun and 304.7 lumens.ft^{-2} in the shade. The same pattern was maintained in the winter, but the shaded crop recorded lower values in the morning with the greatest difference at 7:10 hours (2455 lumens.ft^{-2}) with an average difference of 1665 lumens.ft^{-2} in the day.

Righi *et al*. (2007) reported that changes in microclimate can interfere with the coffee crop behaviour, mainly changing the morphology, growth, anatomy, photosynthesis parameters and reproductive development, which consequently reflected in its yield. Bote and Struik (2011) also reported these shade-related changes in shade-grown coffee crops in Ethiopia, and they reported 31% higher photosynthetic rates and 40% greater stomatal conductance, as well as lower leaf transpiration and temperature.

Coffee crops intercropped with *Cocos nucifera*, *Macadamia integrifolia* and *Inga densiflora* present attenuation of up to 80% of the luminosity with attenuation of extreme temperature values (SILES; HARMAND; VAAST, 2010). Studies have shown that 40 to 50% interception of the incident solar radiation does not alter the growth, maturation, production and size of the grains (PEZZOPANE *et al*., 2010b, 2011).

Studies on agroforestry systems show that Arabica coffee has limited stomatal conductance and light availability for the photosynthesis of the coffee leaf with shading levels greater than 45% (FRANCK; VAAST, 2009). Ronquim *et al*. (2006) reported that Arabica coffee leaves increase their net daily photosynthesis by three times in the morning on cloudy days with an irradiance of approximately 800-1100 $\mu mol.m^{-2}\ s^{-1}$ and vapour pressure of 0.5 - 2.5 kPa.

Figure 1 - Variation of daily luminosity values in the coffee crop grown at full sun and shaded by rubber trees in the summer (A) and in the winter (B) of 2012. Jaguaré, Espírito Santo, Brazil

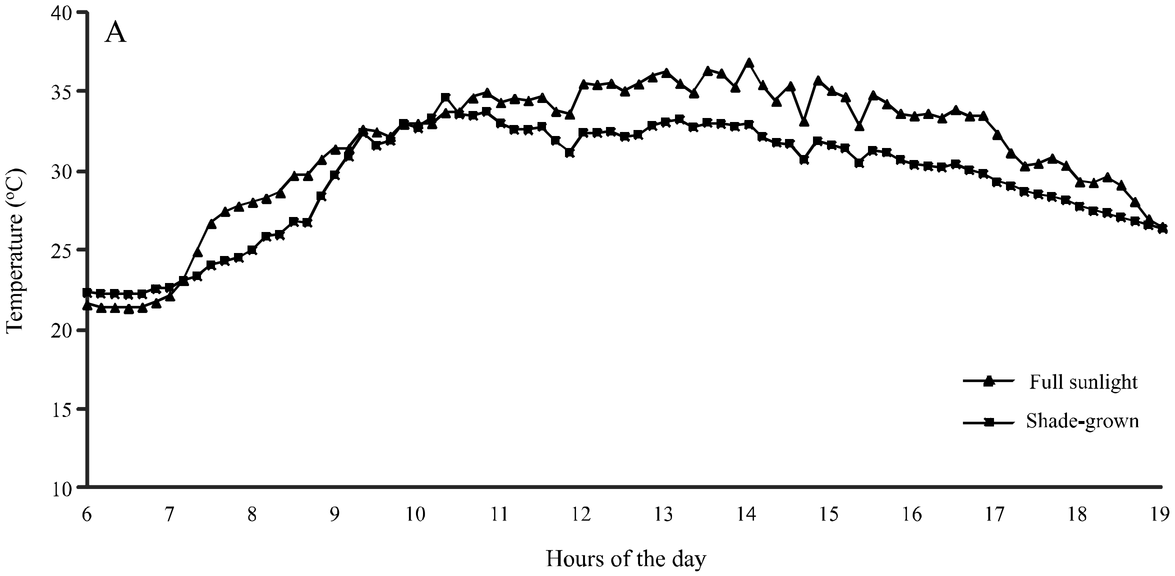


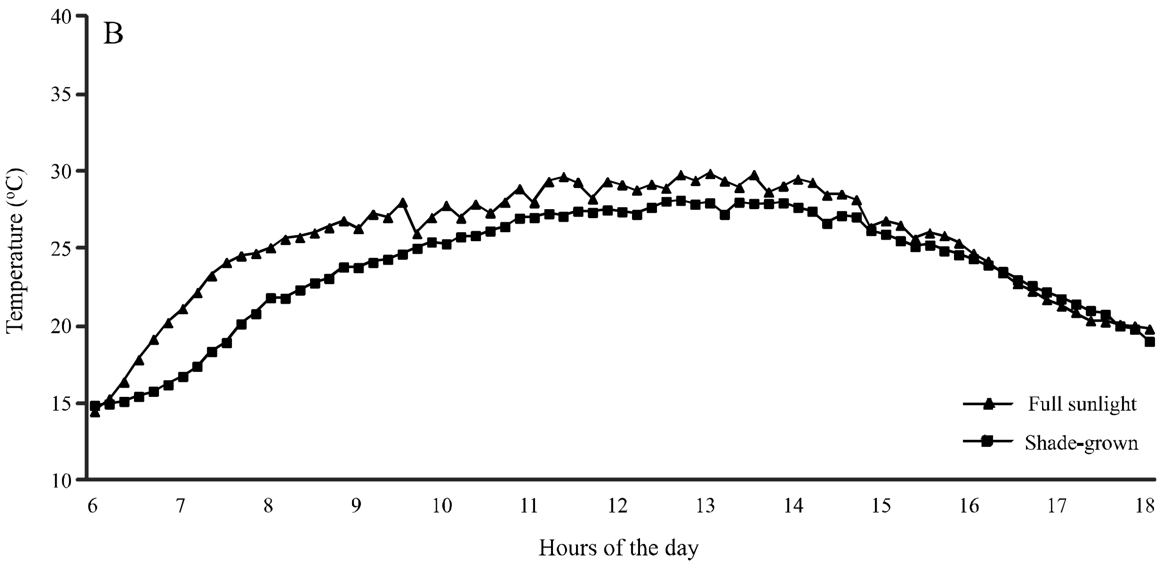
The highest air temperature values were obtained in the summer in the crop at full sun (36.8 ºC at 14:00 hours), and a temperature of 32.9 ºC was recorded at the same time in the shade-grown crop with a 3.9 ºC difference (Figure 2A). In the winter, the highest air temperature in the crop at full sun was obtained at 13:00 hours (29.8 ºC) with the shaded crop reaching 27.9 ºC at the same time, but the greatest difference was obtained at 7:20 hours with a 4.8 ºC difference (Figure 2B). High temperatures can disrupt many metabolic processes and promote the production of reactive molecules, thereby damaging the leaves (DAMATA; RAMALHO, 2006).

Crops of Arabica and Robusta coffee intercropped with trees show a decrease of up to 3 ºC in temperature in the warmer months and critical periods of flowering and fruiting (PEZZOPANE *et al.*, 2010a; VALENTINI *et al.*, 2010). The average temperature values obtained during the summer and winter showed the potential of intercropping with trees, and the rubber trees decreased the average temperature values, thereby making the environment more amenable to cultivation (Figure 2).

The relative humidity values behaved inversely to the thermal regime (Figure 3). The effect of growing

Figure 2 - Variation in daily temperature values in the coffee crop grown at full sun and shaded by rubber trees in the summer (A) and in the winter (B) of 2012. Jaguaré, Espírito Santo, Brazil





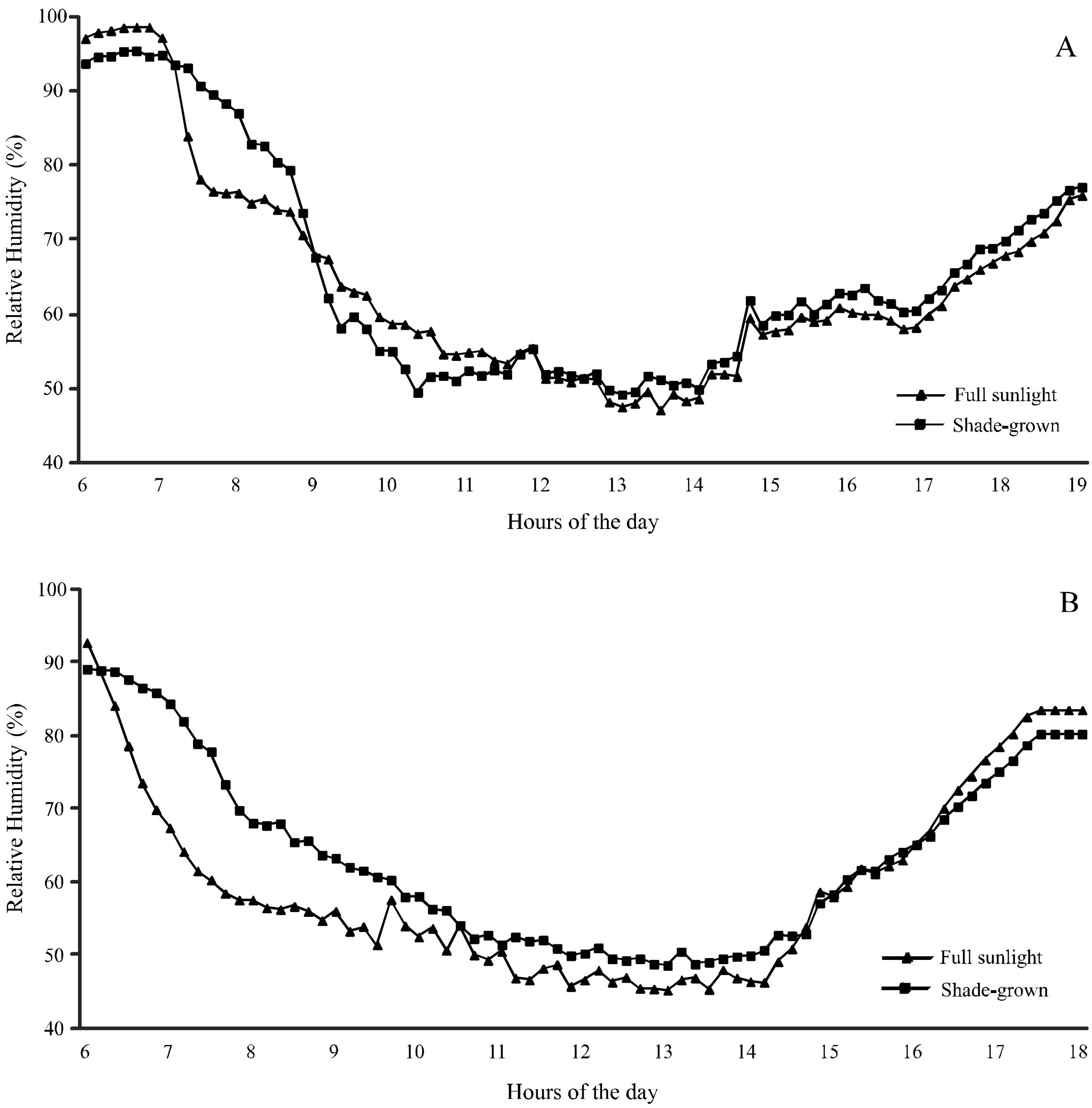
coffee under the canopy of trees was more significant in the winter because the shaded crop recorded several temperature peaks throughout the day in the summer when the measurements were close to those of the crop at full sun.

With regard to relative humidity, the highest values obtained in the summer were in the shaded crops, and the lowest values were recorded in the crop at full sun with the greatest difference between both crops found at 7:40 hours (89.5% in the shaded crop and 76.4% in the crop at full sun) with an average difference of 1.09% throughout the day. The lowest averages were recorded in the winter, and the greatest difference between the two crops was at 7:10 hours with values of 81.9% in the shaded crop and 64.1% in the crop at full sun maintaining an average difference of 4.05% throughout the day. Studying Robusta coffee crops shaded by macadamia nut trees, Pezzopane *et al*. (2010b) recorded a daily average increase of up to 5% in the relative humidity compared to sole crops.

Plant Assessment

Shading induced an increase in the average internode length of the young fruitless plagiotropic branches and orthotropic branches of the coffee crops in

Figure 3 - Variation in daily relative humidity values in the coffee crop grown at full sun and shaded by rubber trees in the summer (A) and in the winter (B) of 2012. Jaguaré, Espírito Santo, Brazil



both evaluation periods (Table 2). In the winter evaluation, however, there was a more pronounced elongation of the branches. The difference in internode length in the young plagiotropic branch was 4.3 cm in the winter, and this difference was 3.8 cm in the summer. This sharp increase may have occurred due to a mechanism called etiolation, which optimises light gathering (TAIZ; ZEIGER, 2010).

According to Ricci *et al*. (2006), branch elongation caused by shading occurs to avoid low irradiance, and higher densities result in greater etiolation. According to Morgan and Smith (1979), in low luminosity conditions due to shading, the environment is relatively rich in extreme red light. Thus, plants lengthen the stem and branch out less with an extra expense of reserves due to an inhibition of the development of lateral buds.

The chlorophyll *a* values showed data homogeneity among both evaluation periods without any statistical variance in both the summer and winter (Table 3). These results corroborated with results reported by Gonçalves, Gallo and Favarim (2007), who observed similar responses for chlorophyll *a* in different seasons of the year in coffee crop studies.

The chlorophyll *b* and total chlorophyll values statistically differed in the summer and winter with the highest values occurring in the crop at full sun (Table 3). Gonçalves, Gallo and Favarim (2007), Matos *et al*. (2009) and Senevirathna, Stirling and Rodrigo (2003) recorded similar results with the greatest values for chlorophyll *b* and total chlorophyll for less shaded leaves.

A low chlorophyll *a*/*b* ratio in shaded plants indicates an increased participation of chlorophyll in light-gathering complexes, thereby increasing the efficiency of light harvesting in low light environments (EVANS; POORTER, 2001). Morais *et al*. (2004) stated that plants that have phenotypic plasticity, as in the case of coffee, show an increase in chlorophyll contents and a decrease in Rubisco activity (ribulose 1,5 biphosphate carboxylase/oxygenase) when developing in environments with low availability of radiation.

The shading increased the average leaf size of the coffee plants in the shaded crop in the summer and winter showing that they were significantly affected by shading ($p<0.01$) (Table 4). Evaluating seedling growth of Arabica coffee under different levels of radiation, Tabagiba *et al*. (2010) observed an increase in the leaf area as a function of light decrease. Valladares, Sanchez-Gomes and Zavala (2006) documented this effect in different plant species in which shade leaves receiving a lower intensity of photon flux translate this effect by the increase of leaf area per unit of mass. The increase in leaf area is an acclimation strategy of plants subjected to shading, thereby intercepting a greater intensity of light (TAIZ; ZEIGER, 2010). Another acclimation strategy is the reduction of cuticle thickness and parenchyma layers, which facilitates the passage

Table 2 - Internode length (cm) of fruit-bearing plagiotropic branches (FBPBs), tip of productive plagiotropic branches (TPPBs), young plagiotropic branches (YPBs) and orthotropic branches (OBs) of Robusta coffee plants cultivated at full sun and shaded by rubber trees in the summer (S) and winter (W) of 2012. Jaguaré, Espírito Santo, Brazil

Treatment	FBPBs(S)	TPPBs(S)	TPPBs(S)	OBs(S)	TPPBs(W)	OBs(W)
Full sun	3.6 b	2.6 b	3.8 b	2.5 b	2.9 b	1.7 b
Shade-grown	6.2 a	4.3 a	7.6 a	6.5 a	7.2 a	4.6 a
VC (%)	47.72	34.88	14.93	22.78	16.74	38.12

Means followed by the same letter in the column do not differ according to the F-test (ANOVA at 5%)

Table 3 - Average estimated content of chlorophyll *a*, chlorophyll *b* and total chlorophyll (ICF) in leaves of the coffee produced at full sun and shaded by rubber trees in the summer and winter of 2012. Jaguaré, Espírito Santo, Brazil

Treatment	Chlorophyll a		Chlorophyll b		Total Chlorophyll	
	Summer	Winter	Summer	Winter	Summer	Winter
Full sun	42.0 a	42.0 a	29.3 a	28.4 a	71.3 a	70.5 a
Shade-grown	41.5 a	41.2 a	20.8 b	20.8 b	62.3 b	62.1 b
VC (%)	4.98	4.56	40.53	42.78	17.29	17.84

Means followed by the same letter in the column do not differ according to the F-test (ANOVA at 5%)

of light to increase the interception of irradiance by the innermost leaves of the canopy.

The leaf concentrations of N, P, K, Ca, Mg, S, Zn, Cu and B did not differ between treatments (Table 5). Comparing shaded systems with the crop at full sun, Ricci *et al*. (2006) obtained similar results for N, P, K, Ca and Mg, thereby confirming the results observed in this study. However, the concentration of Fe and Mn showed significant differences, with the highest value in the shaded crop. With Arabica coffee plants, Gonçalves, Gallo and Favarim (2007) corroborated the Fe results. Fe is a micronutrient also found in the form of complexes, which are an integral part of several proteins, enzyme activators, electron transfer, oxidative phosphorylation and photosynthesis I (EPSTEIN; BLOOM, 2006).

In contrast, Campanha *et al*. (2007) and Gonçalves, Gallo and Favarim (2007) recorded higher Mn values in conditions of greater light availability. Manganese is part of the photosystem II assisting in the photolysis of water and transfer of electrons to chlorophyll. Manganese is also an integral part of the protein superoxide dismutase, which has an antioxidant function. Manganese also activates many other enzymes (EPSTEIN; BLOOM, 2006).

The yield of the plants cultivated at full sun was superior to plants shaded by rubber trees in the two evaluated years (Table 6), thereby indicating that a retention of luminosity equal or greater than 72.49% in the summer and 88.04% in the winter disrupted the performance of the coffee crop, which corroborated the studies by Ricci *et al.* (2006) and Souza, Graaff and Pulleman (2012). However, the average yield obtained by the shade-grown coffee crop was above the national and world averages (CONAB, 2015; ICO, 2015).

It is noteworthy that the rubber tree was planted in spacing traditionally used for growing in monoculture, so

Table 4 - Leaf expansion (cm^2) of the coffee grown at full sun and shaded by rubber trees in the summer and winter of 2012. Jaguaré, Espírito Santo, Brazil

Treatment	Summer	Winter
Full sun	31.8 b	32.5 b
Shade-grown	120.1 a	123.5 a
VC (%)	24.65	24.82

Means followed by the same letter in the column do not differ according to the F-test (ANOVA at 5%)

Table 5 - Leaf nutrient concentration in the coffee crop grown at full sun and shaded by rubber trees in the summer and winter of 2012. Jaguaré, Espírito Santo, Brazil

Nutrientes	N	P	K	Ca	Mg	S	Fe	Zn	Cu	Mn	B
Treatment	---------------------------- g kg^{-1} ----------------------------						--------------------- mg kg^{-1} ----------------------				
Full sun	25.8 a	1.5 a	19.6 a	19.8 a	2.7 a	1.8 a	67.5 b	9.7 a	8.2 a	89.2 b	61.5 a
Shade-grown	26.5 a	1.4 a	22.0 a	22.2 a	2.4 a	2.0 a	100.7 a	11.0 a	9.7 a	141.0 a	74.7 a
VC (%)	7.06	2.59	8.09	7.10	16.16	9.82	19.02	10.22	16.67	22.63	8.25

Means followed by the same letter in the column do not differ according to the F-test (ANOVA at 5%)

Table 6 - Yield of coffee crop (kg ha^{-1}) grown at full sun and shaded by rubber trees in 2012 and in 2013. Jaguaré, Espírito Santo, Brazil

Treatment	2012	2013
Full sun	7061.0 a	2984.5 a
Shade-grown	2035.9 b	794.3 b
VC (%)	16.72	29.22

Means followed by the same letter in the column do not differ according to the F-test (ANOVA at 5%)

that the initial seven years of cultivation, the Seringueira formation period, the farmer can count on the production of coffee, and then, the rubber tree will start productive period. This practice reduces costs in the implantation of the rubber tree because the crop treatments performed for the coffee crop were also used for the rubber trees, making it an economical and sustainable activity.

CONCLUSIONS

1. Under the studied conditions, the shading of Robusta coffee by rubber trees significantly decreased luminosity and temperature throughout the day, promoting greater etiolation of branches as well as greater leaf expansion;
2. The growth of the coffee crop under the canopy of trees promoted an increase in chlorophyll *b* content, total chlorophyll content and leaf concentrations of Fe and Mn;
3. The growth of rubber trees at a spacing of 7.8 x 2.3 m promoted losses in coffee yield. However, the formation of rubber tree occurred simultaneously with the coffee, optimizing resources and manpower and diversifying production.

ACKNOWLEDGMENTS

To Universidade Federal do Espírito Santo (Ufes), for partial financial support; and to Mr. Fabrício Felisberto Fiorot, for allowing the use of the experimental area.

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