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Thermal environment in an agroforestry system of coffee and rubber tree in Southern Brazil

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ABSTRACT

Climate change poses a significant risk to the production of *Coffea arabica* in currently cultivated areas, as the species has low tolerance to extreme temperature. Agroforestry systems are an alternative to contribute to the adaptation of this species and to continue the production in the regions where it is currently cultivated. This study assesses the thermal environment of an agroforestry system (AFS) composed of coffee and rubber trees (*Hevea brasiliensis)* planted in double rows with different spacings in Londrina, Parana state, Southern Brazil. Data of global solar radiation and temperature of air, leaves, and soil were continuously collected from 2015 to 2018. The findings reveal that the presence of rubber trees affected the microclimate by reducing extreme temperatures and decreasing mean temperatures. In the experimental conditions of limited size of the plots, leaf and soil temperatures represented more realistically the modifications in the microclimate induced by the rubber trees. The study concludes that this system can effectively contribute to the adaptation of coffee plantations in a warmer environment, in order to continue producing in traditional regions in Brazil.

Introduction

Climate variability is the main cause of oscillations of coffee yields in traditionally producing regions in Brazil (Camargo et al., 2010). The climatic variables that compromise the growth and production of *Coffea arabica* the most are solar radiation, temperature and water availability (Camargo et al., 2010; Martins et al., 2015). Given the scenarios of global climate change (IPCC, 2014, 2018) and the expected impacts on coffee production (Assad et al., 2004; Ovalle-Rivera, 2015; Bunn et al., 2015; Läderach et al., 2017; Gomes et al., 2020), it is imperative to research alternatives that will allow to continue growing coffee in traditional areas in Brazil.

The use of agroforestry systems (AFSs) is one of the strategies with potential to minimize the effects of climate change on the coffee crop (Gomes et al., 2020) through attenuation of solar radiation and air temperature (Pezzopane et al., 2010; Valentini et al., 2010). Well-managed AFSs can contribute to improve the physical and chemical qualities of the soil, promote system sustainability (Alves et al., 2016), increase carbon sequestration and provide additional and more stable income to farmers (Meylan et al., 2017; Zaro et al., 2020; Nunes et al., 2021). The AFSs have also being successfully used to avoid frost damage in coffee plantations in Southern Brazil (Caramori et al., 1996; Baggio et al., 1997; Morais et al., 2006; Caramori et al., 2021).

In its early years, coffee cultivation in AFSs in Brazil lost momentum due to the use of high density of trees, which induced low productivity of plants under excessive competition for light, water, and nutrients (Pezzopane et al., 2010). From 1970s onwards, new studies with moderate shading demonstrated benefits for coffee crops (Caramori et al., 2004; Caramori et al., 2021). Nevertheless, there is still a need to evaluate the use of different tree species and population in AFSs, in order to maximize the benefits for coffee crops and ensure their adaptation to regional peculiarities, without reducing productivity.

The rubber tree (*Hevea brasiliensis* Muell) meets optimal climatic conditions for production in the Central West and Southeast of Brazil, and in the North of the state of Paraná (Camargo et al., 2003). The double rows cultivation system in AFS with coffee has been recommended for these regions, as it facilitates the management practices of the coffee plantation. In addition to providing potential additional income to farmers (Zaro et al., 2020), the rubber tree root system absorbs and recycles fertilizers not used by the coffee plants (Pereira et al., 1998).

We were based on the hypothesis that under a warmer environment this AFS will be an alternative to help minimize the impacts in the coffee business. Thus, the present research aimed to characterize the thermal changes in an AFS of coffee and rubber trees with different shading densities, compared to open-grown coffee in Southern Brazil.

Material and methods

Site description

The study was carried out in the experimental farm of Institute of Rural Development of Parana (IDR Paraná) in Londrina, Paraná State, Brazil (23°23' S, 50°11' W, and altitude of 585 m). The site faces South/Southwest, with a uniform slope around 5%. The local soil is a Dystroferric Red Latosol, according to the Brazilian soil taxonomy (Embrapa, 2013), a Typical Rhodic Haplustox according to the United States Department of Agriculture taxonomy. The climate is Cfa - a humid subtropical consisting of hot summers, according to Koppen's classification. The mean annual temperature is 21.2 °C; the hottest month is February (24.0 °C); and the coldest month is July (17.0 °C). The mean annual precipitation is 1,632 mm; the wettest months are December, January and February; and the driest months are June, July and August (Nitsche et al., 2019; IDR Paraná, 2021).

Coffee seedlings of *Coffea arabica* cultivar IAPAR 59 were planted in February 2000 spaced 2.5 m between rows and 0.80 m in the rows, with one plant per hole. Rubber trees of clone PB 235 were planted in May 1999 in double rows perpendicular to the coffee rows, spaced 4.0 m between alleys and 2.5 m in alleys, with spacings of 13, 16 and 22 m between the double rows. One treatment denominated "shade" was placed underneath the crowns between two rows of rubber trees, as a reference of maximum interference. An adjacent area of coffee plants exposed to full sun was simultaneously implanted to represent the monocropping condition. The dimensions of each plot were 18x34 m (13 m), 18x40 m (16 m), 18x52 m (22 m) and 44x15 m (open-grown). Figure 1 illustrates the experimental area with coffee, rubber trees and the meteorological stations. The current recommended management practices for coffee and rubber trees were applied in the experiment. During the period evaluated, the coffee plants were 1.5 to 2.0 m high and the rubber trees 18 to 20 m high.

Microclimatic monitoring

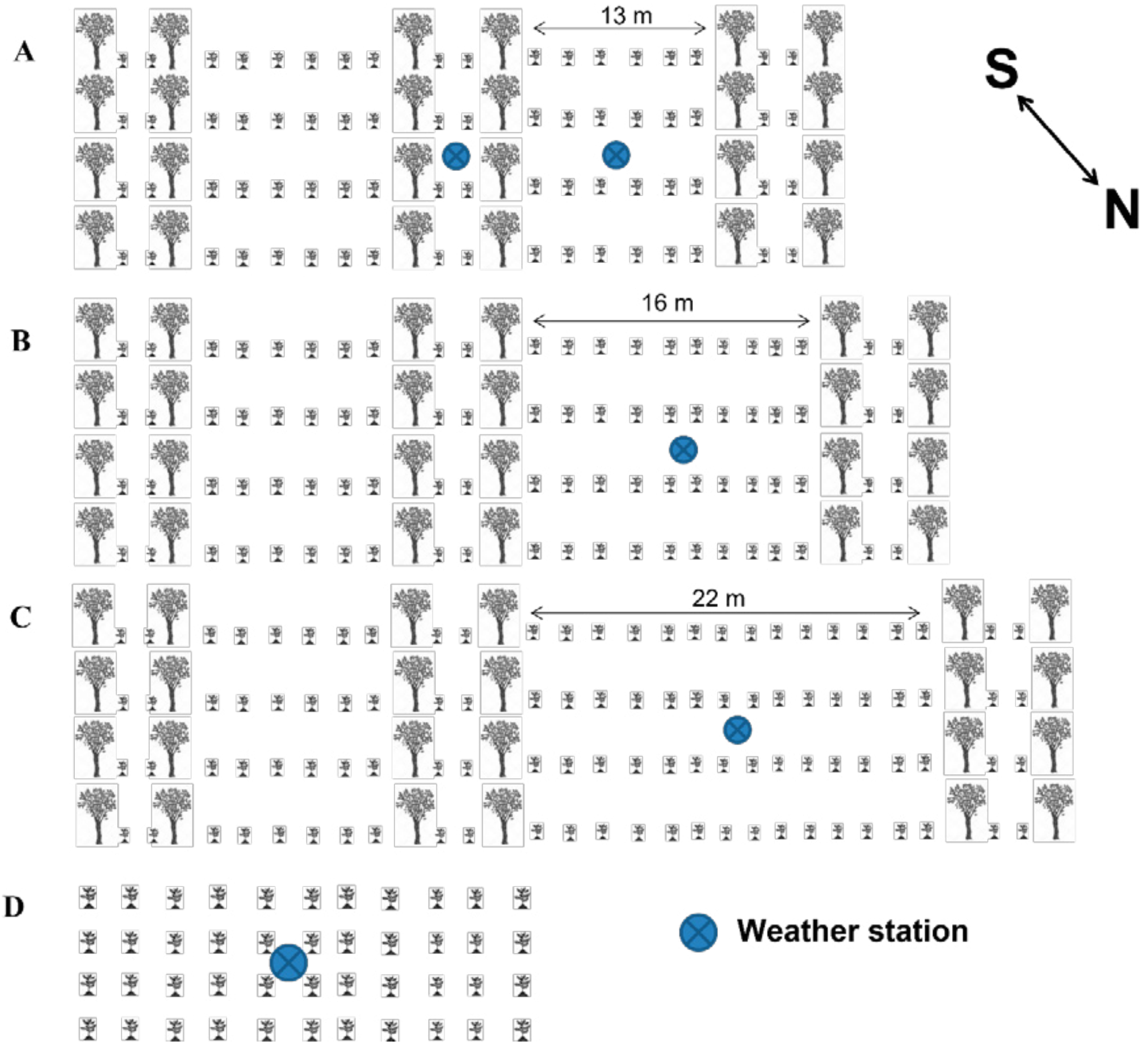
One automatic weather station was installed in each treatment: between double rows of rubber trees (shaded); at the center of an open-grown plot; and at the mid distance between the double rows spaced 13 m, 16 m and 22 m (Figure 1). The variables global solar radiation, air temperature, leaf temperature, and soil temperature were continuously monitored in each treatment from January 1st 2015 to December 31st 2018. The measurement conditions of each variable are described in the following paragraphs.

Global solar radiation - The sensors utilized were LI-COR (Model LI200X) pyranometers made with photodiodes composed of silicon cells, with a sensitive spectrum of 0.2 kW m^{-2} mV^{-1}. Before installation, sensors were calibrated using a Keep-Zonen model CMP6 pyranometer as standard. The sensors were equally calibrated on an annual basis using the same standard. The sensors were positioned at the height of 2 m above a central row of coffee plants, cleaned and checked for leveling every two weeks.

Air temperature - The measurements of air temperature were taken at a height of 2 m, with copper-constantan thermocouples positioned inside shelters of overlapping plates.

Leaf temperature - Copper-constantan thermocouple sensors were attached to the underside of leaves exposed

Figure 1. Schematic diagram of the field experiment. A, B and C represent the experimental plots with double rows of rubber trees spaced 13, 16, and 22 m apart, respectively. The larger and smaller plants represent rubber trees and coffee plants, respectively. The blue dots represent the position of each weather station. The station denominated 'shade' was placed within a double row of rubber trees of the 13 m spacing.



to the north and located in the upper third of the coffee plants, corresponding to the second pair of fully developed leaves from the apex of plagiotropic branches. The second to fourth pairs of leaves reflect the mean conditions in term of nutrition and exchange processes of the coffee plants and have been sampled in many studies (e.g. Sousa et al., 2018). The attachments were inspected twice a week to assure leaf contact and the position of the sensors changed every one to three months, according to the growth of the plagiotropic branches.

Soil temperature - Soil temperature was measured with thermistor-type sensors placed in the soil at a depth of 10 cm, at the crown projection of north facing coffee plants.

Data were collected from January 2015 to December 2018. Readings were taken every 10 seconds, with mean, maximum and minimum temperatures and global solar radiation obtained at every 15 minutes. Data were stored in a datalogger (ref. com. Campbell Sci. Datalogger 21X) and transferred to spreadsheets for further analyses.

The variables were inspected for consistency by eliminating suspect data, including positive or negative extremes and poor sensor contact. In order to compare the data in the same period, if there was malfunctioning of one sensor, the data from all treatments were disregarded for that period. The data was then processed to obtain maximum, minimum and mean temperatures and global solar radiation at every 24 hours. Temperature data were also separated in daytime periods, considered as a time zone from 9 am to 5 pm, and in the night periods from 10 pm to 6 am.

Statistical analysis was performed to compare the results using the Statistica software version 12. After passing the normality test of Shapiro-Wilk, the values of each variable for the treatments were compared using the Student's t test at 5% significance.

Results and discussion

Global solar radiation - In general, there was a gradual reduction of incident radiation proportional to the shade level (Figure 2). The interception of solar radiation varies according to the time of year, due to changes in zenithal angle, exposure face of the terrain, tree species, canopy porosity, population density and distance of the shading species from the measurement point (Farfan-Valencia, 2003; Pezzopane et al., 2005). In the present study, the average annual percentages of interception at the center of each plot were 72.0% under the rubber trees (shade), and 49.3%, 30.3% and zero for the spacings 13 m, 16 m and 22 m, respectively. Maximum interception of incident radiation between 30 and 50% are recommended for coffee based on several studies in different soil, climate and socioeconomic conditions (Morais et al., 2006; Siles et al., 2010; Alemu, 2015). Zaro et al. (2020) observed that there were no differences in coffee yield after seven harvests between the spacing of 16 m and the open grown in the same area of the present study.

Air temperature - The mean air temperature (Figure 3) during the period from 2015 to 2018 showed differences consistent with the seasons of the year. Some aspects should be highlighted regarding the daily mean air temperature in this environment. First, the penetration of outside air in the plots with limited size may have diluted the effect of the partial shading of rubber trees on the microclimate. Valentini et al. (2010) observed a decrease of maximum temperatures of up to 3°C and an increase of minimum temperatures of up to 2°C, in a coffee AFS with rubber trees spaced 16 x 16 m, in 1,600 m^2 plots. When average temperature is calculated based on 24 hours (Figure 3A) all data from the day and night periods are included. In the AFS environment during the day temperatures are usually milder, while in the open-grown temperatures reach higher values due to direct exposure to sunlight. During the night, the trees act as a screen that partially blocks the long wave radiation emitted by the surface, keeping the environment warmer (Morais et al., 2006). On the other hand, exposed plants lose heat and cool more intensely. Thus, when the 24-hour average is considered, there is attenuation in the average values.

The mean air temperature from 9 am to 5 pm was

Figure 2. Daily mean global solar radiation (Qg, MJ m^{-2} day^{-1}) incident on coffee plants grown in full sun and in AFS with double rows of rubber trees spaced 13, 16 and 22m. Shade represents the station within a double row of rubber trees. Averages represent the annual and seasonal scales. Londrina, Parana state, Brazil. *Bars of the same color and with the same letter do not differ by t test at 5% significance. LSD is the least significant difference.

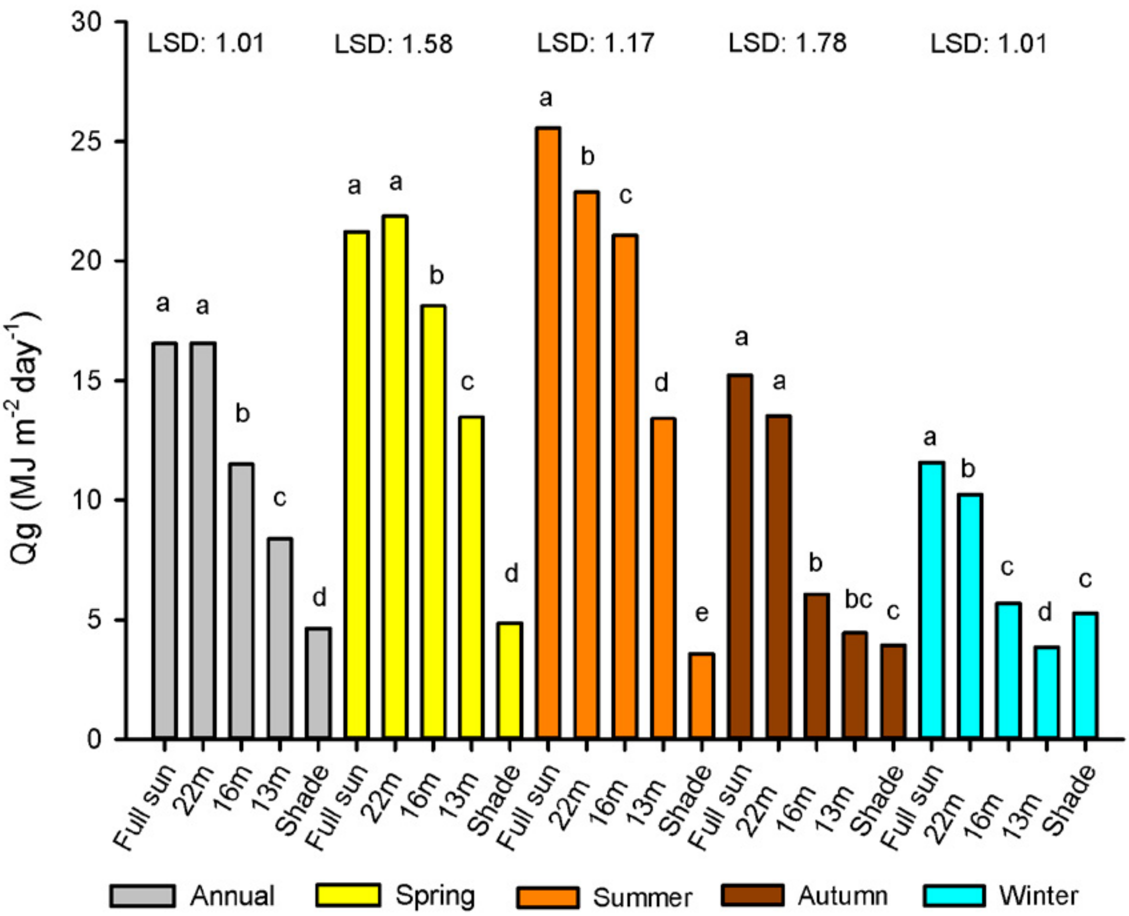
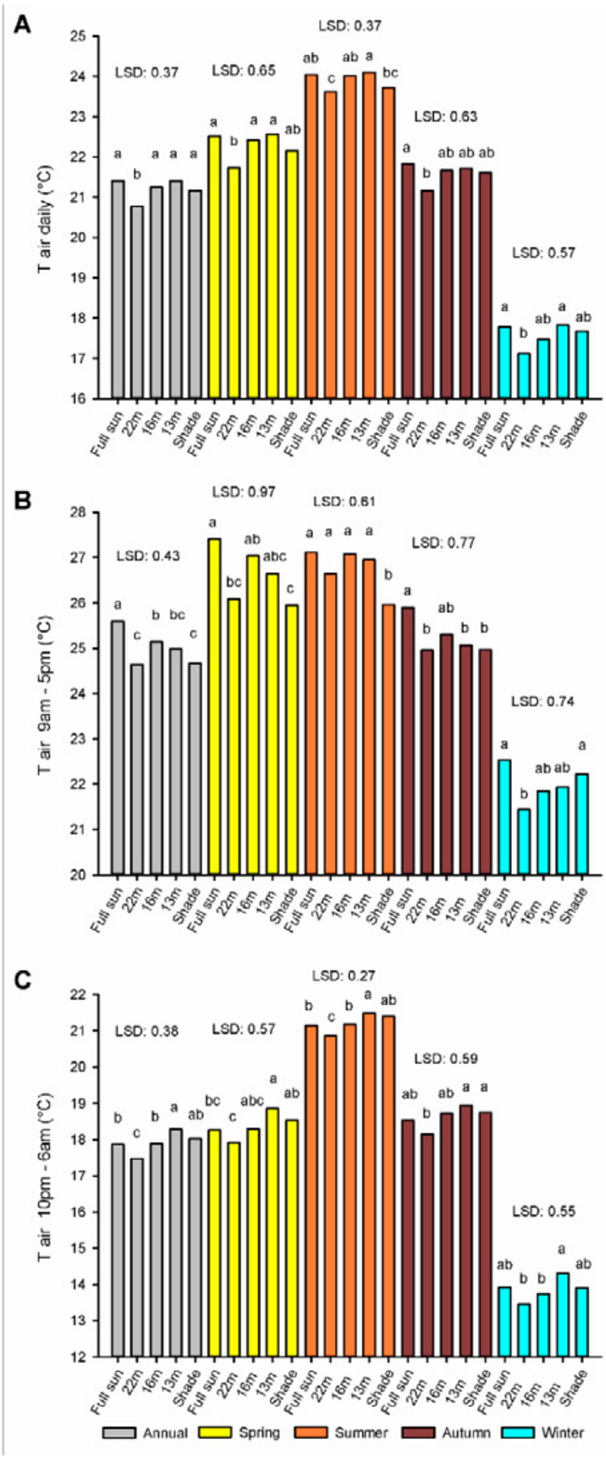


Figure 3. Average daily air temperature at 2 m height (Tair) in the coffee plots cultivated in full sun and in AFS with double rows of rubber trees spaced 13, 16 and 22m. Shade represents the station within a double row of rubber trees. Averages represent the annual and seasonal scales. Londrina, Parana state, Brazil. A) 24 h; B) 9 am-5 pm; C) 10 pm-6 am. *Bars of the same color and with the same letter do not differ by t test at 5% significance. LSD is the least significant difference.



higher in the open-grown for all seasons of the year, but showed greater variability in the seasons, when although it always had the highest average, in some cases did not differ statistically from the AFS (Figure 3B). As mentioned, the limited size of the plots in relation to the measurement height may have interfered, due to possible contamination by external air transport.

The mean air temperature from 10 pm to 6 am was highest between the double rows spaced 13 m and under the double rows (Figure 3C). In this case, the protective effect of the rubber trees on the coffee plants was evident, keeping the night temperatures higher. During nights with clear skies there is large heat loss from the surface and stability conditions cause the stratification of cold air close to the ground (Vieira Junior et al., 2018). The protective effects of trees taller than coffee plants are well known and have been widely studied as a method of protection against frost in coffee plantations (Caramori et al., 1996; Morais et al., 2004).

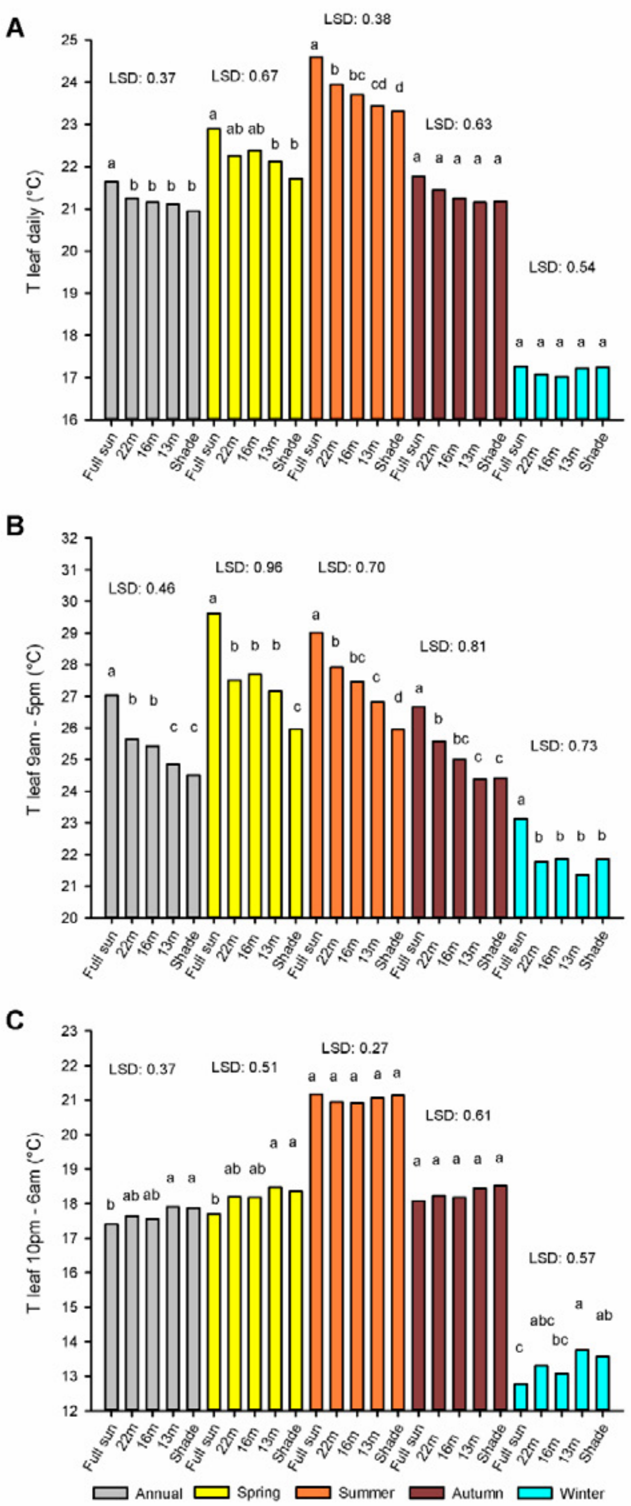
Leaf temperature - The mean daily leaf temperature (Figure 4) evidenced the greatest heating in exposed plants that occurs in the spring and summer seasons, when temperatures are higher. Under the rubber trees and at the 13 m spacing temperatures were lower than in the open-grown. As observed with the air temperature, in this case there is also a different effect between the day and night periods. Exposed plants get warmer during the day, but cool down more intensely at night, reducing differences.

Considering that with global climate change there will be increases of temperature during the hottest hours of the day, the analysis of daytime temperatures helps to verify whether there is sufficient attenuation to aid adapting Arabica coffee crops grown in AFS. The mean temperatures from 9 am to 5 pm show greater differentiation between treatments, clearly reflecting the differences in exposure to solar radiation incident on the canopy.

The effect of afforestation on leaf temperatures is much more evident than on air temperature. During the day, exposed surfaces are heated directly and transfer heat to the adjacent air by diffusion and convection processes. In this case, the limited size of the plots is of less importance, enabling better identification of the effect of rubber trees.

During daytime when temperatures reach maximum values there can be serious damage to the coffee plants. Flower abortion can occur if temperatures reach values above 30 °C for prolonged periods during flowering. The excess of heat during fruit development causes decreases on fruit size and drinking quality. Selected periods from beginning of flowering to maturity, in which temperatures were higher than the expected historical averages, were inspected to verify the maximum temperatures in the different environments evaluated (Figure 5). These periods were associated with high insolation and absence of rainfall. August-September corresponds to the beginning of flowering period, November-December is the end of flowering and fruit set, January-February is the period of grain filling, and April-May is the period of fruit maturity. For all

Figure 4. Average leaf temperature of coffee plants cultivated in full sun and in AFS with double rows of rubber trees spaced 13, 16 and 22m. Shade represents the station within a double row of rubber trees. Averages represent the annual and seasonal scales. Londrina, Parana state, Brazil. A) 24 h; B) 9am-5pm; C) 10pm-6am. *Bars of the same color and with the same letter do not differ by t test at 5% significance. LSD is the least significant difference.



situations the maximum leaf temperature in full sun was significantly higher than in the other treatments. In the heat wave of November-December of 2017, maximum leaf temperatures in full sun were up to 10°C higher, indicating a condition of elevated stress.

The species *Coffea arabica* has low light saturation, around 600 μmol m^{-2} day^{-1} (Kumar and Tieszen, 1980; DaMatta, 2004). The leaves exposed to incident radiation, after reaching saturation close the stomata to reduce plant metabolism. The excess of heat absorption and reduction of transpiration induces the rise of leaf temperature. Furthermore, under dryland conditions and high evaporative demand, radiation causes excessive transpiration, which also leads to stomata closing and leaf temperature increase. If the dry period is prolonged, there may be leaf chlorosis, burning and death of branches with full load of coffee berries (die-back) (DaMatta and Ramalho, 2006; DaMatta, 2007). Under scenarios of global warming, the heat waves are likely to become more frequent (IPCC, 2014, 2018) and will be a constraint to cultivation of Arabica Coffee.

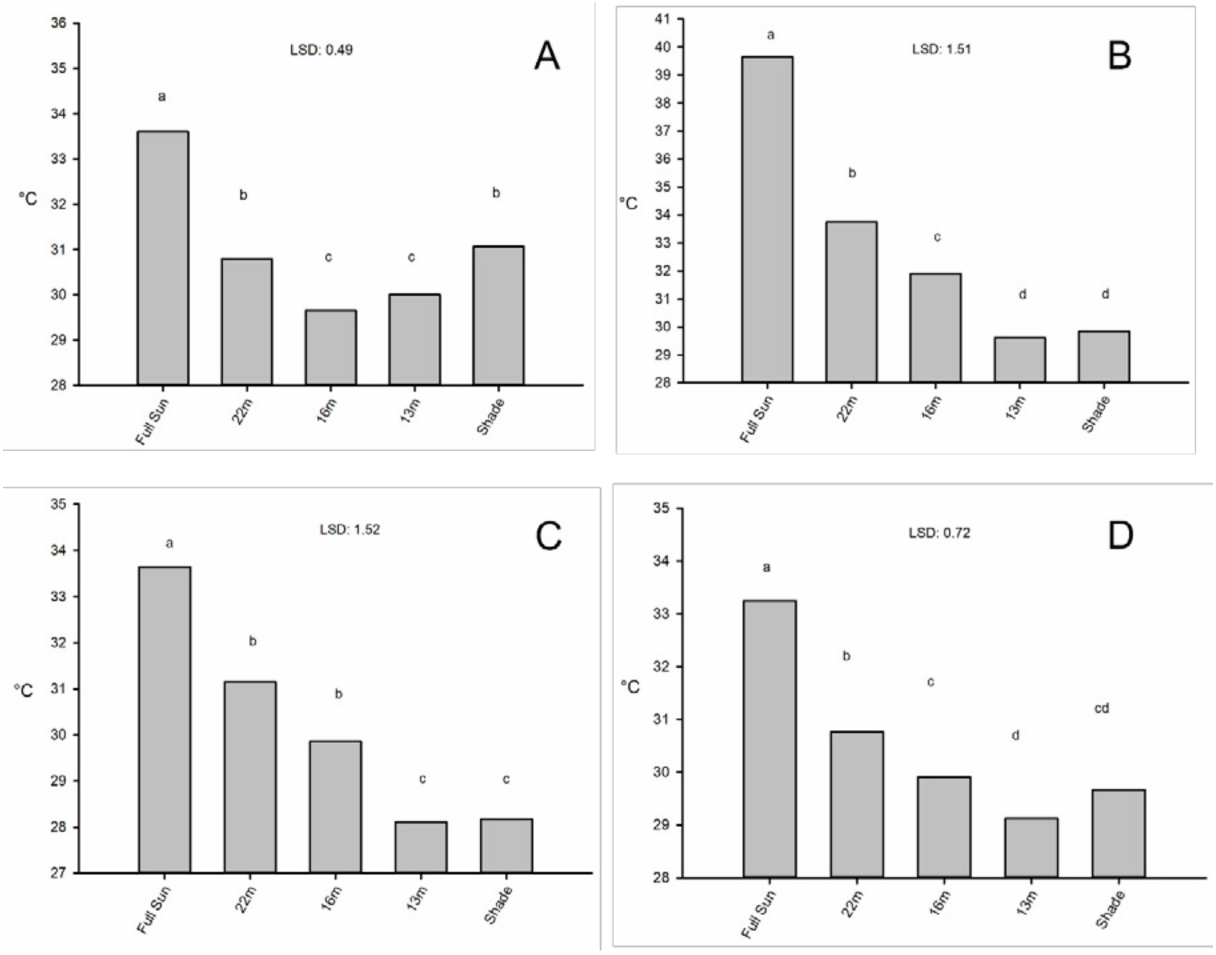
The excess of heating is attenuated by the self-shading of coffee plants, which makes rainfed crops that are well-leafed, with adequate nutrition and favorable water balance to be productive in open-grown plantations. The use of irrigation is also a practice that contributes to reduce heat stress.

Soil temperature - Soil temperatures at 0.10 m depth, measured continuously and separated into averages of 24 h, 9 am to 5 pm and 10 pm to 6 am (Figure 6) showed a similar behavior to leaf temperature, with a gradual reduction proportional to the level of shading much more evident. In general, the lower temperatures were for shade and 13 m, reflecting the amount of solar radiation incident on the soil surface and the energy diffusion into the profile. The decrease in soil temperature affects evaporation, macro and microfauna activity and the rate of decomposition of soil organic matter, with beneficial effects to the system.

Considering that with global climate change it is very likely that there will be increases of temperature beyond the limits supported by Arabica coffee during the hottest hours of the day, the analysis of daytime temperatures helps to verify whether there is sufficient attenuation to aid adapting Arabica coffee crops grown in AFS. The mean temperatures from 9 am to 5 pm show greater differentiation between shade levels, clearly reflecting the differences in exposure to solar radiation incident on the canopy.

Global warming and climate change scenarios (IPCC, 2018) have caused great concern for the coffee agribusiness. The use of AFS is one of the adaptation measures to help maintain coffee production. However, there is a lack of systematic studies on different experimental conditions, including climate and soil, species with different canopy porosities, competition between root systems, planting density and trees orientation. Lin (2007) observed that tree cover density had a direct relationship with air temperature inside the canopy and soil moisture, in a study

Figure 4. Maximum leaf temperature of coffee plants cultivated in full sun and in AFS with double rows of rubber trees spaced 13, 16 and 22m. Shade represents the station within a double row of rubber trees. Londrina, Parana state, Brazil. A) September 2017; B) November-December 2017; C) January-February 2018; D) April-May 2016. *Bars with the same letter in each graph do not differ by t test at 5% significance. LSD is the least significant difference.

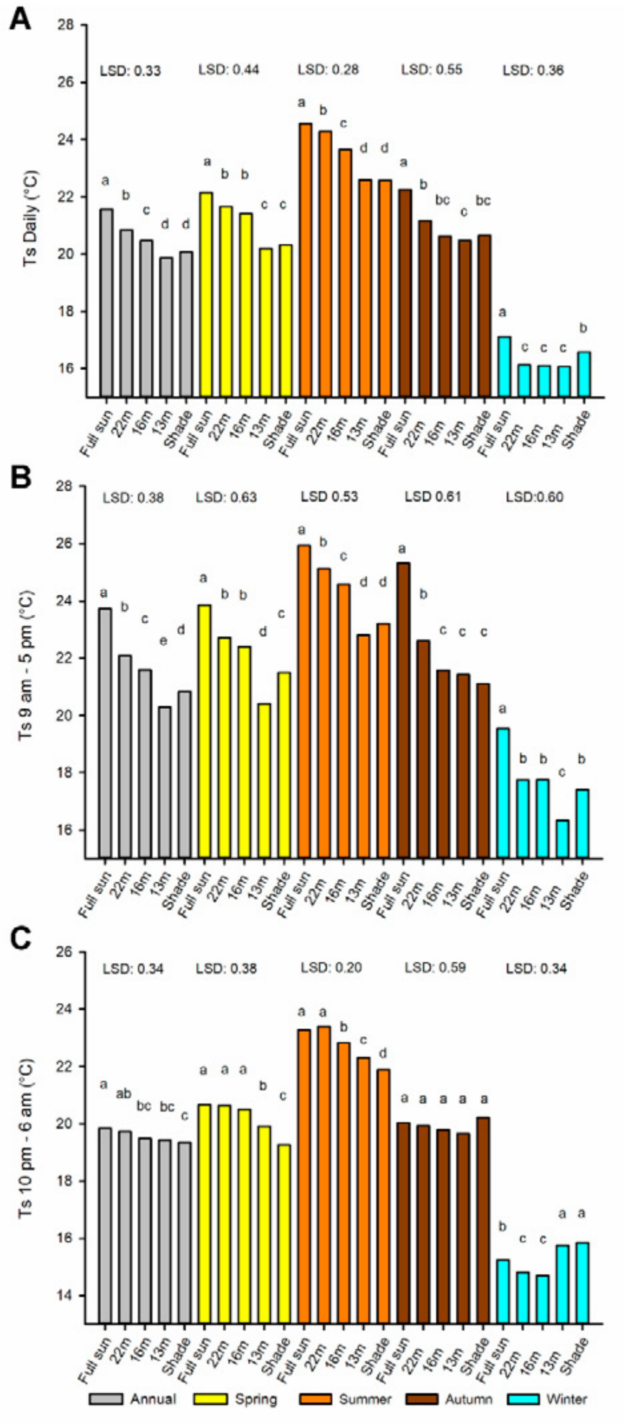


carried out on different exposure faces of the terrain and canopy densities. The wide variety of experimental conditions explain the variation of the results in the field trials. As observed in our study, in general there is a reduction of temperature amplitude in coffee areas with AFS, with a decrease in daytime temperatures and less nighttime cooling. The choice of the best AFS depends on a number of variables, including climate, soil and farmer profile. Producers that make use of external inputs to achieve high productivity normally prefer systems in full sun or low shading densities. Family producers and those looking for more balanced and sustainable systems with less external inputs use higher shade densities, exploring the productivity and stability of the production system (Alemu, 2015). AFSs usually contribute to improve the quality of beans and beverages in environments that are less favorable to the coffee crop, by attenuating the microclimate and inducing a slower development of the fruits and their complete formation (Muchler, 2001). Under conditions of climate change, there will be a need to increase the density of shade and seek other mechanisms to compensate for possible losses in productivity (Coltri et al., 2019). Leaf and soil temperature measurements offer conditions more representative of the microclimate under very limited border conditions. The results obtained in this study corroborate others that show the ability of AFSs to contribute to the adaptation of species sensitive to temperature increases, such as the case of *C. arabica*.

Conclusions

The presence of rubber trees in AFS with coffee caused changes in the thermal environment inside the coffee plantation. Coffee plants fully exposed to the sunlight had higher daytime temperatures and lower nighttime temperatures. Leaf and soil temperatures had more evident effects compared to air temperature at 2 m height, due to the limited size of the plots. Maximum leaf temperatures were attenuated under shade during heat waves with potential to cause damages to flowering and fruit growth. The differences observed are important to contribute to the adaptation of coffee plantations to climate change environ-

Figure 6. Average soil temperature (Ts) at 0.10 m depth of the coffee plots cultivated in full sun and in AFS with double rows of rubber trees spaced 13, 16 and 22m. Shade represents the station within a double row of rubber trees. Averages represent the annual and seasonal scales. Londrina, Parana state, Brazil. A) 24 h; B) 9am-5pm; C) 10pm-6am. *Bars of the same color and with the same letter do not differ by t test at 5% significance. LSD is the least significant difference.



ments. Attenuation of temperatures can also contribute to maintaining the normal cycle of the coffee plants and the quality of grains and beverages in warmer environments. In conditions of limited border area, leaf and soil temperature are better indicators of microclimate changes.

Author´s contributions

J. R. ROSISCA, P. H. CARAMORI, H. MORAIS, M. A. SILVA: work design, data collection, data analysis, writing, text review; G. M. Y. JUNIOR: data consistency, data analysis, text review, elaboration of graphics and figures; D. C. CARAMORI: Data analysis, writing, English review.

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Ambiente térmico em um sistema agroflorestal de café e seringueira no Sul do Brasil

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RESUMO

As mudanças climáticas representam um grande risco para a produção de *Coffea arabica* nas áreas atualmente cultivadas, pois esta espécie tem baixa tolerância a temperaturas extremas. Portanto, os sistemas agroflorestais (SAFs) são uma alternativa para contribuir com a adaptação do café arábica e manter a produção nas regiões onde é cultivado atualmente. Este estudo avalia o ambiente térmico de um SAF composto por cafeeiros e seringueiras (*Hevea brasiliensis*) plantadas em fileiras duplas com diferentes espaçamentos no município de Londrina, estado do Paraná, sul do Brasil. Dados de radiação solar global e temperatura do ar, folhas e solo foram coletados continuamente de 2015 a 2018. Os resultados revelam que a presença de seringueiras afetou o microclima ao reduzir as temperaturas extremas e diminuir as temperaturas médias. Nas condições experimentais de tamanho limitado das parcelas, as temperaturas das folhas e do solo representaram de forma mais realista as modificações no microclima induzidas pelas seringueiras. O estudo conclui que esse sistema pode contribuir efetivamente para a adaptação dos cafezais a um ambiente mais aquecido, a fim de continuar produzindo em regiões tradicionais do Brasil.

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