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Low levels of shade and climate change adaptation of Arabica coffee in southeastern Brazil

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Abstract

Coffee is one of the most consumed beverages in the world, and its international market has been growing for many years. Unfortunately, the Brazilian coffee production is threatened by high temperatures projected by climate change models. We evaluated three schemes of low levels of shade, which avoid the loss of production, as a strategy to adapt coffee to possible climate change. Additionally, as field measurements are expensive and often difficult to implement, we used numerical simulation to complement the evaluation. The microclimate simulator software Envi-met is a computer program often used to simulate urban environments, and we tested it on agriculture design. We verified that the shaded schemes assessed in the field decreased the air temperature in 0.6 °C in the studied period and reduced other possible climate stressors such as wind speed, radiation and raised air humidity in the dry period. Envi-met described the studied meteorological variable cycle very well, showing that combining numerical modelling and field research may be an important tool for planning the adaptation of the coffee sector to possible climate change, allowing growers choose a proper technique for their regions and environmental conditions. Finally, we highlighted the importance of planning the shade scheme

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on coffee areas in an interdisciplinary approach, including local climate evaluation to achieve a balance between temperature attenuation and production.

Keywords: Agriculture, Environmental science

1. Introduction

Coffee is the most consumed and popular beverage in the world after water, having 155.469 thousand of 60 kg bags (ICO, 2017) consumed worldwide in 2015/2016, and an average of $20 billion dollars of exports per year (according to the Global Coffee Industry). Consumers prefer *arabica* specie because it tastes better than *robusta* (Mehrabi and Lashermes, 2017) so that the "specialty" and "gourmet" segments have been growing fast in coffee industry, mainly in producing countries such as Brazil, Colombia, Vietnam, Ethiopia, and Indonesia.

The industry and consumers are increasingly demanding for quality and sustainability. Nevertheless, although the global demand increases, coffee production may be seriously threatened by a changing climate (Chemura et al., 2016; Assad et al., 2004), specially the *arabica* specie, due to its sensitiveness to high temperatures, and changes of seasonal rainfall pattern (Zullo et al., 2011; Assad et al., 2004; Bunn et al., 2015). These conditions make coffee lose suitable areas (Tavares et al., 2017; Fain et al., 2017; Chemura et al., 2016; Zullo et al., 2006; Gay et al., 2006), quality, and yield production (Bunn et al., 2015), impacting the food security and farmer's vulnerability (Drabo, 2017). In Brazil, it is especially relevant because it is the largest and most important coffee producer in the world, with a production sector that generates many jobs, moves the economy, and gives opportunities to smallholders.

In this context, the future of coffee production in climate change scenarios demands knowledge and proper plans (Baca et al., 2014; Bunn et al., 2015; Craparo et al., 2015), based on investments in public programs and regional management practices aiming synergies between adaptation and mitigation actions (Rahn et al., 2014). The perennial nature of coffee crop requires careful planning to adaptive management actions (Rahn et al., 2014), and alternatives must be proposed to smallholders considering local characteristics as market demand, climate, and tradition.

The challenges of coffee production in a climate change context are the following: (i) mitigation, linked to the reduction of greenhouse gas emissions, and stocking of atmospheric carbon; and (ii) adaptation, based on the development of techniques to allow coffee growth in different climatic scenarios that present high frequency of extreme events, and warmer temperatures than the current.

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Shading is a likely management technique for adapting coffee to warmer climates (Lin, 2007; Pinto et al., 2008). Previous studies suggested that shade trees protect crops from high temperatures (Barradas and Fanjul 1986; Morais et al., 2006; Lin, 2007), frosts (Caramori et al., 1986), strong winds (Pezzopane et al., 2011) and, in extended dry periods, increase soil moisture and air humidity (Beer et al., 1998). The benefits reduce coffee physiological stress, adapting the plants to high climate variability.

Additionally, shaded coffee agroforests play an important role as mitigation action. Carbon stocking and sequestration have been documented in the biomass associated with the shade tree component of coffee agroforestry, making the system a carbon sink (Coltri et al., 2015; Segura et al., 2006; Gay et al., 2006). Shaded-grown coffee is important to preserve natural resources (Perfecto and Vandermeer, 1996; Jha et al., 2014), improving biodiversity, social and financial characteristics (Lin, 2007).

Shaded-grown system is a relevant mitigation strategy, however, it is not always considered as an adaptive option. The main limiting factors to adopt shaded-grown systems are the competition (for light, water, and nutrients), the intense labor required to manage the system (Cerda et al., 2017), the decline of coffee yield (Cerda et al., 2017; López-Bravo et al., 2012), and the changing pathogens and insects attack pattern (Staver et al., 2001; Pumariño; 2015). On the other hand, the full sun system does not provide ecosystem service benefits, such as carbon sequestration and climate regulation, pest and disease control (Jha et al., 2014; Jose, 2009). Shaded-grown coffee has different functional roles when compared to full sun system, making it more ecologically sustainable (Rahn et al., 2014; Atallah et al., 2018), and less economically fragile. In this context, some studies suggested that from low to moderate shade level (10%−60%), it is a good balance between ecological, climate, and yield gains (Atallah et al., 2018; Jha et al., 2014; Soto-Pinto et al., 2000; Perfecto and Vandermeer, 1996; Staver et al., 2001; Cerda et al., 2017).

Despite all benefits, especially for mitigation purposes, there is still a gap of knowledge to understand the ideal level of shade cover and how shade trees may affect coffee meteorological variables inside the gradient of shading, especially considering low to moderate shade (30% or less). Previous studies reporting temperature decrease, cup quality, yield, coffee disease in shaded-grown coffee areas, normally assessed extreme treatment, including less than 15% or more than 70% of shading (Barradas and Fanjul 1986; Morais et al., 2006; Soto-Pinto et al., 2000).

The understanding of how high temperatures may be reduced in coffee production systems through the microclimate modification provided by shade cover is still limited (Van Oijen et al., 2010a). One way to increase the knowledge about these systems is the use of mathematical models and numerical simulations (Van Oijen et al., 2010b). The Envi-met microclimatic simulation software has emerged as a good microclimate simulator (Salata et al., 2016; Skelhorn et al., 2014), because

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of its capacity of simulate several phenomena (Amborsini et al., 2014), specially the impact of vegetation on cities microclimate (Zolch et al., 2016; Morakinyo and Lam, 2016; Ambrosini et al., 2014; Middel et al., 2014). The software allows the user to design an area (such as trees and buildings) providing real meteorological data as input parameters for simulations, and surface-to-atmosphere interactions. However, the model has never been used to simulate coffee production systems.

Considering all the challenges, our research combines field experiments and numeric simulations to assess the climatic variable patterns of three different low levels of shade schemes (up to 30% of shade), in order to analyses these shade arrangement as an adaptation option in one of the most traditional coffee region in Brazil.

In this study, we investigated: (i) the pattern of the meteorological variables (such as temperature, radiation, and wind speed) in different coffee shading schemes (up to 30% of shading); (ii) the performance of Envi-met software as a simulator of shaded-grown coffee microclimate; and (iii) if the shade schemes tested may be an adaptation technique to future climate scenarios in the south of Minas Gerais.

2. Material and methods

2.1. Study site description

The experimental area of the study was carried out in São Sebastião do Paraíso, south of Minas Gerais, in the southeast of Brazil (Fig. 1). Historically, the region is the most important coffee area in Brazil, and one of the most important coffee producers worldwide. The average altitude is 950 meters, and the average temperature and rainfall are adequate to high quality Arabica coffee (Coltri et al., 2015). The experimental area had four coffee plantation systems: three in shaded systems, and one in full sun (the control). The shading was considered "in row", as demonstrate in Fig. 2. Fig. 2a and b present the study area in a Geoeye-1 satellite image (having 1.84 meters of spatial resolution), and Fig. 2c and d show the scheme of the study area as an input data to Envi-met model.

The shaded systems were: (i) coffee with Pigeon pea (*Cajanus cajan*) to the north, and Leucena (*Leucaena leucocephala*) to the south (SH1); (ii) coffee with Leucena (*Leucaena leucocephala)* to the north, and gliricidia (*Gliricidia sepium)* to the south (SH2); (iii) coffee planted with Macadamia nuts (SH3), and (iv) full sun system (control). Shaded tree dimensions are shown in Table 1. The cultivation orientation was northeast. SH1 and SH2 were arranged sequentially, in a homogeneous slope with 20° inclination. SH3 presented the same characteristics but with 30° inclination. The neighborhood of experimental area was also occupied by coffee fields.

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Fig. 1. Geographical location of São Sebastião do Paraíso (study area), in the south of Minas Gerais State.

2.2. Field measurements

A meteorological station was installed in the coffee planting line of each treatment, in the middle of the plot (Fig. 2c and d). To prevent sensor interferences from the leaves, meteorological stations were installed in a coffee plant place (we cut off one coffee tree), and the surroundings of the stations were cleaned monthly. All sensors were located at the standard height of 1.60 m, as recommended by the World

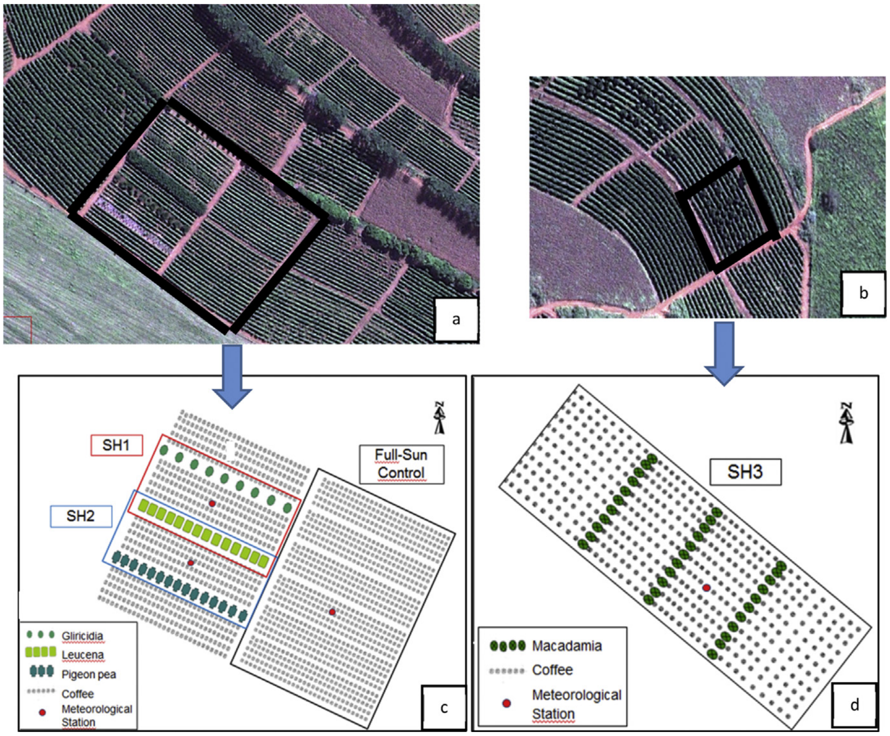

Fig. 2. Satellite view of experimental fields (a and b) and correspondent modeling used at Envi-met system (c and d).

Table 1. Shaded tree dimensions.

Species − trees	Plant height (h) − meters	Leaf area index (LAI)
Pigeon pea (*Cajanus cajan*)	2.30	2.75
Gliricidia (*Gliricidia sepium)*	4.5	2.15
Leucena (*Leucaena leucocephala*)	6.2	3.10
Macadamia nuts (*Macadamia* sp)	7.0	4.08

Meteorological Organization (WMO). However, the anemometers were installed at the height of coffee canopy, as proposed by Marin (2003). Radiation (W/m^2), Temperature (°C), relative humidity (%), and wind speed (m/s) were measured every hour from April to November 2009. The sensors of all stations were calibrated before installation and gauged regularly during the experiments.

We chose 10 coffee bushes and 10 shading trees in each shaded-grown coffee system, and measured the following biophysical parameters to model the coffee system on Envi-met software: (i) plant height (h); (ii) basal circumference at 10 cm from ground level (bc10 cm), (iii) canopy height (ch); (iv) basal canopy diameter (bcd), (v) height of first pair of branches (h1bs), and (vi) canopy volume (cv).

The canopy volume was measured considering the coffee geometry (Favarin et al., 2002) by using Eq. (1).

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$$cv = \pi * bcd^2 ch/12 \tag{1}$$

We also measured the following parameters related to the 10 shading trees chosen: (i) basal circumference at 10 cm from ground level (bc10 cm), (ii) diameter at breast height (DBH), (iii) plant height (h), and (iv) leaf area index (LAI). To calculate coffee and shading tree LAI, we used the instrument LI-COR LAI-2000 Plant Canopy Analyzer, operated with one sensor mode. The mode makes two measurements: out of canopy and below canopy. The measurement was done according to the operation mode described in LAI 2000 manual, beginning with out of canopy reading (open sky) to calibrate the sensor, and then, the below canopy reading. We used 270° view cap to avoid interferences (operator, soil, etc). We did all the measurements in stable sky conditions, at sunset.

2.3. Envi-met model setup

It is possible to simulate the plant-atmosphere interaction, fluxes of shortwave and longwave radiation, pollutant emissions, and complex structures using the ENVI-met software suite. The simulated area was designed using a high spatial resolution satellite image (Geoeye-1), having 1.84 meters of spatial resolution on multispectral bands (Fig. 2).

The ENVI-met software has a dynamic vegetation model in, and it was parameterized using field data from the experimental area. It was used the version 3.1 of ENVI-met that allows the explicit input of meteorological parameters, enabling accurate control of them. We also used site attributes such as:

- farm geographic coordinates (latitude, longitude, and altitude);
- characteristics of farm soil (% of clay);
- experimental coffee design (coffee spacing, legume and macadamia spacing, and geographic planting orientation), collected at farm level;
- planting density (drawn from the high spatial resolution Geoeye-1 satellite image); and
- biophysical characteristics of coffee measured at ground level, such as: plant height (h), leaf area index (LAI), basal circumference (bc), basal canopy diameter (bcd), canopy height, and local meteorological data.

Additionally, we added coffee nested grid cells, reproducing the study area to minimize boundary effects.

To model coffee plants, we assumed that coffee architecture may be represented by a cylinder (representing the stem), and a cone (representing the canopy), as suggested by Favarin et al. (2002) and illustrated in Fig. 3. After that, the tree was divided in ten parts (Fig. 3c), and the LAI - leaf area index - was proportionally distributed in the

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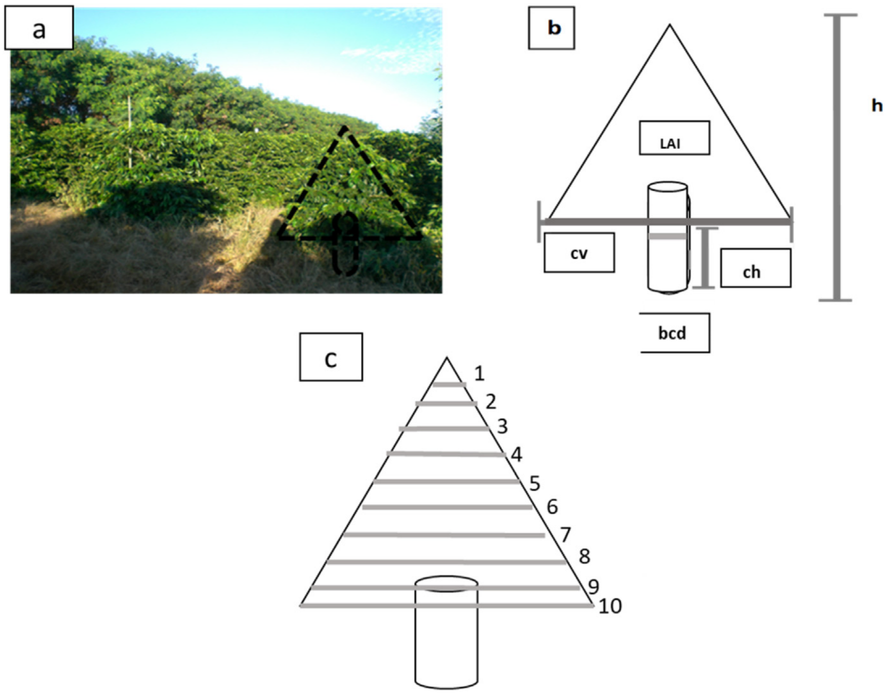

Fig. 3. Modeling of coffee bushes at Envi-met: a) geometric forms of coffee bushes; b) coffee with field measurements - coffee high (h), basal canopy diameter (bcd), canopy high (ch), canopy volume (cv), and leaf area index (LAI); c) ten parts used to proportionally distribute the leaf area index (LAI).

canopy parts (part 1 to 7 in Fig. 3c), as required by Envi-met software. To model shaded trees, we used the Envi-met library, adding real characteristics measured in field area as Leaf Area index (LAI), plant height (h), diameter at breast height (DBH), and basal circumference.

The simulation was run for three days, from 23h00 of September 13th to 0h00 of September 17th, to reduce the computation time. It was performed for the months of coffee blossoming, since the previous knowledge of the planting microclimate on this phase may determine the production of the culture, and the suitable area.

We used temperature, relative humidity, and radiation of full sun (control) meteorological station in an hourly basis as initial data input. Meteorological receptors were created in the model for the same locations and at the same height, as those installed in the field, to be comparable. The simulation was done choosing predominantly cloudless days (14^{th}, $15^{th,}$ and 16^{th} of September). After that, we assessed the model performance, comparing it to real data.

2.4. Statistical analyses

Descriptive statistics (means and standard deviations) for meteorological variables (temperature, wind, radiation, and relative humidity) and experimental data were submitted to average comparison with the Student t-test at 5% of probability.

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We used the Willmott's index (Willmott et al., 1985) to quantify the agreement between observed and Envi-met's simulated values of temperature, radiation, and humidity. The agreement index estimates the degree to the observed variable accurately estimated by the predicted variable, ranging from 0 (disagreement) to 1.0 (total agreement). It is represented by Eq. (2), where P = variable predicted by the model; O = observed variable; O = mean of the observed values.

$$d = 1 - \frac{\sum_{i=0}^{n}(Pi - Oi)2}{\sum_{i=1}^{n}\left(\left|Pi - \overline{O}\right| + \left(\left|Oi - \overline{O}\right|\right)\right.} \tag{2}$$

The accuracy of software performance was analyzed using the following quantitative metrics: Root Mean Square Error (RMSE), which expresses the difference between values predicted by the model and values actually observed from the environment being modelled; Mean absolute deviation (MAD), which expresses the accuracy in the same unit as the original data, helping us to conceptualize the amount of error, and Mean absolute percentage error (MAPE), which expresses the accuracy as a percentage of the error.

3. Results

3.1. Meteorological variables of full sun and shaded-grown production systems

3.1.1. Radiation

Field measurements show that full sun system received the highest amount of radiation, followed by SH1, SH2, and SH3 shaded systems. SH1 radiation did not differ statistically from the control (full sun). SH2 and SH3 received, on average, 15.2% and 29.4% less radiation than the control, respectively, differing statistically from the other treatments, as shown in Table 2.

3.1.2. Wind speed

The wind speed was the meteorological variable that presented higher difference between the treatments. Statistical differences between mean values of wind speed were significant by the t test, and all treatments differed statistically (Table 2). Compared to the control (full sun), SH1 had 21.7% of reduction in wind speed, SH2 had 65.2% reduction, and SH3 had the wind speed almost totally attenuated, with 99.3% of reduction. The result suggests that in these schemes, as shading increases, wind speed decreases. In SH2 and SH3 systems, the shading functioned even as a "windbreak".

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Table 2. Mean maximum and minimum temperatures, relative humidity, radiation and wind speed during field experiments. Means sharing the same letter in the column do not differ significantly at 5% probability level using t-Student test.

Coffee production system	Meteorological parameter				
	Radiation (W/m^2)	Wind (m/s)	Temperature		Relative humidity (%)
			Maximum (°C)	Minimum (°C)	
Full sun (control)	204.8^a	3.31^a	20.3^a	19.6^a	74.47^b
SH1	202.7^a	2.59^b	20.0^{ab}	19.4^a	73.84^b
SH2	173.7^b	1.15^c	19.9^{ab}	19.1^b	74.50^b
SH3	144.5^c	0.02^d	19.8^b	18.9^b	75.53^a

3.1.3. *Relative humidity*

As expected, relative humidity behavior varied inversely to temperature behavior. The biggest difference between relative humidity averages occurred in the driest period of the year, mainly in August. The relative humidity was higher in SH3 (75.5%) than in the other treatments. SH1, SH2, and full sun varied between 73.8 and 74.5% and did not differ statistically. In rainy season, we had not much difference between treatments. In the hourly analyses, the largest variation occurred in the treatment with more shade (SH3), following the temperature pattern.

3.1.4. *Maximum temperature*

In the measured period, the mean maximum temperature was 2.5% lower in the higher shaded-grown coffee, when compared to full sun system. SH3 registered 19.8 °C, followed by SH2 (19.9 °C), SH1 (20.0 °C), and full sun (20.3 °C). Comparing the values, there is statistical differences between full sun and SH3, but not between SH2 and SH1 (Table 2).

The distribution of maximum temperature data is similar in the treatments throughout the measured period, but the full sun presented higher amount of inferior outliers when compared to other treatments. Monthly, we observed the same maximum temperature pattern with the highest maximum temperature in the full sun system. In May, June, and August, the maximum temperature attenuation was 0.6 °C in the SH3 treatment. In May and August, SH2 treatment had the maximum temperature reduced by 0.4 °C. The highest temperature reductions occurred in May and August, when SH3 system recorded 0.56 °C and 0.63 °C lower than full sun, respectively. The difference was higher in drier months (May, June, July, August, and September) than in wetter months (October, November, and December). The differences are presented in Fig. 4.

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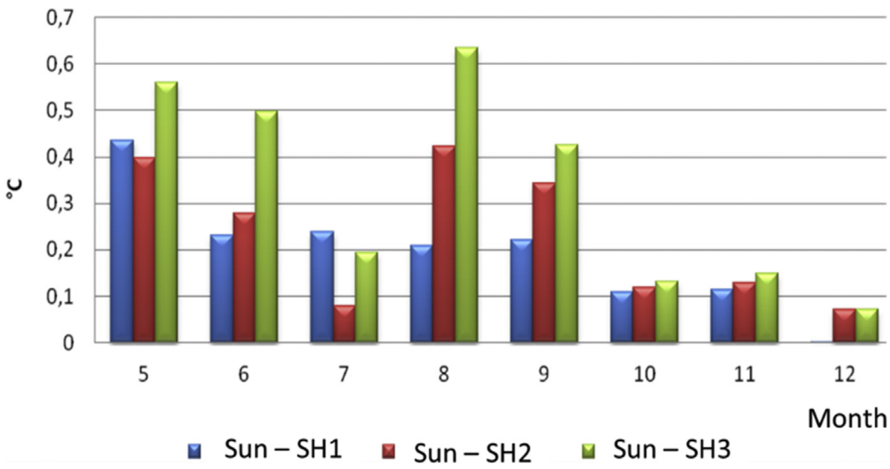

Fig. 4. Monthly differences of mean maximum temperatures between coffee treatments: full sun and SH1 in blue; full sun and SH2 in red, and full sun and SH3 in green.

Analyzing hourly data, the monthly trend is maintained at nighttime (without radiation from 7 pm to 8 am), and the lowest maximum temperature was observed in the higher shading systems (SH2 and SH3). However, the same pattern was not observed in the hourly average of daytime period (with radiation − from 9 am to 6 pm). In this case, there was an inversion and the higher shading treatments (SH3 and SH2) had higher maximum temperature than SH1 and full sun system (Fig. 5). The inversion pattern started at 8 am and ended at 4 pm. Shaded treatments and control had similar temperatures in the end of day, at 5 or 6 pm.

3.1.5. Minimum temperature

The average minimum temperature was lower in higher shading treatments (SH2 and SH3). Full sun was statistically different from SH2 and SH3 (Table 2). Monthly, in the driest period (May, June, July, and August), we observed the same pattern, and the control (full sun) was 0.8 °C higher than SH3, and 0.6 °C higher than SH2.

In the hourly analyses, the minimum temperature followed the same pattern that maximum temperature, and the higher shading treatment (SH3 and SH2) had higher minimum temperature than SH1 and full sun. During the cold morning period (4−7 am), SH3 had lower minimum temperature. However, the same behavior was not observed in SH2 and SH1, which registered higher minimum temperatures when compared to full sun.

3.2. Modeling coffee production systems at envi-met: evaluating model performance

Table 3 shows the Willmott agreement index between modelled and measured data, while Table 4 presents values of quantitative metrics MAD, MSE, RMSE, and

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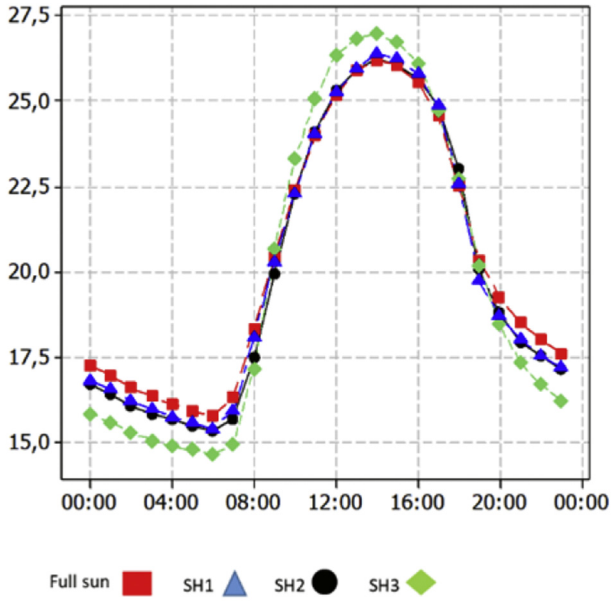

Fig. 5. Average of maximum temperature in an hourly basis. X-axis is local hour and Y-axis is temperature in °C. In red: full sun (control), in blue SH1, in black SH2 and in green SH3.

Table 3. Willmott's concordance index "d" for temperature, radiation and relative humidity, three simulation days, and SH1, SH2, SH3 and Full sun (control) treatments.

Simulation day	Treatment	Meteorological parameter		
		Temperature	Relative humidity	Radiation
3 days − All simulations	**Full sun (control)**	**0.91**	**0.84**	**0.96**
1st day − 09/14	Full sun (control)	0.79	0.66	0.92
2nd day − 09/15	Full sun (control)	0.94	0.89	0.98
3rd day− 09/16	Full sun (control)	0.98	0.88	0.98
3 days − All simulations	**SH 1**	**0.91**	**0.85**	**0.96**
1st day − 09/14	SH1	0.81	0.69	0.92
2nd day− 09/15	SH1	0.95	0.89	0.96
3rd day− 09/16	SH1	0.97	0.88	0.98
3 days − All simulations	**SH2**	**0.93**	**0.87**	**0.92**
1st day − 09/14	SH2	0.83	0.70	0.86
2nd day− 09/15	SH2	0.95	0.92	0.93
3rd day− 09/16	SH2	0.98	0.88	0.95
3 days − All simulations	**SH3**	**0.91**	**0.89**	**0.92**
1st day − 09/14	SH3	0.80	0.72	0.87
2nd day− 09/15	SH3	0.94	0.97	0.94
3rd day− 09/16	SH3	0.97	0.89	0.94

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Table 4. Quantitative evaluation of Envi-met performance based on MAD, MSE, RMSE and MAPE.

Treatment	MAD	MSE	RMSE	MAPE
Temperature (°C)				
Full sun (control)	2.56	9.40	3.07	11.29
SH1	2.52	9.72	3.12	11.18
SH2	2.26	7.97	2.82	9.98
SH3	2.73	12.42	3.52	12.93
Relativity humidity (%)				
Full sun (control)	11.20	172.48	13.13	19.72
SH1	11.40	173.42	13.17	20.26
SH2	10.48	161.48	12.71	18.75
SH3	9.87	158.63	12.59	17.87
Radiation (W/m^2)				
Full sun (control)	83.03	21260.54	145.81	32.59
SH1	84.93	21730.28	147.41	34.84
SH2	105.76	38834.88	197.06	133.79
SH3	97.57	32992.72	181.64	119.08

MAPE. The better agreements between simulated and measured data ranged from 0.66 to 0.98. The best one occurred in the third day of simulation for temperature and radiation, ranging from 0.97 to 0.98 for temperature, and 0.94 to 0.98 for radiation, which is considered a great performance. On the other hand, for radiation, SH3 had the best agreement (0.97).

3.2.1. Relative humidity

For relative humidity, the best correlation occurred in the second day of simulation, ranging from 0.89 to 0.97. Shaded treatments presented better agreement indexes than full sun system. In this context, SH3 (higher shade) had the best agreement index (0.89), followed by SH2 (0.87), SH1 (0.85), and full sun (0.84). The largest residual errors occurred during the wettest hours of the day (at night).

In average, for all treatments and simulated days, the model tends to overestimate the relativity humidity during the night and underestimated during the driest hour (3 pm) of the day. SH3 presented the best agreement index and the lowest accuracy metrics with less variance, errors, and percentage of errors between simulated and real data, followed by SH2, full sun, and SH1.

3.2.2. Temperature

For temperature, the best agreement index between real and simulated data occurred for SH2 (d = 0.93), followed by the other treatments that presented d = 0.91.

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Analysing temperature residual error, the most expressive difference for average simulation (all simulations and treatments) occurred at 5−6 pm, 7 am, 10 am, and 3 pm. The third day of simulation had the best agreement index, ranging from 0.97 to 0.98 to the treatments. The most expressive error for the third simulation occurred at night (8−9 pm), when the model underestimated the values. The residual errors of temperature and relative humidity behaved inversely.

In average, for all treatments, the model tends to overestimate the temperature. During the day (from 7 am to 5 pm), the temperature was 2.2 °C overestimated (in average, for all treatments), and during the night (6 pm−6 am), the temperature was 1.3 °C overestimated. SH2 simulation presented less variance, errors, and percentage of errors, followed by SH1, full sun, and SH3.

3.2.3. Radiation

For radiation values, full sun and SH1 presented the best agreement index and lowest variance, errors, and percentage of errors between simulated and real data, followed by SH3, and SH2. The most expressive errors occurred after sunrise and at sunset. When radiation increases (6 am) the model overestimates the values tending to increase the radiation faster than the reality. The error increases until 7 am, and after that, the residual error decreases. At the end of the day, when the sun sets, the model also overestimates the radiation, decreasing the error when the experimental radiation equals zero.

All simulated meteorological variables (temperature, relative humidity and radiation) presented the same curve pattern as experimental measured data (Fig. 6), suggesting that the model presents similar trends for these variables. Thus, ENVI-met simulated well the radiation, temperature, and the humidity cycle in all coffee treatment conditions considered in this study.

4. Discussion

4.1. Meteorological variables in shaded systems and the opportunity for adaptation to climate change scenarios

The studied shaded schemes using canopies of Pigeon pea, Leucena, Gliricidia, and Macadamia nuts influenced most part of monitored meteorological variables, mainly the light availability inside coffee canopy that varied from 15% (SH2) to 30% (SH3) of total radiation measured. It influenced wind speed, air humidity, and temperature, as observed in previous studies (Siles et al., 2010; Pezzopane et al., 2007; Meylan et al., 2017).

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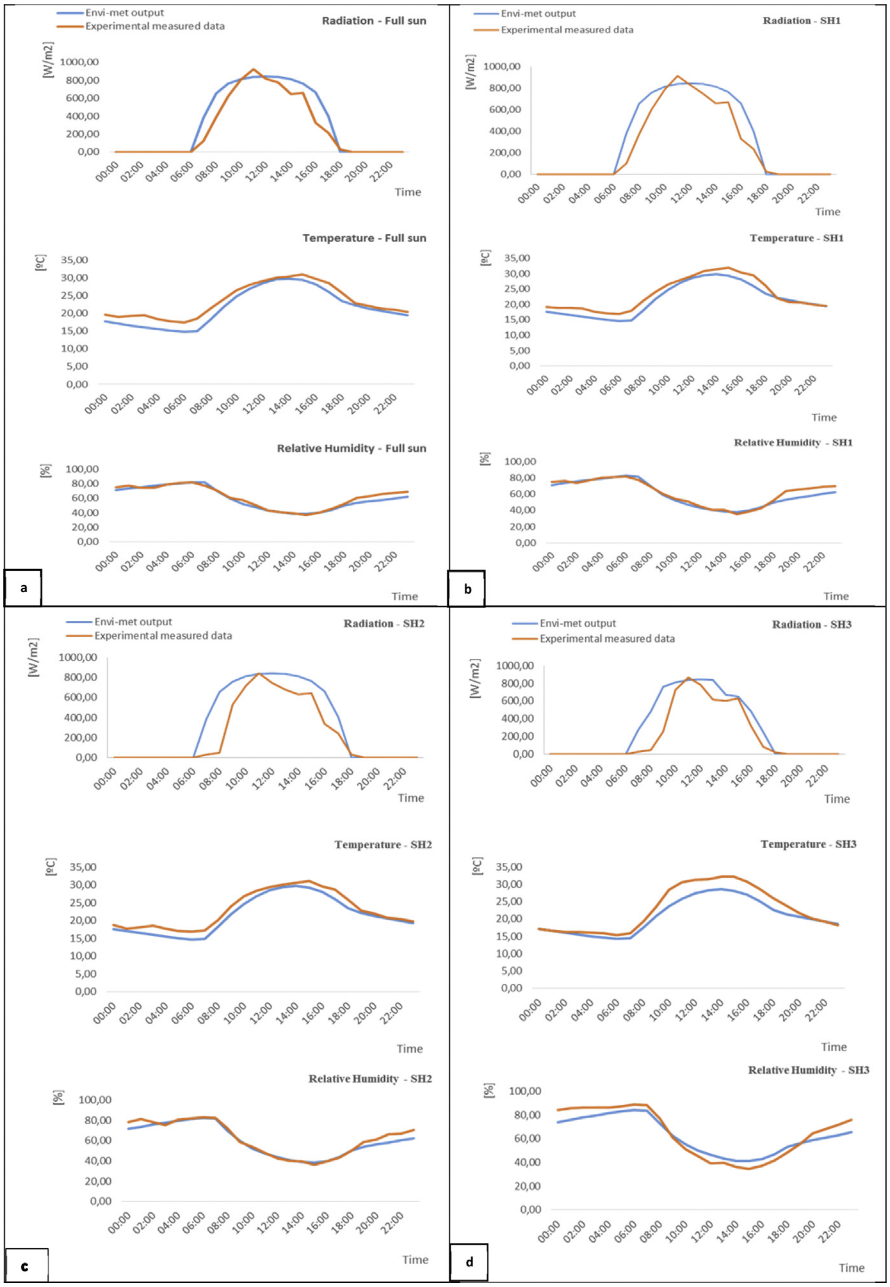

Fig. 6. Radiation, temperature and relative humidity provided by Envi-met system (blue) and experimental measured values (orange) in the following coffee production systems: full sun (a), SH 1 (b), SH 2 (c) and SH 3 (d).

4.1.1. Wind speed

The total attenuation of wind speed observed in SH3 may prevent crop damages (DaMatta et al., 2007) improving crop performance, mainly in young plants (Caramori et al., 1986). Some studies highlighted that hot and cold winds cause injuries on coffee plants by the following ways: directly, cold winds may cause severe

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damage to leaves, fruits, and flowers (Caramori et al., 1986; Camargo, 1985; Damata et al., 2007); and indirectly, the wind may break the plant tissues facilitating disease infections. Wind coffee stress also reduces leaf area and vegetative growth (Caramori et al., 1986). Hot winds increase evapotranspiration requiring more water from rainfall or artificial irrigation (DaMatta, 2004).

4.1.2. Air humidity

In addition to total wind reduction, SH3 also presented higher relative humidity in the driest period, suggesting that the shaded-grown system presented more humidity in the driest period of the year. Air humidity affects coffee vegetation growth and evapotranspiration (DaMatta et al., 2007). Therefore, drought stress caused by low humidity air is harmful to coffee photosynthesis and respiration (DaMatta and Ramalho, 2006), especially in the driest period of the year. In the shaded schemes, drought stress could be reduced to coffee plants. On the other hand, the humidity registered in SH2 and SH3 was not very high in rainy season, suggesting that the shaded schemes do not raise the humidity significantly in the Arabica coffee canopy. This is especially important to avoid diseases (Staver et al., 2001), and under ideal conditions, Arabica coffee plants prefer low atmospheric humidity to that where coffee origins (DaMatta et al., 2007).

4.1.3. Temperature

Although wind speed and air humidity presented significant reduction in shaded treatments, especially SH3, comparing to full sun system, the light reduction did not decrease the temperature significantly, as observed in previous studies, where temperature reduction was superior to 2 °C (Barradas and Fanjul, 1986; Soto-Pinto et al., 2000). The temperature behavior in coffee systems studied here is related to shade behavior during the day. To better understand it, Figs. 7 and 8, presented the simulation of shade behavior during the day (9 h, 12 h, 15 h, and 17 h − local hour) for all the treatments, for two dates: 21st of June (winter solstice), and 23rd of September (vernal − Spring-equinox). We observed that at 12 h and 15 h, coffee systems SH1 and SH2 did not receive shade of the trees, having only a self-shadowing of coffee trees, making it difficult to attenuate the temperature.

In conditions of high shade level, such as those of Barradas and Fanjul (1986) in Mexico, and in Brazil, the temperature reduction reached 4 to 5 °C. By contrast, we found that in the hourly average data of daytime period, the higher shading treatment (SH3 and SH2) had higher maximum temperature than SH1, and full sun systems.

Brenner et al. (1995) reports that under protected crop conditions by windbreaks, where the radiation incidence is similar to unprotected crops, diurnal temperatures are higher due to lower movement of atmospheric air, which changes the energy

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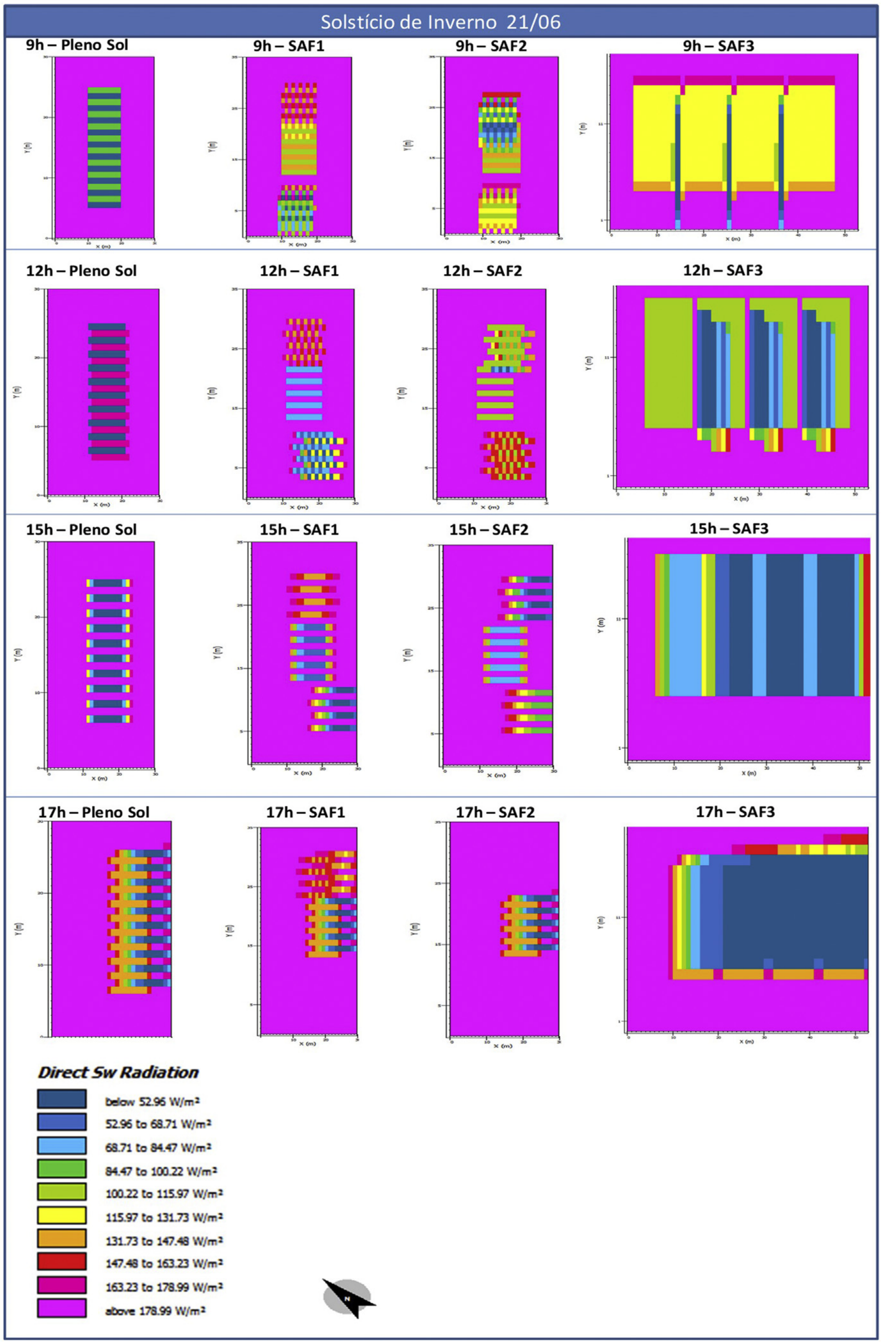

Fig. 7. Simulation of the shade behaviour on winter solstice.

balance, increasing the sensible heat flow. High diurnal temperatures in crops protected by windbreaks, when the incidence of solar radiation is similar to unprotected crops, were also obtained by Ujah and Adeoye (1984) in crops protected by artificial windbreaks, and Pezzopane et al. (2007), in a system of production of consorted coffee and banana.

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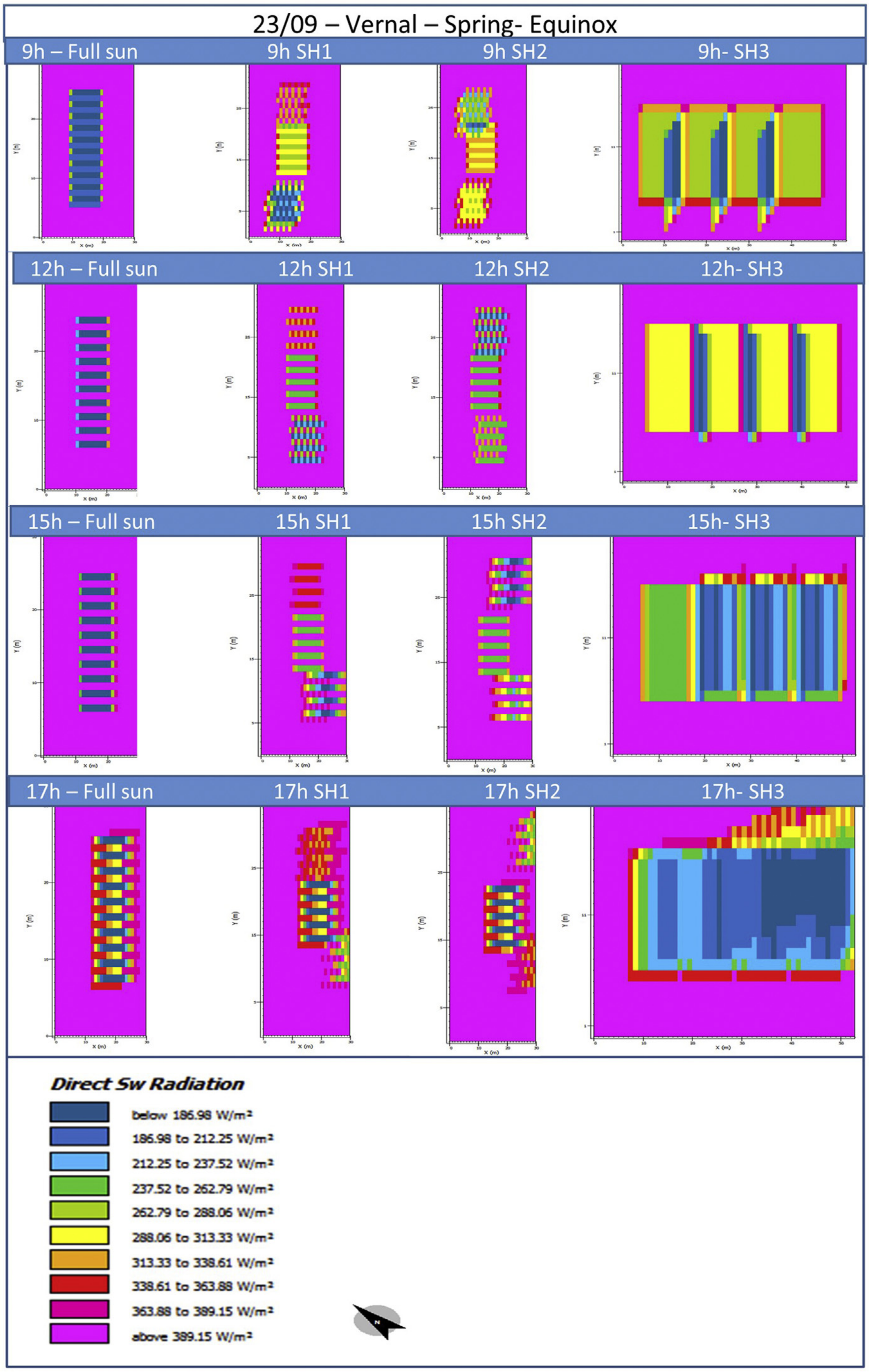

Fig. 8. Simulation of the shade behaviour on vernal Spring equinox.

Analyzing monthly data and still regarding temperature reduction, in the driest period of the year (June to September), which is winter time in the Brazilian Southeast, temperatures reduced more than in wet and hot periods (Fig. 4), not reducing thermal stress. During the blossoming, high temperatures may cause abortion of flowers (Camargo, 1985), and temperature reduction is important in this time of the year. In monthly average, the most significant temperature reduction occurred in August (0.63 °C for SH3, 0.4 °C for SH2, and 0.2 °C for SH1 compared to full sun system), and the blossoming period occured in the end of September and October. In this context, it is important to study the shade scheme before implementing it, preferably in an interdisciplinary scope. To implement efficient management, it is essential to study current and future climate projections, coffee flowering time, orientation (scheme) of cultivation in the field, mathematical modelling, and local (producers) acceptance to combine the balance between adaptation and production.

The traditional south region of Minas Gerais may lose suitable areas for coffee growing over the years (Tavares et al., 2017; Pinto et al., 2008; Zullo et al., 2006; Assad et al., 2004), especially due to temperature increase and modified rainfall pattern. Temperature is the most important and decisive meteorological variable to define suitable coffee areas (Rahn et al., 2014), interfering in the blossoming, fruit quality, and growth. Adaptation is therefore required and, since shade management reduces temperature, the practice may be considered a significant option to adapt coffee to climate change. However, as suggested in this study, the low level of shades may not reduce temperature in the blossoming period, but may reduce it along the year. Therefore, it is essential to plan shade schemes to reduce thermal stress.

Nevertheless, one facet of adaptation actions to climate change is the diversification (Schroth and Ruf, 2014). It may be achieved with moderate to high level of shade in coffee production, as suggested by Barradas and Fanjul (1986), Soto-Pinto et al. (2000). Although high levels of shade in coffee cultivation is not possible without yield reduction (Rahn et al., 2014; Morais et al., 2006), financial and ecological possibilities may ariseby joining REDD program (Reducing Emissions from Deforestation and Forest Degration). in developing countries, with carbon credits (Rahn et al., 2014), sustainable management, significant reductions in N-fertilizer inputs (Rosenstock et al., 2014), and timber sales (Sousa et al., 2016). Additionally, Rahn et al. (2014) highlights that sustainable coffee production reduces coffee carbon footprint, resulting in a financial gain in coffee commercialization.

Analyzing gains and losses of high level of coffee shading in present time, means that this management seems to be more appropriate and efficient to the studied region, because it collaborates to both activities: mitigation and adaptation. Finally, the system may be conveniently used as proposed by Torres et al. (2010) and Luedeling et al. (2011) to reforest degraded lands, improve ecosystem services, sustainability, carbon sequestration and stock, and to reduce the environment degradation.

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4.2. Modelling coffee production systems: envi-met as a planning management tool

The data available for model parameterization of coffee agroforestry systems is limited (Van Oijen et al., 2010a). Understanding how meteorological variables work in shaded-grown system is relevant to improve coffee agrosystem management. The objective of modelling managed ecosystems is to understand how the process works, and how the elements interact with each other, trying to predict their behavior to anticipate answers and minimize gaps in our knowledge.

The present work shows that Envi-met system, created and largely used to simulate urban climate (eg. Zolch et al., 2016; Morakinyo and Lam, 2016; Middel et al., 2014; Coltri et al., 2015) and thermal comfort (eg. Acero and Arrizabalaga, 2016), may simulate the microclimate of coffee production systems. However, the model has limitations and studying them provides help to set the research agenda and how to use the results in practice.

According to RMSE, MADE, MSE, and MAPE, modelled data presented errors, and radiation had the most expressive errors. An important variable inserted in the ENVI-met program refers to cloudiness. It is known that clear sky (without clouds) is the ideal measurement condition (Minella et al., 2012), however, in simulated data, we had no very clear sky, which could have influenced the model accuracy. Minella et al. (2012) found similar results. Most studies using Envi-met had clear sky to run the simulations (Yang et al., 2013; Zolch et al., 2016; Morakinyo and Lam, 2016; Ambrosini et al., 2014; Middel et al., 2014).

The systematic errors (RMSE) of temperature ranged from 2.82 to 3.5 °C, which is superior to the error found in the South of China by Yang et al. (2013), and in Germany by Jänicke et al. (2015) Lee et al. (2016). It may be attributed to the high values measured and not observed in other studies. Acero and Arrizabalaga (2016) found similar results for high values. Additionally, the simulation has to start in the beginning of the day, due to the neutral atmosphere, avoiding errors in radiation pattern.

Eventually, for the shaded-grown schemes considered here, the results suggest that Envi-met is a competent microclimate simulator of coffee production systems. The "d" Willmott agreement index ranged from 0.80 to 0.98 demonstrating that the model reproduces radiation, temperature, and the humidity cycle in all coffee treatments considered in this study. The results suggest that Envi-met model reproduces the main characteristics of meteorological variable patterns measured in the field. Therefore, the modeling approach proposed in here is indicated to be used for other coffee production areas, requiring the local adjustment of parameters and inputs, such as soil, geographical coordinates, trees attributes (LAI, high, form, etc), and local meteorological data. An option like that is particularly important, as the

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customer may choose different options of trees to shade the coffee plants and test them in the software.

The chosen tree of shade-grown system is crucial for the success of the management (Morais et al., 2006), and has to be according to: (i) the objective of the system (frost protection, windbreak, high temperature protection, buffer humidity, and ecological services); and (ii) the local conditions (soil, climate, and adaptability of species to the region). Using Envi-met, an easily accessible freeware, as an operational application helps decision makers and farmers to adopt the most adequate species to shade the coffee, evaluating real actions to adapt to climate change scenarios.

5. Conclusion

The present study investigated how meteorological variables behave in low levels of shade in coffee agrosystems, and the possibility of using an accessible microclimate simulator software (Envi-met) to simulate shaded-grown coffee systems. We also addressed the possibility of conducting coffee in low levels of shade avoiding the productivity losses and acting as an adaptive management to climate change scenarios in the South of Minas Gerais.

We concluded that the shaded schemes here with up to 30% of shading, reduced radiation, total temperature and wind speed. The systems reduced the wind speed up to 99%, working as a "wind break". In the driest period of the year, humidity was superior on shaded-grown systems than in full-sun system. All these modifications may minimize the coffee stress in a different climate scenario, as proposed by IPCC. Along the period, the maximum temperature attenuation registered was 0.6 °C, but the temperature reduction was not significant in the blossoming period.

In this context, we discussed the importance of planning shade scheme before implementing them, because sometimes the shade scheme meteorological result is not the appropriate adaptation option to the study area. Analyzing current climate and the feedback that shading schemes may produce are important issues to implement an efficient management. It is relevant to emphasize that in order to decrease temperature, the best schemes are those with high tree density, which, even reducing production, bring other benefits such as stocking carbon, ecosystems services, high quality of coffee, and economic opportunities.

The results show that Envi-met system is adequate to model coffee systems with accuracy, reproducing radiation, temperature, and humidity patterns. This study proposes microclimate model ENVI-met as an option and efficient tool for managing shaded-grown coffee analysis. Additional assessment of the model is necessary, using other data sheets in different environments, crops, and climate conditions to make it largely used in agricultural planning.

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Declarations

Author contribution statement

Priscila P. Coltri: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Hilton S. Pinto, Jurandir Z. Junior: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Renata R. do Valle Gonçalves: Analyzed and interpreted the data; Wrote the paper.

Vincent Dubreuil: Analyzed and interpreted the data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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