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Microclimatic characterization of a conilon coffee plantation grown in an east-west orientation

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Abstract

Plant microclimate is seasonally influenced by the Earth's rotation and the orientation of sun-exposed slopes. As such, understanding the system which constitutes the microenvironment is essential to create strategies to optimize plant performance in a changing environment. The objective of this work was to evaluate the influence of planting coffee in an east-west orientation on microclimatic aspects, plant growth and nutrient content. The experiment was conducted in a farm located in the northern region of the State of Espírito Santo, Brazil. Data collection was carried out on a 30-month old conilon coffee crop under full sun, with spacing of 3.0 m x 1.0 m and a plant height of *ca.* 1.6 m, from December 2016-September 2017. The irradiance, air temperature and vapor pressure deficit variables were reported by means of external data loggers. Leaf temperature (determined using thermal images), plant growth and leaf concentration on both sides of the plant were evaluated. Highest irradiance, air temperature and vapor pressure deficit values were observed on the north side, with the maximal difference reaching 4°C. This microclimate led to the highest leaf temperature on the north side, with a maximal difference of *ca.* 11°C around midday. Differences in macro- and micronutrient leaf concentrations were observed with a trend toward higher values on the north side probably associated with increased transpiration rates due to a high vapor pressure deficit. Higher macro- and micronutrient leaf content led to the better performance of coffee plants on the north side to some extent. There was no significant difference between the two sides of the plant for the growth variables.

Keywords: *Coffea canephora*, irradiance, temperature, vapor pressure deficit.

Introduction

The production and commercialization of coffee represents a significant economic activity for several countries including Brazil, which is the largest producer and the second largest consumer of coffee in the world (ICO, 2018). World coffee production in 2017 exceeded 158 million bags, with approximately 62% of production comprising arabica coffee (*Coffea arabica*) and 38% robusta/conilon (*Coffea canephora*) coffee (ICO, 2018). In Brazil, production in 2017 was 44.9 million bags and conilon production represented 24% of total production, maintaining Brazil's position as the second largest conilon producer in the world (CONAB, 2017).
Solar radiation is the main climatic element responsible for influencing the other meteorological variables. The intensity of the radiation that reaches the Earth's surface is characterized by the movement of the Earth around the Sun throughout the year and by the inclination in its imaginary axis of rotation in relation to the plane of the Earth's orbit (Ferreira et al., 2012). In addition, high temperatures combined with high irradiation values may damage leaves, hindering various foliar metabolic processes and also increasing the yield of highly reactive chlorophyll and oxygen molecules (Ramalho et al., 1998; DaMatta and Ramalho, 2006).
The conilon coffee cultivated at minimum average temperatures lower than 17ºC or maximum averages higher than 31ºC undergoes a decrease in the growth rate, directly damaging production (Partelli et al., 2010, 2013). The coffee crop is exposed to high temperatures that can reach as high as 38°C in the summer, which is the grain-filling phase (Partelli et al., 2010, 2013, 2014). DaMatta and Ramalho (2006) report that extreme temperature and water deficit not only affect growth, but also impact the crop development and productivity. These microclimatic conditions, combined with strong winds and high evapotranspiration rates cause stress to the plant, requiring different techniques to mitigate these problems (Partelli et

al., 2013). In hillside regions, the climatic elements that characterize the microclimate are influenced by the rotation of the Earth, seasonality and the orientation of a slope's exposure to the Sun (Ferreira et al., 2012). In flat regions, the climatic elements are also defined by these characteristics and in this case the orientation in which the crop is inserted is one of the factors that can influence the local microclimate. Accordingly, understanding the system that constitutes the microenvironment is essential to create strategies to adapt to the effects of climate change (Craparo et al., 2017).

Considering the above, several variables can alter the climatic conditions and the response of a coffee crop due to the plant's orientation of exposure to the Sun. In this sense, the understanding and combination of these variables can contribute to more sustainable management of coffee crop. The objective of this work was to evaluate the influence of an east-west plantation alignment on microclimatic aspects and plant growth in order to quantify these variables and to identify their possible effects on the coffee crop.

Results and Discussion

On the dates 12/15, 03/05 and 09/20, the values of average irradiance were similar between the two sides of the plant. This can be explained by the fact that the azimuth representing each alignment for these dates (75-255°, 99-279°, 107-287°, respectively) is close to the alignment that refers to the daily apparent movement of the Sun. This means that on those days when the Sun is at its peak, the radiation is distributed almost equally on both sides in the afternoon and morning (Figure 1). Consequently, the alignment close to the apparent daily movement of the Sun provides greater efficiency in the interception of photosynthetically active radiation, as observed by Cunha and Volpe (2010) in *C. arabica* cv. Obatã IAC 1669-20. Considering that the coffee tree presents a limited distribution of light within the canopy (Rodrigues et al., 2016a), an alignment close to the daily apparent movement of the Sun can improve the photosynthetic efficiency at the plant scale.

On 06/18, the northern side of the plant presented higher values of irradiance throughout the day. This result can be attributed to the fact that the azimuth representing the alignment of this date (48-228°) was further from the alignment of the daily apparent movement of the Sun. As such, the trajectory that the Sun traveled on this date was closer to the north, so higher irradiance values were observed on the north side of the plant.

Lower irradiance values were observed on 06/18 in comparison with the other dates. This occurred because at that time, the Sun is more distant from the zenith. The zenith angle is therefore larger and the Sun's rays fall more obliquely and less intensely on the Earth's surface.

Similar values of mean air temperature on both sides of the plant were found on dates 12/15, 03/05 and 09/20 in the afternoon and morning (Figure 2). On these days, the trajectory that the Sun traverses from sunrise until sunset is very close to the alignment of the crop orientated in the east-west direction. On 06/18, the Sun was not at its peak because its daily trajectory is more to the north. Accordingly, higher mean values of temperature were observed on this side of the plant. A notable difference in the average temperature of up to approximately 4°C between the two sides was observed at 13 hours (h) on 06/18. In addition, the temperatures were numerically smaller in the morning compared with the afternoon, since there is accumulated heat resulting from the heating of the surface by the Sun. Since the VPD depends inversely on the relative humidity and directly on the air temperature, the VPD followed a pattern similar to that of the temperature for the four dates evaluated in this work (Figure 3). High temperatures may cause damage to photosynthetic machinery, due to protein denaturation and the increased permeability of the chloroplast membrane (Dusenge et al. 2018). Conilon coffee plants did not present damage to the photochemical apparatus until they were exposed to 30-37ºC in the long term (Rodrigues et al., 2016b), mainly due to the increase of enzymatic and non-enzymatic antioxidant compounds and by means of protein activity (Martins et al., 2016). On the other hand, it was observed by DaMatta et al., (2012, 2018) that high temperatures can compromise both the fruit set and development, which can result in premature ripening and the generation of fragile fruits, consequently negatively affecting the quality of the beverage. However, Ramalho et al. (2018) did not observe a negative effect on the bean quality. As such, the higher temperature observed on the north side on 06/18 (approximately 35°C) had little or no impact on the productivity and quality of the conilon coffee.

An interaction was observed for the leaf temperature variable on date 12/15, presenting significant differences on both sides of the plant at 8 h and 14 h with higher averages on the south side (Figure 4). Comparing the five schedules in relation to the north side of the plant, the highest significant averages were observed at 12 h and 14 h, as opposed to 14 h on the south side. On 03/05, the averages differed between the two sides at 12 h, 14 h and 16 h with higher values on the north side. Comparing the five schedules with respect to the plant side, the highest significant mean was observed at 12 h on the north and south sides.

On 06/18, there was a statistical difference on both sides of the plant in the five evaluated schedules, where the highest averages correspond to the north side at all times. In relation to the north side of the plant, the highest significant mean was observed at 12 h and 14 h on the south side. Figure 5 illustrates this difference between the five schedules on 06/18. On 09/20, no significant difference was observed for leaf temperature at 8 h and 14 h. The averages of the other schedules were higher on the north side of the plant. Comparing the five schedules, the highest significant mean was observed at 10 h on the north and south sides. The differences of the most notable averages were found on the north side in relation to the south side, reaching an average difference of approximately 11°C between the two sides at 12 h on 06/18.

The highest leaf temperatures corresponded to the times with the highest incidence of direct solar radiation on the sides of the plant. In addition, the increase in leaf temperature coincided with increases in air VPD. This is because coffee plants can reduce stomatal conductance due to increased air VPD (Rodrigues et al., 2016a, 2018). In this study, values close to 5 kPa were found on the north side of the plant on 06/18 and in the afternoon on 03/05. These values were well above the maximum limit (around 2 kPa) reported for coffee (Barros et al., 1997; Rodrigues et al., 2016a; Rodrigues et al., 2018). Since the transpiration rate

Table 1. Sunrise and sunset times, hour angle, sun declination, zenith angle, and solar azimuth for conilon coffee crop cultivated in the east-west alignment.

Date	Sun Hours (h)		Hour Angle	Declination of the Sun	Zenith Angle	Azimuth
	Sunrise	Sunset	(h)	(d)	(Z)	(a)
12/15/2016	05:59	19:14	45°	23.37° S	42.14°	75.33° - 255.33°
03/05/2017	05:41	18:04	45°	6.76° S	45.31°	99.02° - 279.02°
06/18/2017	06:12	17:13	45°	23.41° N	60.72°	48.07° - 228.07°
09/20/2017	05:32	17:37	45°	0.20° S	47.81°	107.38° - 287.38°

Table 2. Leaf concentrations of the N, P, K, Ca, Mg, and S macronutrients (mg kg^{-1}) and micronutrients (g kg^{-1}) B, Cu, Zn, Fe, and Mn on the four dates evaluated (plots) and two sides of the plant (subplots) in a conilon coffee crop cultivated in the east-west alignment.

Date	N		P		K		Ca	
	North	South	North	South	North	South	North	South
12/15	31.62Aa	32.27Aa	1.20Aa	1.13Ab	12.03Bc	15.47Aab	13.25Aa	14.6Aab
03/05	30.53Aa	30.31Aa	1.27Aa	1.24Ba	17.19Aa	16.52Aa	15.16Aa	14.84Aa
06/18	33.21Aa	33.07Aa	1.14Ba	1.22Aab	15.31Aab	15.63Aab	13.69Aa	13.86Ab
09/20	34.87Aa	29.66Ba	1.55Aa	1.22Bab	14.37Abc	14.06Ab	14.22Aa	12.57Ab
CV Plot	6.58%		3.48%		10.07%		8.74%	
CV Subplot.	6.98%		4.05%		7.80%		7.29%	
	Mg		S		B		Cu	
	North	South	North	South	North	South	North	South
12/15	3.76Aa	3.81Aa	1.68Ba	2.29Aa	59.00Aa	61.00Aa	21.50Aa	22.25Aa
03/05	3.97Aa	3.34Ba	1.91Aa	2.06Aa	64.50Aa	61.00Aa	20.75Ba	23.00Aa
06/18	3.83Aa	3.50Aa	2.06Ba	2.44Aa	64.50Aa	65.50Aa	21.00Aa	22.00Aa
09/20	3.51Aa	3.86Aa	2.06Aa	2.26Aa	63.00Aa	58.50Aa	23.75Aa	20.00Ba
CV Plot	9.32%		11.64%		8.65%		6.64%	
CV Subplot.	13.90%		13.75%		7.89%		7.96%	
	Zn		Fe		Mn			
	North	South	North	South	North	South		
1215	13.00Aa	13.25Aa	91.00Aa	90.75Aa	107.75Aa	105.25Ab		
03/05	12.00Aa	11.00Aa	104.75Aa	91.75Aa	111.75Aa	109.75Aab		
06/18	13.25Aa	12.50Aa	120.75Aa	109.00Aa	106.25 Aa	111.00Aab		
09/20	12.00Aa	10.75Aa	110.00Aa	80.00Ba	113.50 Aa	115.50 Aa		
CV Plot	7.88%		17.31%		4.48%			
CV Subplot	10.05%		17.20%		4.21%			

Means followed by the same uppercase letters in rows and lowercase in columns do not differ statistically from each other by the Tukey test at 0.05 probability.

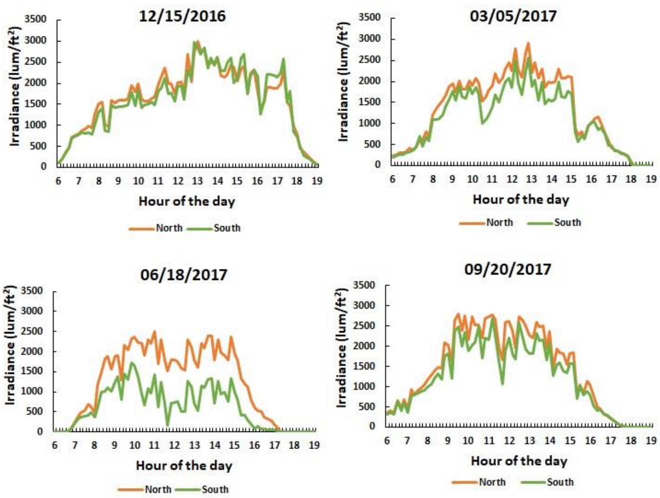

Fig 1. Average daily irradiance for four dates (12/15/2016, 03/05/2017, 06/18/2017, and 09/20/2017) in a conilon coffee cultivated in the east-west alignment.

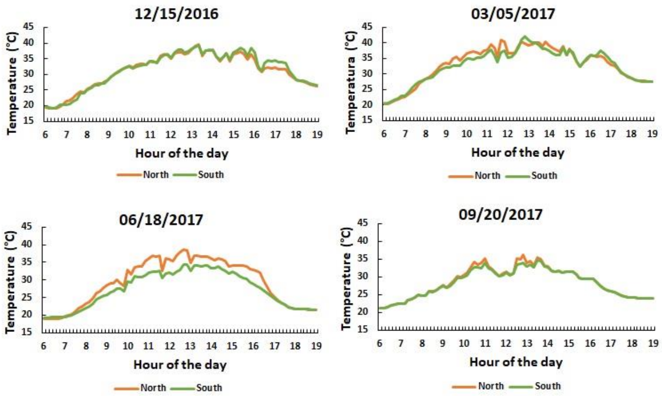

Fig 2. Daily average temperature for four dates (12/15/2016, 03/05/2017, 06/18/2017, and 09/20/2017) in a coffee conilon cultivated in the east-west.

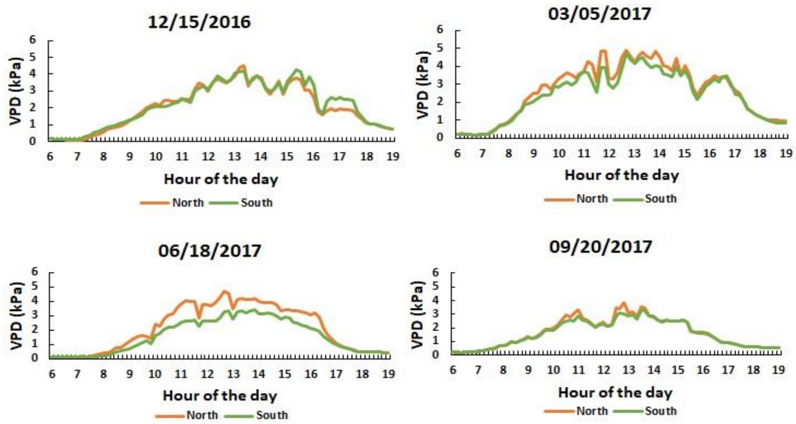

Fig 3. Daily Vapor Pressure Deficit (VPD) for four dates (12/15/2016, 03/05/2017, 06/18/2017, and 09/20/2017) in a coffee conilon cultivated in the east-west alignment.

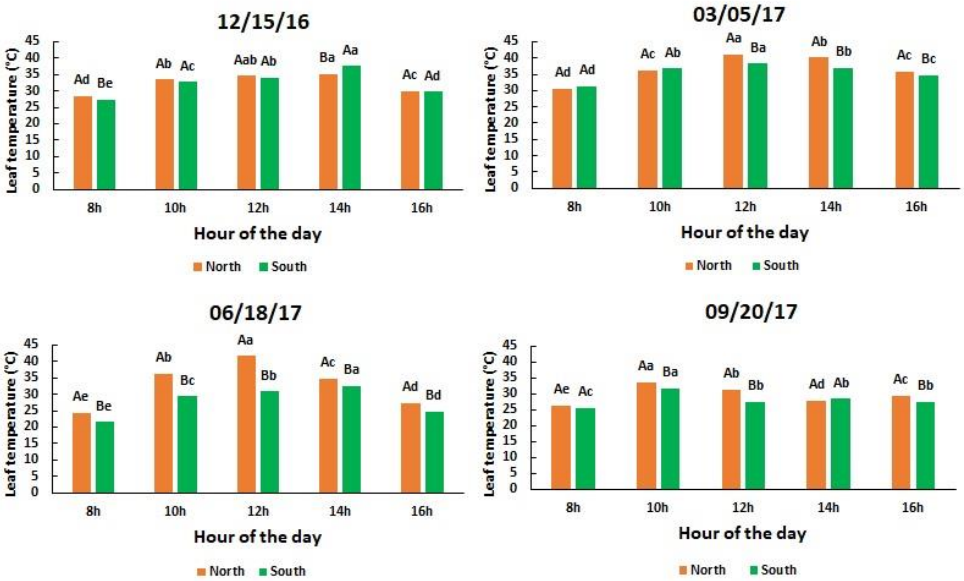

Fig 4. Average leaf temperature at five hours of the day (plots) on both sides of the plant (subplots) throughout the year of a conilon coffee crop cultivated in the east-west alignment. CV (%): Plot 12/15 = 2.63%; Subplot 12/15 = 2.33%; Plot 03/05 = 2.38%; Subplot 03/05 = 1.91%; Plot 06/18 = 2.62%; Subplot 06/18 = 1.93%; Plot 09/20 = 2.63%; Subplot 09/20 = 2.40%. Means followed by the same uppercase letters representing the two sides of the plant, lowercase representing the fifth hour, do not differ statistically from each other by the Tukey test at 5% probability.

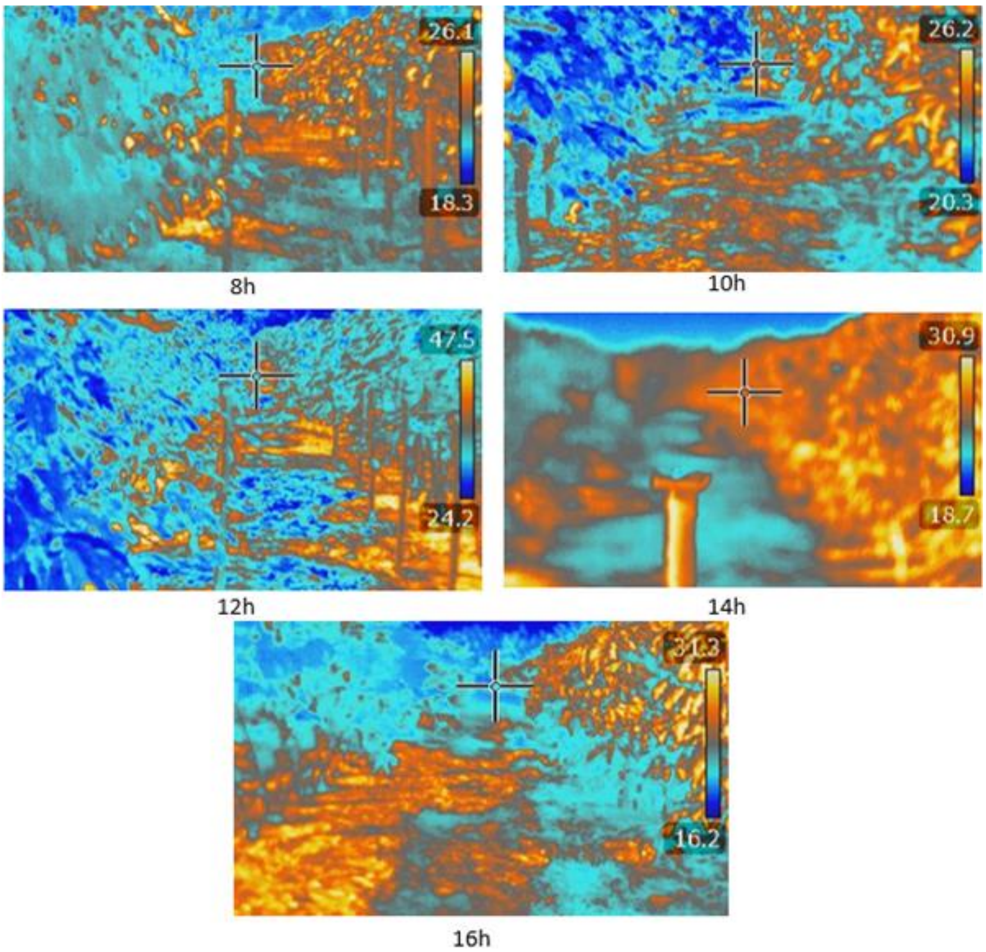

Fig 5. Thermal image of the conilon coffee crop illustrating the north (right) and south (left) side of the plants 8, 10, 12, 14 and 16 h in June 18, 2017 under a clear sky in conilon coffee grown in an east-west alignment. Color bars on the right indicate the maximum and minimum leaf temperature.

contributes to leaf cooling through latent heat loss (Nobel 2009), stomatal closure results in an even greater increase in leaf temperature, which probably occurred at warmer times when the VPD of the air was above 3 kPa.

In addition to physiological effects, air VPD is one of the psychrometric factors that must be evaluated before spraying because values of 0.76-1.90 kPa are characterized as the best spray conditions (Raetano 2011; Minguela et al. 2010; Alvarenga et al. 2014). When evaluating three values of VPD (0.76 kPa, 1.76 kPa and 2.63 kPa), Alvarenga et al. (2014) concluded that as the VPD increases, the droplet density, relative amplitude and droplet size are affected, thus impairing the spray. In this study, values close to 5 kPa were found on the north side of the plant on 06/18 and in the afternoon on 03/05. During this time, greater evaporation occurs and consequently, greater loss of the phytosanitary product. This suggests a lower efficiency of applications during this period, or even the recommendation that spraying be avoided during these periods.

No significant difference was observed between the treatments for the length variables of plagiotropic and orthotropic branches, the number of nodes per plagiotropic branch and branch elongation (data not shown). As such, the most unfavorable microclimate in the hotter hours of the north side on 06/18 was not sufficient to impair the coffee growth of the coffee. This result may have suffered interference from the time this occurred, since it coincided with the vegetative rest period of conilon coffee (Partelli et al. 2010; Covre et al. 2016).

Among the analyzed nutrients, the B and Zn leaf concentration did not show significant interaction with the four evaluated dates and the two sides of the plant (Table 2). The means of the nutrients Ca and Mn were not statistically different between the two sides of the plant, but on the south side, the means on the four evaluated dates were different, presenting a higher mean Ca on 03/05 and a higher mean Mn on 09/20. On the north side of the plant, K was the only nutrient that presented a statistical difference between the four dates evaluated, with a higher value on 03/05. On the southern side, different means were obtained for the nutrients P, K, Ca and Mn on the four dates (Table 2).

On 12/15, only K and S were statistically different on both sides of the plant, presenting higher values for the side of the plant facing south. On 03/05, P and Cu differed from each other and presented larger values on the south side, unlike Mg, the highest value of which pertained to the leaves on the north side of the plant. On 06/18, when the Sun shone directly on the north side of the plant, P and S were statistically different and presented higher averages on the south side of the plant. On 09/20, N, P, Cu and Fe differed between the two sides, in which the leaf concentration of N, Cu and Fe was higher on the north side and P was higher on the south side.

On the north side of the plant, K was the only nutrient that presented a statistical difference between the four evaluated dates, with a higher value on 03/05. On the south side, the nutrients P, K, Ca, and Mn had different means on the four dates. On 12/15, only K and S were statistically different on both sides of the plant, presenting higher values for the plant side facing south. On 03/05, P and Cu differed from each other and higher values were obtained on the south side, unlike Mg, where the highest value was observed for the leaves on the north side of the plant. On 06/18, when the Sun shone directly on the north side of the plant, P and S differed significantly and presented higher averages on the south side of the plant. On 09/20, N, P, Cu and Fe differed between the two sides, with the leaf concentration of N, Cu and Fe higher on the north side and P higher on the south side.

In general, a trend was observed for higher nutrient values on the north side of the plant, except for S and N. This is likely related to differences in the transpiration rates associated with the microclimate. Accordingly, the north side may have presented, since many of the evaluated nutrients are absorbed with mass flow (Marschner 2011). The increase of the macro and micronutrients content in *C. arabica* (cv. Icatu and IPR 108) and *C. canephora* (cv. Conilon Clone 153) with increasing temperature up to 42/37 ºC (day/night) was also observed by Martins et al. (2014). In addition, greater translocation of nutrients to the north side may contribute to the reduction of stress at the cellular level because of its participation in stress signaling pathways (particularly Ca), as well as its participation as cofactors in enzymatic complexes, namely Cu, Fe and Mn (Marschner 2011). Despite the observed differences, the values of the nutrients found in this study are within the range considered adequate for the coffee tree (Partelli et al. 2016) and as such did not influence the different growth variables evaluated.

Materials and Methods

Experimental area, plant material, growth conditions and microclimate variables

The experiment was conducted in a rural property located in the northern region of Espírito Santo in the municipality of Boa Esperança (18° 31' 06.01" south latitude and 40° 20' 36.17" west longitude) at an altitude of 146.3 m above sea level and on flat terrain. According to the classification of Köppen (Alvares et al. 2013), the climate of the municipality is classified as Aw - tropical humid with dry winter and hot and humid summer. The study was carried out from December 2016-September 2017.

Data collection was carried out in a conilon coffee plantation (*Coffea canephora*) at two years and six months of age at the beginning of the experiment in full sun with spacing of 3.0 m x 1.0 m and a height of approximately 1.6 m. It was maintained under conventional sprinkler irrigation and oriented in an east-west alignment.

Four alignments were determined for the coffee plantation according to four dates throughout the year: 12/15/2016, 03/05/2017, 06/18/2017 and 09/20/2017. The four alignments were calculated by determining the position of the Sun at a given time for a given location and date by using the zenith angle.

The 9 h time was established for calculation purposes as for a given latitude and date, the positioning of the Sun at this time will form a 45°-hour angle with a reference point on Earth. At this point, there is a greater availability of solar radiation due to the maximum angular displacement of the Sun (Cunha et al. 2011).

The four alignments were determined from the calculation of the azimuth of the Sun, based on the angle in the horizontal plane between the projection of the radius of the sun and the north-south cardinal direction in relation to the zenith angle. This is because it is responsible for defining the position of the Sun in relation to the local vertical plane. The azimuth characterizing each alignment for the established dates, sunrise and sunset times, hour angle, sun declination and zenith angle is therefore presented in Table 1.

The climatic data were obtained by measuring the variables irradiance (lum ft^{-2}), temperature (°C) and relative humidity (%). These variables were acquired through external data loggers (HOBO U12 Temp/RH/Light/External Data Logger) that were implanted at 1.20 m above the plant lines and in two different positions per plant: the north side and the south side. The device was programmed to record the data every 10 minutes, between 6 h and 19 h.

The vapor pressure deficit (VPD) was determined from the data of the relative humidity and air temperature obtained in the microclimatic evaluations, according to the model proposed by Tetens (1930).

Leaf temperature, plant growth and leaf nutrient content

To determine leaf temperature, thermal images were obtained using a Flir T440 infrared camera with a thermal resolution of 76800 pixels and a thermal sensitivity of 0.035°C. Newly expanded leaves were randomly selected in the upper third of the plant in order to quantify their point temperature on the sides of the plant facing north and south. The experimental design was divided into split plots, where the plots comprised the five schedules of the evaluations: 8 h (T1), 10 h (T2), 12 h (T3), 14 h (T4), and 16 h (T5), and the subplots constituted both sides of the plant (north and south). The experimental plot consisted of eight plants (replicates), in which growth, branch elongation, number of nodes per branch and microclimatic evaluations were performed.

Plant growth was measured from plagiotropic and orthotropic branches containing two to three nodes. The measurements were carried out on both sides of the plant on the same day of the first and last climatic evaluation, using a graduated ruler. The number of nodes on the plagiotropic branches was identified on each side of the plant on the last day of the experiment. The experimental design used in these evaluations was completely randomized.

Four leaves were collected on each side of the plant with four replicates to analyze the leaf concentration. The third and fourth leaves were collected from the apex of the branches. The leaves were stored in designated paper containers and sent to a plant tissue analysis laboratory for analysis of the following nutrients: N, P, K, Ca, Mg, S, B, Cu, Zn, Fe and Mn, in accordance with Silva (2009). The experimental design was conducted in subdivided plots, where the plots corresponded to the four dates evaluated and the subplots on both sides of the plant (north and south).

Statistical analysis

Experimental data on leaf temperature, growth, branch elongation and concentration were subjected to an analysis of variance and the averages were compared by Tukey's test at 5% probability, using the Genes statistical program (Cruz 2013).

Conclusion

Our results showed that the north side of the plant presented higher irradiance, air temperature and VPD values, reaching an air temperature difference of 4°C between the two sides. Leaf temperature behaved similarly to air temperature, reaching a difference of approximately 11°C between the two sides at noon, with higher stress observed on the north side of the plant. Together, these differences led to a tendency toward the highest leaf nutrient content on the north side. However, on both sides macro- and micronutrients were kept within the range considered suitable for conilon coffee trees, so that there was no significant difference between the two sides for the evaluated variables that characterize the plant's growth.

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