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Article

A Spatial Analysis of Coffee Plant Temperature and Its Relationship with Water Potential and Stomatal Conductance Using a Thermal Camera Embedded in a Remotely Piloted Aircraft

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Abstract: Coffee is a key agricultural product in national and international markets. Physiological parameters, such as plant growth indicators, can signal interruptions in these processes. This study aimed to characterize the temperature obtained by a thermal camera embedded in a remotely piloted aircraft (RPA) and evaluate its relationship with the water potential (WP) and stomatal conductance (gs) of an experimental coffee plantation using geostatistical techniques. The experiment was conducted at the Federal University of Lavras, Minas Gerais, Brazil. A rotary-wing RPA with an embedded thermal camera flew autonomously at a height of 10 m and speed of 10 m/s. Images were collected on 26 November 2019 (rainy season), and 11 August 2020 (dry season), between 9:30 am and 11:30 am. Data on gs and WP were collected in the field. The thermal images were processed using FLIR Tools 5.13, and temperature analysis and spatialization were undertaken using geostatistical tools and isocolor maps by Kriging interpolation in R 4.3.2 software. Field data were superimposed on final crop temperature maps using QuantumGIS version 3.10 software. The study found that with decreasing WP, stomatal closure and reduction in gs occurred, increasing the temperature due to water deficit. The temperature distribution maps identified areas of climatic variations indicating water deficit.

Keywords: unmanned aircraft systems; stomatal conductance; water potential

1. Introduction

The coffee-production chain plays a key role in national and international agriculture, contributing directly to the global economy. The estimated Arabica production of coffee (*Coffea* spp.) for the 2024/2025 harvest on a world scale is 99.85 million bags (60 kg); within this estimate Brazil has a significant participation and occupies first position, contributing 48.2% of world coffee production [1]. In national production, the state of Minas Gerais has a significant participation, contributing 30.18 million bags of processed grain, which represents 51.3% of the country's total production [2].

Therefore, precautions are needed to ensure the quality standard and quantity of grain production. According to Voltolini [3], factors such as nutrition, water relations, and soil characteristics may affect fruit yield and quality. In periods of high drought, if irrigation is not used, yield can be reduced by up to 80% [4].

To minimize this water deficit and avoid losses in the growth of coffee plants, water optimization measures are being studied. According to Castanheira [5], the use of soil cover in coffee plantations, whether vegetable plants such as Brachiaria grass or artificial means such as polyethylene film, has shown a beneficial effect, both for soil characteristics and for plants. According to the same authors, agronomic techniques such as controlled-release fertilizers and soil conditioners can mitigate water deficit in coffee plants.

A reduction in transpiration rates is a marked response of plants subjected to water deficit [6]. According to Almeida [7], stomatal opening causes the loss of water from the plant to the external environment; thus, in hot periods, the stomata remain closed, and the photosynthetic rate decreases. This stomatal closure mechanism causes a reduction in stomatal conductance (gs), which contributes to the reduction or maintenance of the leaf water potential (WP) [8].

Geostatistics is a tool that allows the estimation of values in non-sampled locations, generating maps with continuous data in space and allowing the spatialization of the variable of interest [9]. However, the need for a dense sampling grid is a problem, with remote sensing (RS) being an alternative for obtaining data [10].

The RS obtains information about an object from a distance through sensors coupled to a platform such as a satellite at the orbital level or a remotely piloted aircraft (RPA) at the aerial level. Given the above, the monitoring of water conditions using RS has high potential because it is low cost, fast, and nondestructive [11].

Studies carried out by Santos [12] evaluated the spatial and temporal behavior of WP in coffee plantations through geostatistical analysis and the use of high-resolution images obtained by an RPA. However, the authors found a low correlation between WP vegetation indices obtained by the multispectral camera, suggesting that vegetation indices were not as effective in assessing water conditions in coffee plants. Therefore, it is necessary to expand studies using thermal cameras.

According to Viana [13], the use of thermal cameras in agriculture has wide applicability, and phenomena ranging from water stress to damaged fruits can be evaluated. According to the authors, Brazil still lacks advances in research using thermal sensors in agriculture, and there is capacity for expansion and development.

The use of RPA and thermal cameras offers a practical, scalable, and low-cost solution for agricultural monitoring. Unlike orbital sensors, which can be expensive and have lower spatial resolution, and ground-based sensors, which require dense manual sampling and are limited in terms of geographic coverage, RPA equipped with thermal cameras allow for rapid and accurate assessment of crops. This technology is particularly useful in regions of extensive coffee cultivation, such as Minas Gerais, where optimizing irrigation and efficient water management are crucial for productivity.

Additionally, thermal cameras have the ability to detect subtle temperature variations in plants, which can indicate the onset of a water deficit before visual symptoms manifest and offer a proactive tool for agricultural management. Previous studies using multispectral cameras have shown limitations in the correlation with water potential [10], reinforcing the need to explore new technologies, such as thermal cameras, which are more promising in detecting thermal variations directly related to water stress.

Embedding sensors, such as visible spectra and multispectral and/or thermal cameras in RPA, can facilitate the evaluation of the water conditions of coffee plants, providing better management and decision making in relation to agricultural practices. Therefore, studies with this type of technology should be explored to generate discussion and fill gaps.

Given the above, this study aimed to characterize the temperature obtained using a thermal camera embedded in an RPA and to evaluate its relationship with the WP and gs of an experimental coffee plantation using geostatistical techniques.

2. Materials and Methods

2.1. Study Location

The study was conducted on an experimental coffee (*Coffea arabica* L.) plantation located in the coffee sector of the Department of Agriculture (DAG) at the Federal University of Lavras (Universidade Federal de Lavras—UFLA), in Lavras, MG, with the cultivar "Mundo Novo 379-19", spaced at 3.6 m between planting rows and 0.75 m between plants, conducted in the dryland system (not irrigated), and with the planting taking place in January 2016. The crop occupied an area of 0.48 ha. Experimental treatments related to water optimization in coffee production have been described by Castanheira [5] and Alecrim [14]; however, these treatments were not considered as independent variables in the analysis of the results, the area being addressed as a whole. The study area as well as the 90 plants used in the study were georeferenced using a differential global positioning system (DGPS; Trimble Navigation Limited, Sunnyvale, CA, USA), with a horizontal and vertical accuracy of 0.007 m (Figure 1).

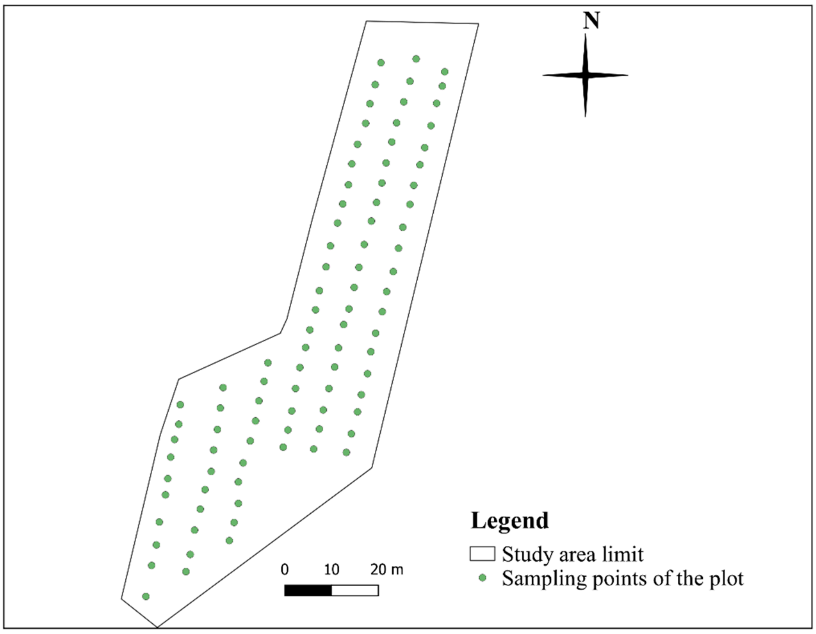


Figure 1. Limit of the study area and location of the sampling points of each plot.

2.2. Measurements of the Physiological Response

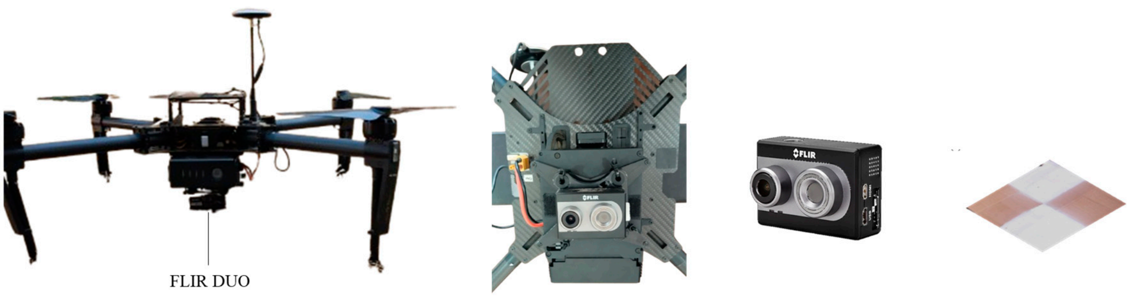
The physiological characteristics (stomatal conductance and leaf water potential) were measured on 26 November 2019 (rainy season) and 11 August 2020 (dry season) in 90 plants distributed in the experimental area. For the evaluations, leaves located in the middle third of the plant, from the third or fourth pair of leaves from the apex of the plagiotropic branch, were fully expanded and free of pests and diseases.

For the evaluation of leaf gs (mmol m^{-2} s^{-1}), a porometer (SC-1, Decagon Devices, Pullman, WA, USA) was used. The readings were taken in the two study periods concomitant with the collection of RPA images in the period between 9:00 am and 11:00 am, according to the methodology of Santos [10].

For the evaluation of leaf WP (MPa), a Scholander pressure chamber (Model 1000, PMS Instrument Company, Albany OR, USA), with operation up to 70 bars, was used. The leaves collected in the field were inserted into the chamber, and subsequently pressure was applied until exudation occurred from the cut leaf petiole. The leaf WP was determined in the morning (3 h to 5 h in the morning).

2.3. RPA Data Collection

To obtain thermographic images of the crop, an RPA (Matrice 100, DJI Innovations, Shenzhen, China) (Figure 2a,b), classified as a rotary-wing platform with four propellers, was used. The RPA was equipped with a DUO model FLIR thermal camera, with a size of 41 × 59 × 30 mm, a weight of 84 g, a visible spectrum sensor, and another in the thermal spectrum ranging from 7.5 to 13.5 µm (Figure 2c). The thermal spectrum resolution was 160 × 120 pixels, a low resolution, and it was possible to record temperature values from −20 to 60 °C with an accuracy of ±5 °C. However, this camera captured the visible RGB spectrum (red—R, green—G, and blue—B) with a resolution of 1920 × 1080 pixels; thus, it had the ability to produce a hybrid image, improving the identification of targets and compensating for the low thermal spectrum resolution. The thermal camera has an internal recalibration system, known as flat-field correction, which uses an internal shutter operating automatically based on the camera's internal parameters and can be initiated using the recalibrate button [15]. This procedure was carried out before measurements as per the suggestions in the camera's instruction manual.



(a) (b) (c) (d)

Figure 2. Equipment: (**a**) RPA (Matrice 100) used for the survey with a thermal camera attached; (**b**) bottom view of the equipment detailing the camera; (**c**) the thermal camera, FLIR DUO (Inc., Boston, MA, USA); (**d**) an example of the control plates used in the study area.

Image acquisition occurred on 26 November 2019 (rainy season), and on 11 August 2020 (dry season), between 9:30 am and 11:30 am, thus allowing for a comparative effect between thermal data and physiological measurements that were also collected in the morning. Before each flight, white and brown control plates were placed in each experimental plot to be highlighted in the images (Figure 2d). The plates were used to enable the location and identification of the 90 plants sampled in the experimental area. To collect the images, the area was divided into 3 parts so that there were 30 plants in each part. The images were obtained at a height of 10 m above ground level and at a speed of 10 m/s. The flights were planned using the application Precision Flight 2.4.2 a free Android-based software. The captured images were stored on an SD card, and the temperature of the plots was analyzed using the software FLIR Tools 5.13.

2.4. Meteorological Data

Monthly meteorological data including total rainfall (mm), relative humidity (RH, in %), minimum temperature (T Min, in °C), and maximum temperature (T max, in °C) were obtained from the meteorological station of the National Institute of Meteorology (Instituto Nacional de Meteorologia—INMET) at the Federal University of Lavras (Universidade Federal de Lavras—UFLA) from 1 November 2019 to 31 August 2020 (Figure 3).

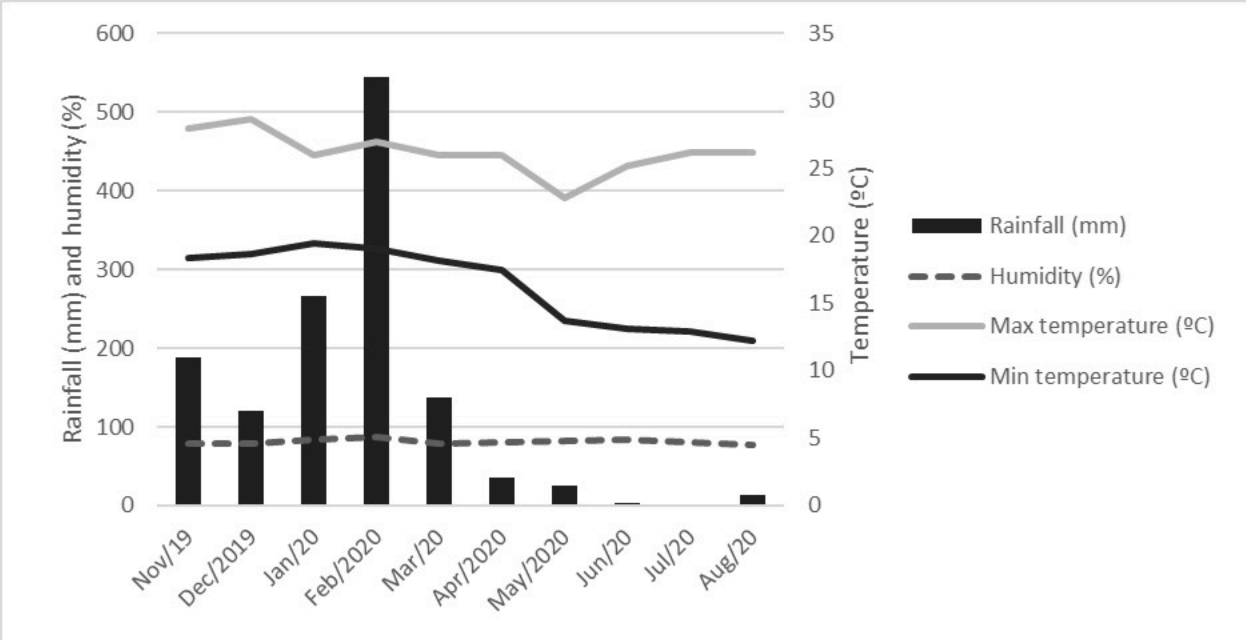


Figure 3. Graphical representation of the meteorological variables recorded monthly in Lavras, MG, from November 2019 to August 2020.

2.5. Analysis and Validation of the Models

With the data of the images obtained for each plot, a study of the variability of the temperature in the area was performed. For this purpose, geostatistics and Kriging interpolation were used. This analysis was performed to obtain a temperature map for the entire study area because the camera did not have geotagging, i.e., geographic position information, capabilities, and it was not possible to obtain a map or a thermographic photo of the entire area.

The spatial dependence of the temperature data of the dry and rainy seasons was analyzed using a classic semivariogram [16].

The model was fitted by eye, with the best being the Gaussian model described by Oliver and Webster [17] (Equation (1)):

$$\hat{\gamma}(\mathrm{h}) = \begin{cases} 0 \text{ if } |\mathrm{h}| = 0 \\ \mathrm{C}\left[1 - \exp\left(-\frac{|\mathrm{h}|^2}{a\prime^2}\right)\right] \text{ if } |\mathrm{h}| < 0 \end{cases} \quad (1)$$

where h is the distance between the samples, C is the sill, and a is the practical range of the spatial dependence.

According to Mendes [18] and Ferreira [19], the Gaussian model is characterized by a spatial dependence with low variations between the nearest neighbors and larger variations for the more distant neighbors. Therefore, the model is justified because temperature has such characteristics.

To estimate the model parameters, the maximum likelihood (ML) method was used. Once the model was chosen, the distribution of the semivariance of the data was used to estimate the model parameters.

Once the best model and its estimated parameters were chosen, the suitability of this model was verified through cross-validation (CV). According to Isaaks and Srivastava [20], CV is a technique that allows errors to be estimated by comparison to the predicted values of those sampled. These analyses were based on the studies [21–23].

After the semivariogram function was fitted, the data were interpolated by ordinary Kriging, and the map of the spatial distribution of the temperature was subsequently generated. The degree of spatial dependence (DSD) was evaluated according to Cambardella [24].

Data on leaf WP and gs were integrated with the final temperature maps to assess the water conditions of the coffee plants. This integration allowed for a comprehensive analysis of the interplay between environmental variables and physiological responses in coffee plants. In addition to analyzing temperature variability, this study examined the relationship between temperature distribution and gs and temperature and WP of coffee. Data gs and WP were collected alongside temperature measurements to explore how these variables influence the temperature distribution across different environmental conditions. For this purpose, Pearson's correlation (r) between temperature and gs and temperature and WP in both seasons was analyzed.

All analyses were performed in the statistical software R (R Development Core), while geostatistics were performed using the geoR version 1.9 package [25]. QGIS version 3.10 software (Quantum GIS Development Team) was used to prepare the map layouts. The data on leaf WP and gs were crossed and overlapped in the final temperature maps for a better evaluation of the water conditions of the coffee plants.

3. Results

3.1. Geostatistical Analysis

The geostatistical analysis of temperature variability provided valuable insights into the influence of environmental conditions on coffee plant physiology. The models and parameters of the experimental semivariograms fitted to the temperature in the crop are shown in Table 1.

Table 1. ML method, Gaussian model, and estimated parameters of experimental semivariograms for temperature in coffee plantations during the rainy season (November) and the dry season (August).

Day	C_0	C_1	$C_0 + C_1$	a (m)	DSD		ME	SDME	RE	SDRE
26 November 2019	0.64	5.66	6.29	9.50	90%	strong	−0.02	1.19	−0.01	1.00
8 November 2020	2.06	6.27	8.34	9.69	75%	moderate	0.02	1.95	0.00	1.02

C_0—nugget effect; C_1—contribution; $C_0 + C_1$—threshold; a—range; DSD—degree of spatial dependence; ME—mean error; SDME—standard deviation of mean error; RE—reduced mean error; SDRE—standard deviation of reduced mean error.

Table 1 shows the values of the nugget effect (C_0) in the different periods analyzed. This value indicates unexplained variability considering the sampling distance used [26]. In the rainy season, the C_0 value was lower than that in the dry season, which can be attributed to macrovariability; i.e., the spatial variability of the temperature in the dry season was higher than that established by the spacing of the samples and/or due to the high variation in temperature amplitude that occurred in this winter period.

The values of the range (a) of the semivariogram (Table 1) for the two periods were similar; thus, the samples were distanced to a value of a′, for which the distance no longer had an influence, resulting in stability in the experimental semivariogram. Studies conducted by [21] corroborate this semivariogram behavior.

In the data analysis, it was found that the temperature values in the rainy season showed strong spatial dependence according to the classification by [24], whereas the temperature values in the dry season showed moderate spatial dependence according to the same classification.

Note that in both study periods, the fit of the experimental semivariogram showed mean error (ME) and reduced error (RE) values close to zero. This result is in agreement with the recommendations by Ferraz [21] and indicates the quality and efficiency of the analyses [23,27].

For the dry period, the temperature presented a CV of 12%, and for the rainy period it presented a CV of 8%, presenting low variability for both periods, according to the criteria of Gomes and Garcia [28].

Spatial temperature variability was found in the fit of the semivariogram in the geostatistical analyses in both periods studied. The temperature showed a nonhomogeneous distribution, and this variability can be observed in Figure 4.

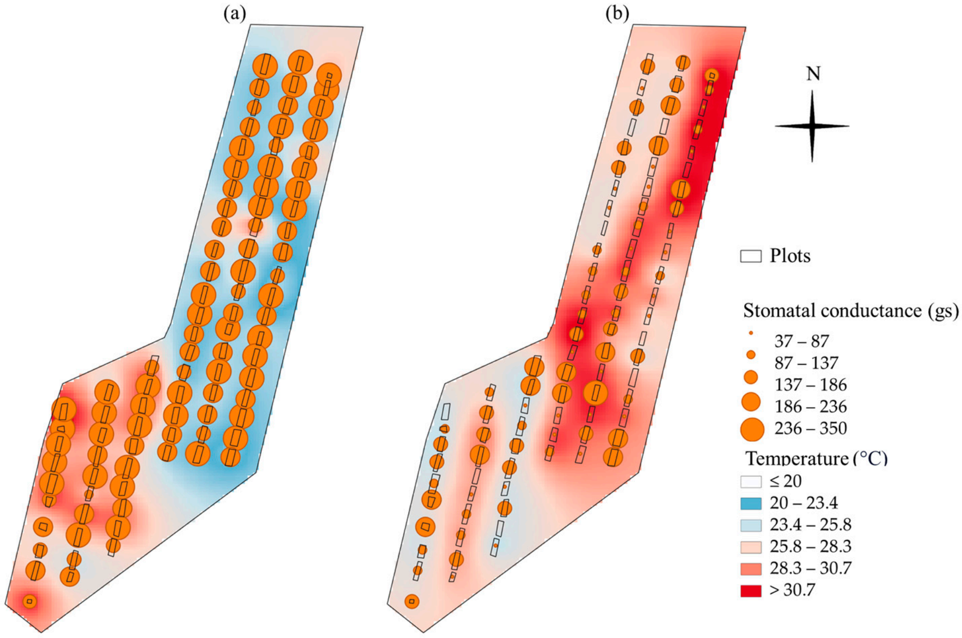


Figure 4. Spatial distribution of the temperature and stomatal conductance (gs) of coffee plants in the (**a**) rainy season; (**b**) dry season.

In the rainy season (Figure 4a), the temperature ranged from 24.5 to 32.9 °C, and the average temperature was 28.4 °C. The highest temperature values were observed in the lower left or southwestern part of Figure 4a. The areas to the southeast and north of the figure showed a light blue color, with milder temperatures. The studies conducted by Crusiol [12] are in line with the observations of this study; the authors, when using thermal imaging coupled to an RPA, observed that plants subjected to greater water availability had the lowest canopy temperatures.

In the dry season (Figure 4b), the temperature ranged from 21 to 33.1 °C, and the average temperature was 25.6 °C. The highest temperature values are represented by the most intense red color in Figure 4b. In the lower or southwestern parts of Figure 4b, the temperature was milder, represented by a light blue color. According to studies by Crusiol [12], plants subjected to water deficit had the highest canopy temperatures. These results are corroborated by this study.

When the gs was evaluated in the two study periods, it was possible to observe that with decreasing water availability (drought period) (Figure 4b) the gs values decreased considerably in most plots, favoring an increase in temperature (Figure 4a,b).

When the WP values were evaluated in the two study periods, it was noted that the WP values decreased from the rainy season to the dry season in most plots (Figure 5a,b), also favoring the increase in leaf temperature.

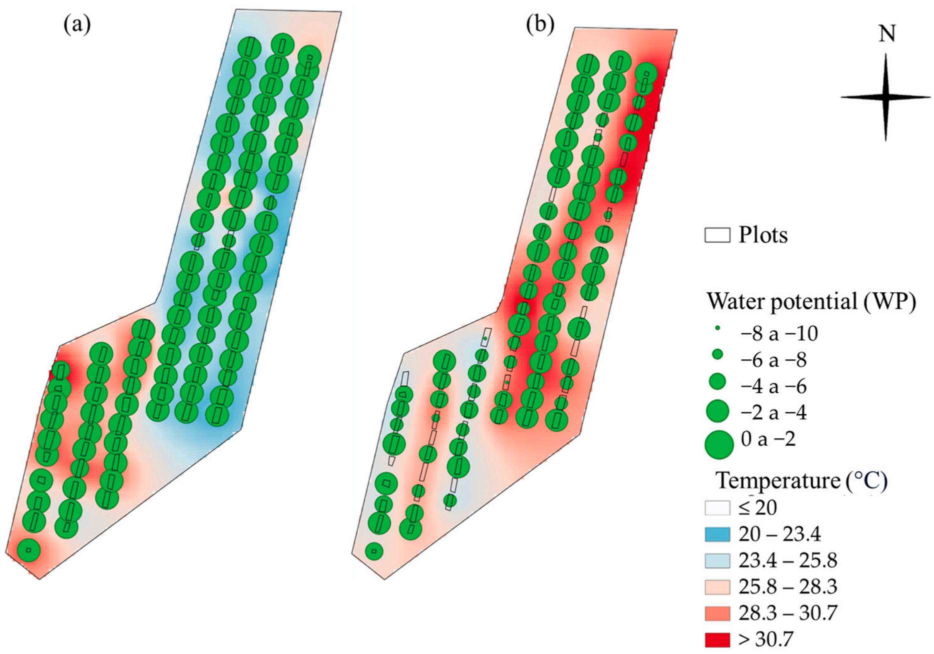


Figure 5. Spatial distribution of temperature and water potential (MPa) of coffee plants. (**a**) rainy season; (**b**) dry season.

3.2. Correlation Analysis between Temperature, gs, and WP

The results of the correlation analyses between temperature, stomatal conductance, and water potential show correlations classified as weak in both seasons (Figure 6). During the rainy season, the correlation between stomatal conductance and temperature was −0.112, indicating a weak and negative relationship, suggesting that the increase in temperature is slightly associated with a reduction in stomatal conductance. In the dry season, the correlation was 0.103, also considered weak and positive, indicating a small tendency for conductance to increase with increasing temperature. For water potential, the correlation with temperature was 0.286 during the rainy season, still classified as weak, but closer to the upper limit of this category, reflecting a slightly more noticeable relationship. In the dry season, the correlation was 0.161, also classified as weak. These results indicate that, in both seasons, the relationships between temperature and the physiological variables analyzed are weak, suggesting that other factors may have a greater impact on these interactions.

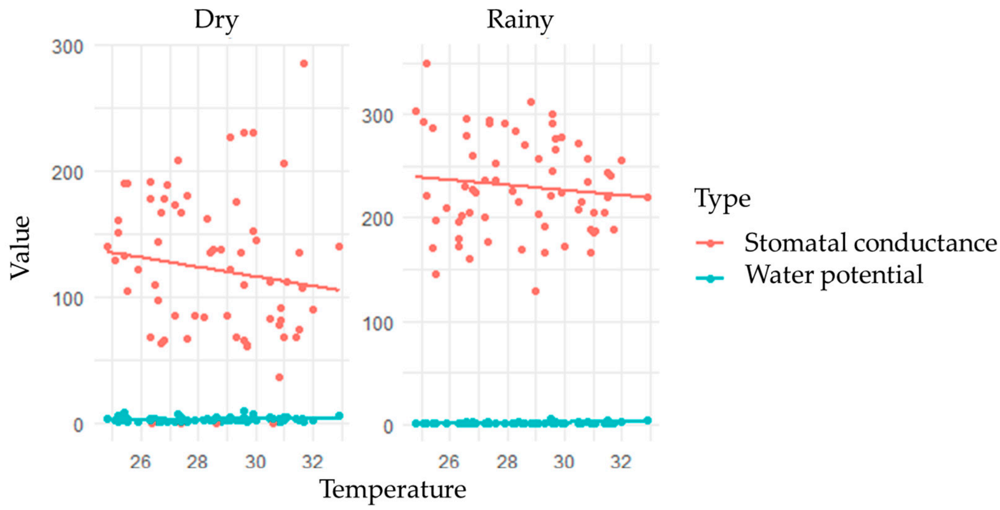


Figure 6. Regression and correlation between temperature and water potential (WP) and temperature and stomatal conductance (gs) of coffee plants in the rainy season and dry season.

4. Discussion

In the rainy season, the C_0 value was lower than that in the dry season, which can be attributed to macrovariability; i.e., the spatial variability of the temperature in the dry season was higher than that established by the spacing of the samples and/or due to the high variation in temperature amplitude that occurred in this winter period.

The values of range (a) for the two periods were similar; thus, the samples were distanced to a value of a′, for which the distance no longer had an influence, resulting in stability in the experimental semivariogram. Studies conducted by [21] corroborate this semivariogram behavior.

Spatial temperature variability was found in the fit of the semivariogram in the geostatistical analyses in both periods studied. The temperature showed a nonhomogeneous distribution, and this variability can be observed in Figure 4. This result can be attributed to variations in characteristics such as gs and WP due to the physiological responses of plants. In addition, the analysis of the spatial variability of the temperature allows us to see the sites that show an increase in leaf temperature. This observation from isocolor maps may indicate water deficiency due to this temperature increase causing closing of the stomata to avoid greater water losses by transpiration [29].

The studies conducted by Crusiol [12] are in line with the observations of this study; the authors, when using thermal imaging coupled to an RPA, observed that plants subjected to greater water availability had the lowest canopy temperatures. According to studies by Crusiol [12], plants subjected to water deficit had the highest canopy temperatures. These results are corroborated by this study.

This response is expected in plants subjected to water deficit. These results are in agreement with those of [30]; the authors state that during a period of water deficit, gs decreases with decreasing soil water content. According to Cornic [31], plants subjected to water deficit show a decrease in gs; this is considered one of the first strategies of the plant to prevent excessive dehydration of the leaves. With the lower water availability in the dry period (Figure 3), the stomata do not open or open less as a defense mechanism against the water deficit, thus avoiding dehydration [32]. As a result of this plant defense mechanism, there was an increase in leaf temperature during the dry season.

The WP indicates the plant's energy state; it is related to the water flows in the soil–plant–atmosphere system and indicates the difference between the energy state in the considered system and in a reference state conceptualized as zero [30]. It is a physiological parameter used as an indicator of water stress in coffee plantations. According to Costa and Marenco [33], the WP decreases if the plant loses water at a rate higher than its absorption and transport capacity, resulting in the closure of stomata and a reduction in photosynthesis, which leads to an increase in leaf temperature. Therefore, this increase in plant temperature was observed due to the reduction in the WP values for the period in which the coffee plant was exposed, with low water availability (Figure 3).

This result was expected because with the reduction in WP (Figure 5b) stomatal closure and a reduction in gs occurred (Figure 4b), favoring an increase in temperature due to water deficit (Figure 3). The opposite was also true; an increase in WP (Figure 5a) favored an increase in gs (Figure 4a), leading to a decrease in temperature due to greater transpiration and water availability in the soil. These results confirm the results obtained by Dominghetti [34], in which the authors observed that with increasing soil water availability, the WP values increased.

Often, plants open their stomata to decrease the leaf temperature by transpiration when subjected to high air temperatures. However, they are unable to perform this stomatal opening when subjected to combined high-temperature and dry conditions [35]. As a result, the temperature of the leaves remained high, as shown in Figures 4b and 5b. This result occurred in the winter period, which was the period that showed high variation in thermal amplitude and water unavailability. Thus, the combination of heat and drought may be more detrimental to the growth and productivity of coffee plants than when these stresses occur individually [35].

The results of the correlation analysis between temperature and physiological variables, such as stomatal conductance and water potential, show that these relationships are classified as weak in both the rainy and dry seasons. According to Callegari-Jacques [36], values between 0 and 0.30 are classified as weak, 0.30 and 0.60 as regular, and 0.60 to 0.90 as strong. This weak correlation indicates that temperature, although influential, is not the sole determinant of variations in stomatal conductance and water potential. Additional factors, such as soil water availability, soil composition, and agricultural management, may play a significant role in determining these physiological variables.

Despite the weak overall correlation between temperature and the physiological variables, geostatistical analysis provides an important advantage by offering a detailed understanding of the spatial variability of these factors. Even with a weak correlation, there may be local spatial patterns that are not evident in traditional correlation analyses. Geostatistics can reveal specific areas where temperature and stomatal conductance or water potential are more closely related, which can be crucial for understanding crop dynamics in different microenvironments within the field.

Spatial analysis of variables with weak global correlation can also aid in identifying environmental or management factors that may be masking stronger relationships at local scales. Using detailed spatial maps can help visualize these variations and identify specific locations that require further investigation or targeted interventions, such as adjusting irrigation practices or applying fertilizers.

Moreover, spatial analysis can be used to develop more complex models that capture nonlinear interactions and spatial dependencies. These models can be more effective in predicting crop responses to environmental conditions, especially in scenarios of climate change. By incorporating spatial variability, agricultural producers can optimize management practices to improve resource efficiency and increase crop productivity.

In summary, although the correlation between temperature and physiological variables is weak, the application of spatial geostatistics offers a rich and detailed perspective on field variability. This approach can not only reveal hidden patterns but also provide valuable insights for agricultural management and decision making, contributing to more precise and sustainable agriculture.

In addition, the results of this study provide significant advancements in the field of remote sensing and temperature monitoring of coffee plants using thermal cameras [37]. The application of geostatistical techniques to thermal images has proven effective in identifying spatial temperature variability within coffee plantations. This precise mapping allows for the identification of areas experiencing water deficit or stress, correlating temperature with physiological parameters such as gs and WP. Such non-invasive monitoring offers a practical and cost-effective method for large-scale agricultural surveillance, utilizing inexpensive thermal cameras embedded in RPA.

5. Conclusions

It was possible to observe the spatial distribution of the temperature with a thermal camera embedded in an RPA. The temperature distribution maps allowed visualization of the heterogeneous spatial distribution, in addition to identifying areas where the plants were exposed to conditions of climatic variations, which may indicate water deficit.

With the data from gs, WP, and the temperature maps, it could be observed that with decreasing WP, stomatal closure and a reduction in gs occurred, favoring an increase in temperature due to water deficit. Such results may help producers to identify, in a clear and fast manner, water variations in crops, thus allowing them to adopt irrigation management for the crop.

Despite weak correlations between temperature and physiological variables, spatial analysis reveals valuable local patterns and highlights the need to consider multiple factors and interactions for more effective agricultural management. Using these tools can complement traditional monitoring practices, helping producers respond more proactively to water stress conditions in crops.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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