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Article

Characterization of Recently Planted Coffee Cultivars from Vegetation Indices Obtained by a Remotely Piloted Aircraft System

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Abstract: Brazil is the main producer and exporter and the second-largest consumer of coffee in the world, and Remotely Piloted Aircraft Systems stands out as an efficient remote detection technique applied to the study and mapping of crops. The objective of this study was to characterize three recently planted cultivars of *Coffea arabica* L. The study area is in Minas Gerais, Brazil, with a coffee plantation of the initial age of 5 months. The temporal behavior was determined based on monthly mean values. The spectral profile was obtained with mean values of the last month of dry and rainy periods. The statistical differences were obtained based on the non-parametric test of multiple comparisons. The estimation of the exponential equation was obtained through the Spearman correlation coefficient of determination and root mean square error. It was concluded that the seasons influence the behavior and development of cultivars, and significant statistical differences were detected for the variables, except for the chlorophyll variable. Due to the proximity and overlap of the reflectance values, spectral bands were not used to individualize cultivars. A correlation between the vegetation indices and leaf area index was observed and the exponential regression equation was estimated for each cultivar under study.

Keywords: *Coffea arabica* L.; precision farming; remote sensing; spectral signature



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1. Introduction

The coffee culture has great socioeconomic importance in Brazil, which is currently the largest world producer, second-largest consumer, and leader in world exports [1]. Since it is a perennial crop culture grown in large areas, it is subject to imminent risks that directly affect productivity and, consequently, the country's economy. The Brazilian coffee industry is constantly growing and is characterized using technologies that ensure the market quantity and quality of the product, counterbalancing the irregularities found in the field [2].

In this context, remote sensing using aerial platforms, through a detailed mapping of the study area, provides accurate information of the culture and in a timely manner for corrective actions. Remotely Piloted Aircraft Systems (RPAS) refers to an alternative of easy data acquisition and considerably more flexibility compared to classic platforms, providing reliable data with a more complex field of view of the conditions of the object of study, ensuring the possibility of accurately discriminating the state of health of plants, since it can carry sensors as a suborbital platform [3].

The use of sensors onboard aircraft in coffee studies is being evidenced in different applications. Carrijo et al. [4] used RPAS for the detection of ripe fruit in coffee plants. Chemura et al. [5] tested the capacity of multispectral imaging to assess water content as a means of detecting and monitoring water stress in coffee plantations. Oliveira et al. [6] studied forms of segmentation to detect nematodes in coffee farming using aerial images from RPAS. Cunha et al. [7] developed a method to determine the volume of coffee plantations from digital images captured by RPAS. Dos Santos et al. [8] proposed an estimation model for indirect measures of coffee plant height and diameter parameters using data detected by RPAS, among other applications.

Studies with sensors coupled to orbital systems are already widespread in the literature in studies in the context of coffee precision agriculture. However, the applicability of studies in this direction with the applicability of suborbital sensors evidenced by the application of RPAS is scarcer, and in the case of the use of this technology in the study of recently planted coffee crop fields even more incipient and less widespread in the literature, but of fundamental economic importance, highlighting the importance of the applicability and development of the proposed study.

The application of remote sensing techniques combined with remote aerial platforms provides efficient, early, objective, and non-destructive assessment through the spectral response of plants to various environmental factors [9]. The post-planted study of coffee seedlings is important, and, in most cases, the driving errors committed in the first months reflect on the entire useful life of the crop, influencing longevity, product quality, crop productivity, production costs, and consequently, the profitability of the activity developed [10].

Thus, this work aimed to characterize three recently planted coffee cultivars (*Coffea arabica* L.) to verify the influence of dry and rainy periods on the development and behavior of the variables measured in the field. The temporal study was conducted on data on height, crown diameter, chlorophyll content, and radiometric data from vegetation indices; the survey of spectral profiles for the two periods of study; statistical differentiation for coffee cultivars; and estimated equations correlating leaf area index (LAI) and total chlorophyll (Chl t) to vegetation indices (VIs).

2. Materials and Methods

2.1. Area of Study

The study area refers to Samambaia Farm, with a total area of 275,000 hectares, between the meridians 506,000 and 508,000 m W, and parallel 7,680,000 and 7,690,000 m S, in the UTM zone 23 S projection and geodesic reference Sirgas 2000 (Figure 1), located in the municipality of Santo Antônio do Amparo, in the Campos das Vertentes zone, Minas Gerais, Brazil [11].

The farm has a coffee plantation area (*Coffea arabica* L.) with different cultivars that was recently planted (in the months of November and December 2018), with an initial age of 5 months old at the beginning of the work. The cultivars include Catucaí (2SL), Catucaí (IAC 62), and Bourbon (IAC J10) (Figure 2), which are registered in the National Registry of Cultivars (RNC) and are focus of this study. The study sub-areas were standardized at 0.60 ha, 3.80 m spacing between rows, 0.50 m between plants, mean altitude of 1022.00 m, and the presence of brachiaria in between rows. The municipality is located in the Atlantic Forest biome and has soil classified as dystrophic Red Yellow Latosol [12].

The farm area was previously destined for pasture (*Brachiaria decumbens*) in the condition of degradation. For the soil preparation for the implementation of coffee plantations, harrowing and subsoiling was initially carried out in the total area of dolomitic limestone, followed by the management of weeds, chemical control, and the opening of furrows. With the soil prepared, planting rows were marked by mechanized alignment and subsequent planting of multi-hole seedlings with 50 cm spacing was carried out in December 2018. In July 2019, the procedure of covering part of the orthotropic branch of the plants with

soil was carried out to balance humidity and temperature, favoring the development of coffee trees.

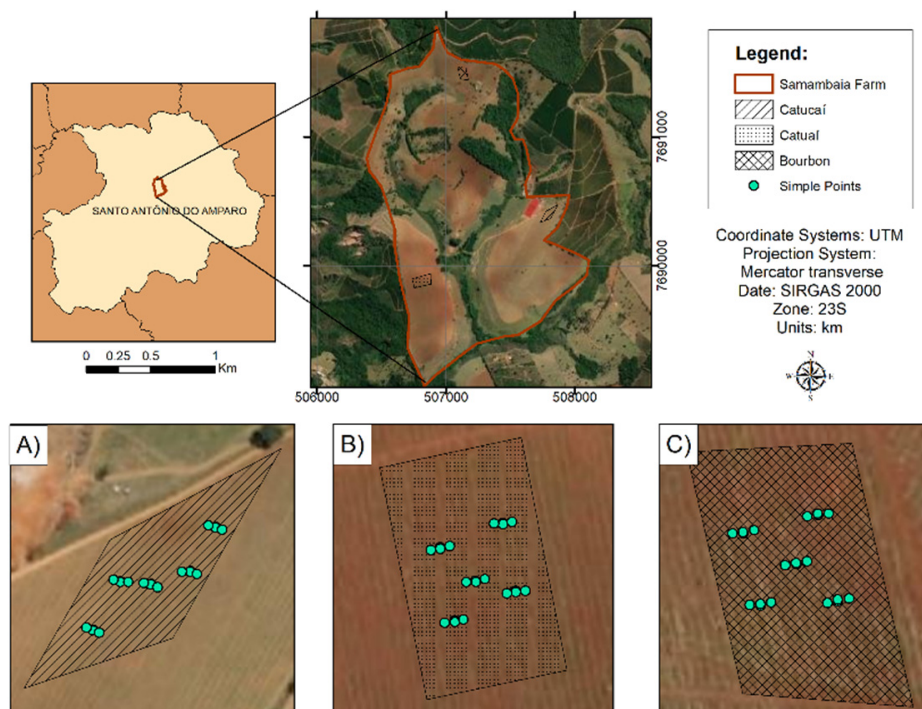


Figure 1. Location of the study area with cultivars (A) Catucaí (2SL), (B) Catucaí (IAC 62), and (C) Bourbon (IAC J10).



Figure 2. Cultivars of *Coffea arabica* L. planted in Samambaia Farm (A) Catucaí (2SL), (B) Catucaí (IAC 62), and (C) Bourbon (IAC J10).

The three study sub-areas were standardized in 0.60 ha, with 15 planting rows and 200 plants per study row, totaling 3000 plants per area. For this study, 5 sampling points were considered, distributed in a systematic way for each area, with each sampling point composed of 4 coffee plants, according to the methodology described by Ferraz et al. [13], which indicates sampling of two plants located in the row of coffee trees (considered the central point) and two more plants in each row on either side of the central point, totaling 20 plants per area and 60 plants in the entire study area, as depicted in Figure 3.

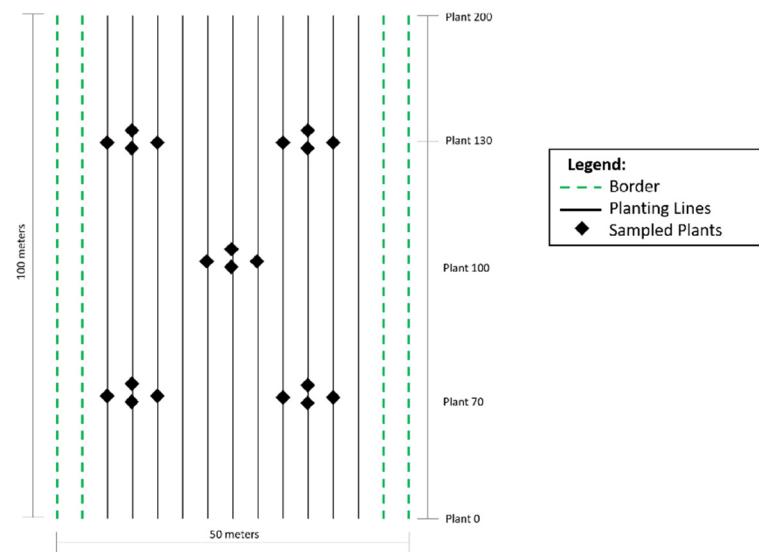


Figure 3. Schematic representation of the experiment with sample points for the experimental area.

According to Köppen's classification, the climate is classified as subtropical rainy (Cwb), with average temperatures ranging from 18 °C to 22 °C [14]. Based on normal climatological data from Inmet (Brazilian National Institute of Meteorology, Minas Gerais, Brazil), it was possible to characterize the annual average precipitation and average, maximum, and minimum temperatures of the region (Figure 4). The months of October to March are rainy and hot and the months of April to September are dry and cold months in the region analyzed, thus allowing the study to highlight the effects of periods on the recently planted coffee crop and its development in the first year of implementation.

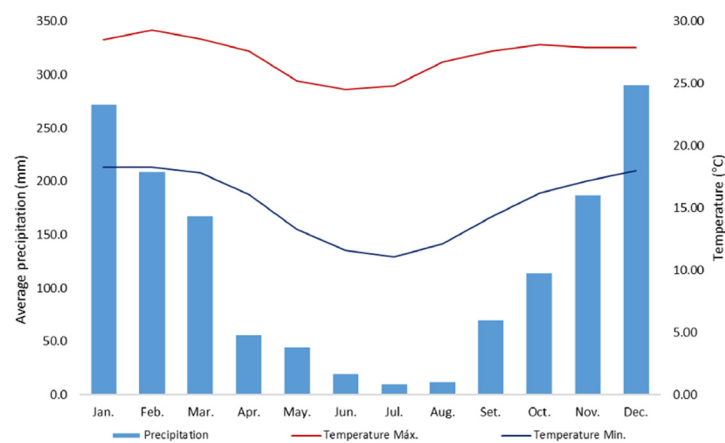


Figure 4. Annual distribution of average monthly precipitation and average maximum and minimum temperatures for the region.

2.2. Obtaining the Aerial Images

The images were collected in 2-month intervals, from May 2019 to March 2020 (May/July/September/November/January/March). The survey of the images used to determine the VIs in the coffee crop study area was carried out by a Matrice 100 Remotely-Piloted Aircraft (DJI, Shenzhen, China) (Figure 5) with an embedded sensor for aerial image capture with a multispectral Parrot Sequoia (MicaSense) camera with 16 MP RGB resolution, 4.88 mm focal length, 1.2 MP single band resolution, and 3.98 mm focal length as a proprietary inertial system (IMU); a magnetometer; GPS; Wi-Fi; a USB power supply; 64 GB internal memory; the ability to shoot 1 photo per second; and brightness correction by the sunshine sensor and reflectance values described in the spectral bands of green (550

to 590 nm), red (660 to 700 nm), red edge (735 to 745 nm), near-infrared (760 to 820 nm), and RGB (380 to 720 nm).



Figure 5. RPA Matrice 100 and Parrot Sequoia embedded sensor.

The flight plan was performed in the Precision Flight software (Version 1.3.2, Precision Hawk, Raleigh, NC, USA) and the system input parameters for flight definition by way-points, considered automatic, with the determination of the launch and landing location of the aircraft, topographic conditions of the area, flight height defined at 50 m, flight speed of 8 m/s, overlap \times sidelap of 80% \times 80%, and flight direction of a transversal type to the planting row.

The extremities of the study areas and the sampled plants were demarcated with control points (targets) by plates arranged in the field. It allowed the correct identification of the positioning of the analyzed plants and guarantee the accuracy of the information collected in the field using the images obtained by the sensor coupled to the RPA. The targets were made of 30 cm \times 30 cm square wooden plates, painted with white and red paint to highlight the images to be collected with the overflight (Figure 6).



Figure 6. Control points: (A) target details, (B) targets set in the coffee tree area.

The radiometric calibration of the sensor occurred before and after the flights, through the precise compensation of the incident light conditions and the generation of quantitative data with a calibration plate to capture the images according to the overflight in the study areas, with the standardized time between 11:00 and 13:00 h, thus allowing a comparative effect between images from the months of study.

2.3. Image Processing

The processing of the images proceeded through the PIX4D Mapper software (PIX4D SA, Prilly, Switzerland), according to the methodology described in Figure 7.

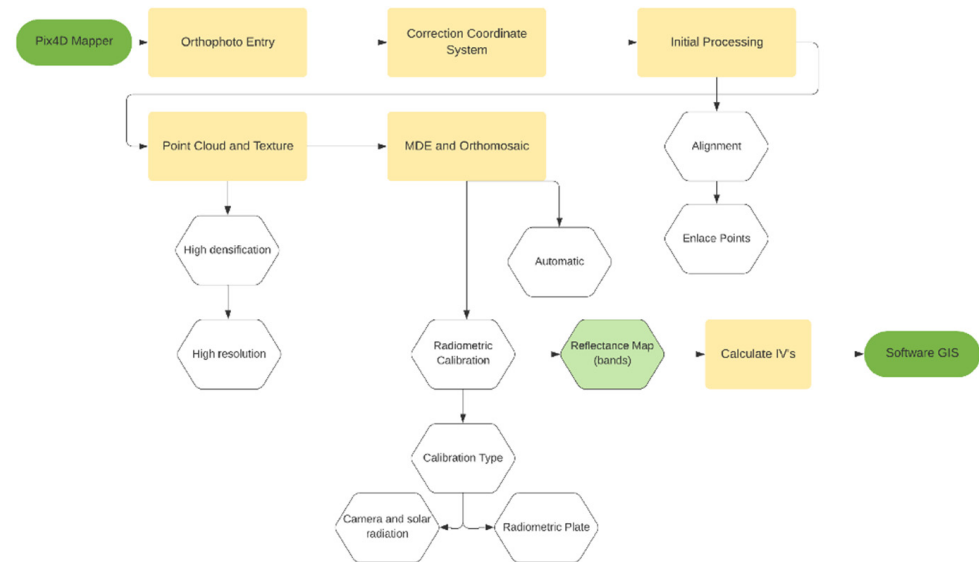


Figure 7. Image-processing flowchart in the Pix4D Mapper software.

All processing items were set as high resolution. Initially, the spatial reference of the images was corrected for Sirgas 2000 UTM zone 23S, and radiometric correction of the images was performed. Then the images were aligned by automatic triangulation and the creation of link points. Sequentially, the creation of a dense cloud and texture of the images was performed to generate the digital elevation model (MDE) and final mosaic generation with reflectance maps for each spectral band for each sub-area of study. From the possession of such mosaics, it was possible to study the VIs.

2.4. Field Data

At the concomitant dates, the images were obtained and field data were collected for plant measurements, height, crown diameter, and chlorophyll content for further study, as well as to help monitor the crops.

The measurements of plant height and crown diameter were performed with a conventional ruler (Figure 8A,B), measuring the distance between the soil level and the insertion of the pair of leaves in the terminal region of the orthotropic branch (vertical measurement) and the largest crown diameter of the plant (horizontal measurement). This information was used to calculate the leaf area index (LAI) according to Equation (1), developed by Favarin et al. [15].

$$\text{LAI} = 0.0134 + 0.7276 \times D^2 \times h \quad (1)$$

where LAI is leaf area index (adimensional), D is plant crown diameter (m), and h is height of plants (m).

The chlorophyll content measurement (photosynthetic pigments or chloroplast pigments) was performed with a portable atLEAF Chl chlorophyll meter (FT GREEN LLC, Wilmington, DE, USA) using an average of three coffee plant leaves with red and near-infrared wavelength readings (Figure 8C). The conversion of units obtained by the chlorophyll meter to total chlorophyll content (Chl t), chlorophyll a (Chl a), and chlorophyll b (Chl b) followed Equations (2)–(4), respectively, according to Padilla et al. [16].

$$\text{Total chlorophyll content} = \text{chlorophyll a} + \text{chlorophyll b} \quad (2)$$

$$\text{Chlorophyll a} = -5774 + (0.43 \times \text{atLEAF}) + (0.0045) \times (\text{atLEAF}^2) \quad (3)$$

$$\text{Chlorophyll b} = 0.04 \times (\text{atLEAF} ^ 1.57) \quad (4)$$

where Total chlorophyll content is (Chl t), Chlorophyll a is (Chl a), Chlorophyll b is (Chl b) ($\mu\text{g}/\text{cm}^2$), and atLEAF is the measurement obtained in the atLEAF chlorophyll meter (IRC).



Figure 8. Measurements: (A) height, (B) diameter, (C) chlorophyll measurement.

Soil sampling for fertility assessment was carried out in August to verify abnormalities in the sampling points through the removal of sub-samples collected in the projection of the skirt of the coffee tree from 0 to 20 cm deep with a Dutch auger for each of the four plants of the sampling point, which were homogenized for the formation of a composite sample and forwarded to a laboratory to analyze fertility and organic matter.

2.5. Vegetation Indices

The vegetation indices (VIs) were calculated based on the combination of spectral bands described in Table 1. For this study, we considered 5 different VIs to identify indirect relationships between the results found through remote sensing images and data collected in the field. The choice of such indexes was based on the ability to discern plant characteristics as well as responses to vegetation stress conditions with remote sensing data.

Table 1. Indices of vegetation used, followed by their acronyms, equations, and references.

Vegetation Index	Acronyms	Equations	References
Normalized Difference Vegetation Index	NDVI	$(RNIR - RR)/(RNIR + RR)$	[17]
Index of the Standardized Difference—Red Edge	NDRE	$(RNIR - RREG)/(RNIR + RREG)$	[18]
First Modification to the Chlorophyll Absorption Ratio	MCARI1	$1.2 [2.5(RNIR - RR) - 1.3(RNIR - RG)]$	[19]
Red Edge Chlorophyll Index	CI	$(RNIR/RREG) - 1$	[20]
Canopy Chlorophyll Content Index	GCI	$(RNIR/RG) - 1$	[21]

Legend: RNIR, reflectance values obtained by the sensor in the near-infrared range; RREG, reflectance in the range between red and infrared; RR, reflectance in the red range; RG, reflectance in the green range.

The VIs were obtained with ArcGIS 10.4 (ESRI, Redlands, CA, USA) and QGIS 3.6.2 (QGIS Development Team, Open Source Geospatial Foundation) software in a GIS environment through the set of functions in the AcrToolbox in the Map Algebra tool, which allows calculations between rasters (pixel by pixel) from scripts written in Python. The images were georeferenced to guarantee the correct positioning of the calculation between bands, with the VI values extracted based on the set of pixels referring to the study plants.

2.6. Analyses

The analysis of the temporal behavior of field data and VIs were obtained based on average monthly data for each coffee cultivar by plotting the values of the indices studied

over time in electronic spreadsheets, considering the dry period (May, July, and September) and rainy period (November, January, and March). In this analysis, the behavior of the rainfall and thermal distribution of the region was considered (Figure 4) since it refers to a recently planted coffee plantation, i.e., in the formation and growth phase, and in the first year of formation of the plantation, the physiological periods are not well defined and, therefore, the rainfall and thermal interference have a significant influence on the development of the coffee plants [22].

The spectral characterization of the three coffee cultivars was performed for the dry period (September) and for the rainy period (March) through the generation of a spectral signature, using the green and red bands of the visible spectrum and the bands of red edge and near-infrared of the infrared spectrum. The amplitude values of each spectral band were obtained from 20 points of interest for each study cultivar with QGIS 3.6.2 to characterize the behavior of the reflectance of pixels in each studied band.

The study of statistical differences consisted of verifying differences between cultivars for two periods of study based on field data and VIs. Initially, the analysis of statistical differences between the months that compose the periods individually was carried out, and since no significant statistical differences were detected, the months were grouped by periods, allowing the analysis in question. The normality of the data was tested using the Anderson–Darling statistical test [23], and since the nonnormality of the data was verified, the analysis of statistical differences was performed based on the Kruskal–Wallis non-parametric test [24]. Later, the Dunn multiple comparisons test [25] was applied at a 5% probability in R software (R Development Core Team, R project, New Zealand).

The correlation between Chl *t* and LAI data obtained in the field with the radiometry values of the VIs was performed to analyze the adjustment and estimation of equations that correlate such information. The correlation coefficient of Spearman (ρ) was verified, and regression analysis was performed to obtain the coefficient of determination (R^2). For validation, the root mean square error (RMSE) was calculated, since it is a widely used method to verify the accuracy of estimator models, through the software R.

2.7. Summary of Resources Used and Importance of Their Use

Therefore, in general, in this work, temporal characterization, spectral characterization, statistical difference analysis, and exponential correlation analysis were used for the study of three different coffee cultivars over a 1-year study period. The temporal characterization for the variables obtained by field measurement (height, crown diameter, and chlorophyll) and data from aerial images collected by RPAS (vegetation indexes) aim to verify the behavior over time of the variables in question, as well as to identify the influence of climatic factors of temperature and precipitation on the response of the variables. The spectral characterization aims to identify differences in the electromagnetic spectra in order to allow differentiating and individualizing coffee cultivars. The analysis of statistical differences aims to verify the difference between the coffee cultivars studied in order to identify the appropriate study variable to differentiate and individualize the coffee cultivars at the time of analysis. The correlation analysis seeks to estimate an equation that describes the response of a variable measured in the field through a variable obtained through data collected by RPAS—in this study, represented by vegetation indices.

The temporal follow-up analyses are essential to understand the behavior of the plant in the field, and in the case of cultivars at the beginning of the development phase, it is essential to carry out this verification, since it allows the presence of stress responses to be observed and early decisions to be made. Spectral behavior and statistical difference analysis, on the other hand, seek to highlight characteristics and variables that are the same and different between different cultivars of study, and when finding a variable with a greater factor of equality or differentiation between cultivars, it is possible to characterize and differentiate cultivars, unfolding more appropriate applications according to the indicated cultivar. The equation estimation to measure data from field measurements by data obtained by remote sensors optimizes the activities, since most of the time data

collected in the field demand more time and labor compared to data obtained by aerial images, and it expands a range of possibilities of investigation of influential factors in the activity developed in the field. Therefore, studies with the use of such resources are important for applicability in agrarian environments.

3. Results

The data obtained in this study for the three recently planted coffee cultivars are described in Table 2. No changes were found between the sampling points based on the soil fertility analysis data, the fertilization in the three areas being equal and enough so that no soil component affected the development of coffee plants differently and, therefore, any type of interference of this type was disregarded.

Table 2. Average values of height and diameter (m); leaf area index (LAI); chlorophyll ($\mu\text{g}/\text{cm}^2$) a (Chl a), b (Chl b), and total (Chl t) content; and vegetation indexes (VIs) of three different coffee cultivars (Catucaí, Catuaí, and Bourbon) for five periods of study.

Variables	Periods of the Year					
	May	July	September	November	January	March
Catucaí						
Height	0.36	0.38	0.43	0.52	0.56	0.70
Diameter	0.36	0.39	0.38	0.54	0.64	0.82
LAI	0.05	0.06	0.06	0.13	0.19	0.38
Chl a	33.42	58.15	27.92	45.99	33.97	57.79
Chl b	22.90	39.35	19.28	31.28	23.26	39.12
Chl t	56.32	97.50	47.20	77.27	57.22	96.92
NDVI	0.66	0.52	0.47	0.79	0.84	0.87
NDRE	0.29	0.14	0.14	0.19	0.24	0.25
MCARI	0.60	0.37	0.18	0.52	0.79	0.80
CI	0.36	0.29	0.19	0.35	0.56	0.61
GCI	3.83	2.93	1.63	2.31	4.40	7.72
Catuaí						
Height	0.29	0.34	0.36	0.47	0.50	0.65
Diameter	0.38	0.40	0.36	0.52	0.61	0.79
LAI	0.05	0.06	0.05	0.11	0.15	0.32
Chl a	36.99	72.89	45.29	38.20	33.77	53.47
Chl b	25.28	49.07	30.81	26.08	23.13	36.26
Chl t	62.27	121.96	76.11	64.29	56.90	89.73
NDVI	0.61	0.49	0.20	0.79	0.84	0.89
NDRE	0.14	0.10	0.12	0.17	0.22	0.27
MCARI	0.40	0.33	0.01	0.58	0.61	0.85
CI	0.23	0.32	0.27	0.41	0.56	0.73
GCI	3.75	2.97	1.41	4.94	6.44	7.74
Bourbon						
Height	0.39	0.45	0.50	0.67	0.71	0.93
Diameter	0.36	0.42	0.39	0.68	0.72	0.94
LAI	0.05	0.07	0.08	0.25	0.30	0.64
Chl a	49.35	65.99	82.45	49.55	37.88	42.77
Chl b	33.52	44.53	55.31	33.63	25.87	29.13
Chl t	82.87	110.52	97.76	83.18	63.76	71.89
NDVI	0.64	0.55	0.36	0.83	0.91	0.91
NDRE	0.12	0.05	0.13	0.21	0.22	0.27
MCARI	0.43	0.10	0.13	0.73	0.77	0.87
CI	0.29	0.14	0.30	0.52	0.64	1.04
GCI	4.47	1.16	1.84	4.74	6.89	8.03

3.1. Temporal Characterization

The temporal behavior of the data obtained from field measurements of height, crown diameter, leaf area index (LAI), and total chlorophyll (Chl t) are presented in Figure 9. When studying the development and behavior of recently planted coffee cultivars, it is important to emphasize the study of these variables, which show the formation phases and growth of the coffee cultivars. So, these variables are fundamental for the LAI study.

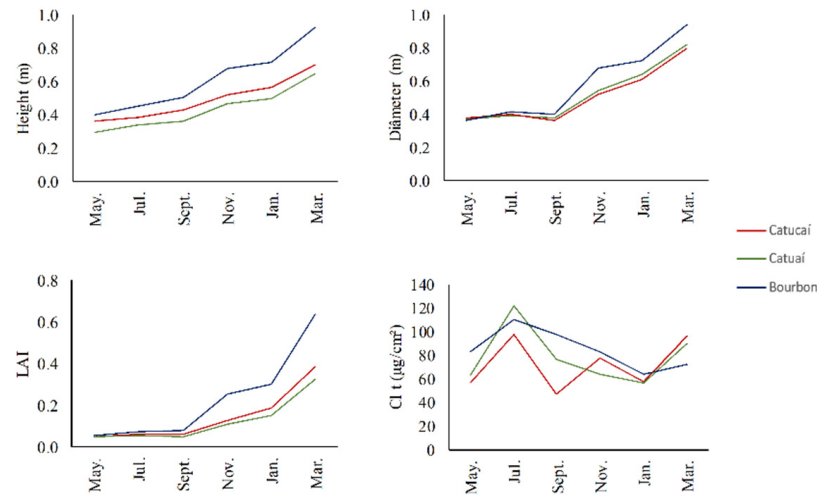


Figure 9. Temporal analysis of data measured in the field: height, crown diameter, leaf area index (LAI), and total chlorophyll (Chl t) for the three study cultivars.

The temporal behavior of NDVI, NDRE, MCARI1, CI, and GCI VIs are presented in Figure 10. The use of remote sensor-derived VIs that highlight specific plant characteristics act as an optimization tool for fieldwork since they promote reliable information for continuous monitoring of development and stress conditions in coffee crops [26].

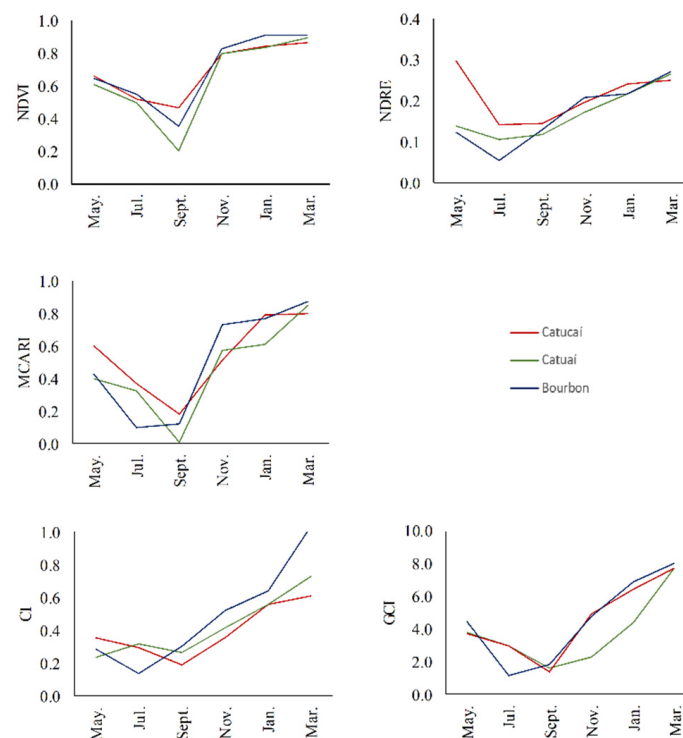


Figure 10. Time analysis of VIs: NDVI, NDRE, MCARI1, CI, and GCI for the three study cultivars.

3.2. Spectral Characterization

The characterization of the spectrum of the reflectance of targets is evidenced by its spectral signature, which refers to reflectance as a wavelength [27]. Each object has a unique spectral signature and can be used in several classifications, and in this study, the spectral differences of coffee cultivars are highlighted. The spectral signature of a leaf is primarily a function of its composition, morphology, and internal structure, since the solutes, intercellular spaces, and pigments in chloroplasts and leaf constituents are considered important factors in such characterization [28].

Figure 11 shows the spectral signatures of the three coffee cultivars for the dry period. There is great similarity between the three cultivars' spectral signatures, with overlap in the range of spectral reflectance values.

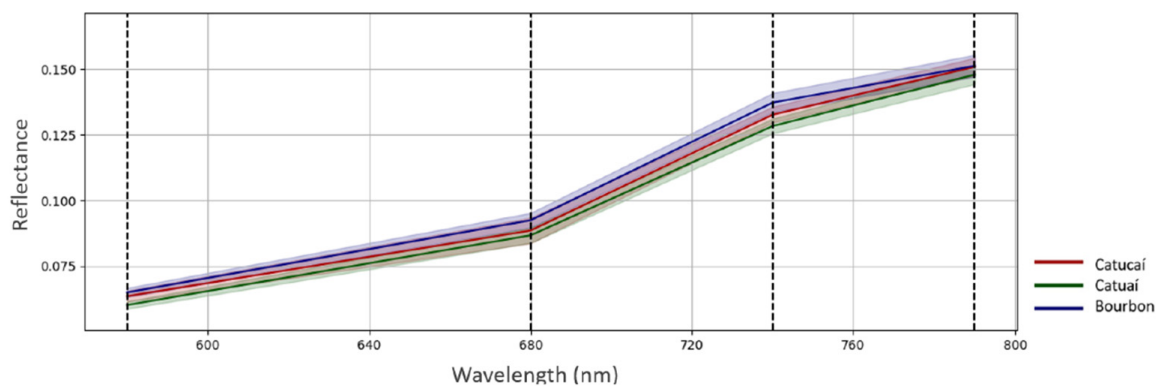


Figure 11. Spectral signatures of the three coffee cultivars Catucaí, Catuaí, and Bourbon for the dry period.

Figure 12 shows the spectral signatures of the three coffee cultivars for the rainy period. In this period, great similarity between the spectral signatures of the Catucaí and Catuaí cultivars was observed and a slight differentiation in the Bourbon cultivar was observed, with an overlap in the range of spectral reflectance values for the green, red, and red edge.

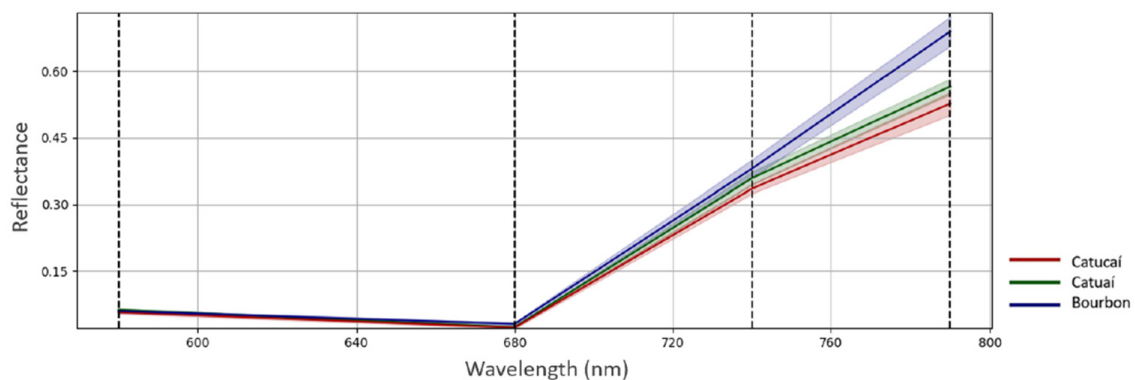


Figure 12. Spectral signatures of the three coffee cultivars Catucaí, Catuaí, and Bourbon for the rainy period.

3.3. Statistical Analysis

Table 3 describes the significant statistical differences determined for the study variables (height, diameter, LAI, Chl t, and VIs), considering the study of coffee cultivars in the study periods, divided into dry (May, July, and September) and rainy (November, January, and March).

Table 3. Results of the analysis of multiple comparison statistical differences by Dunn's test considering dry and rainy periods for the three study cultivars.

Period	Rainy Period			Dry Period		
	Catuaí	Catuaí	Bourbon	Catuaí	Catuaí	Bourbon
Height	39.00 B	34.00 C	43.50 A	55.00 B	53.00 B	74.00 A
Diameter	38.50 ns	38.50 ns	38.50 ns	61.00 B	62.50 B	75.00 A
LAI	0.06 AB	0.05 B	0.06 A	0.16 B	0.16 B	0.30 A
Chl t	60.11 B	76.23 B	107.55 A	62.43 B	67.35 B	72.30 A
NDVI	0.53 A	0.49 B	0.53 A	0.83 C	0.85 B	0.89 A
NDRE	0.16 A	0.12 B	0.11 B	0.21 B	0.21 B	0.22 A
MCARI1	0.35 A	0.29 B	0.15 B	0.77 B	0.66 B	0.81 A
CI	0.30 A	0.27 B	0.25 B	0.54 B	0.54 B	0.64 A
GCI	2.67 ns	2.71 ns	2.75 ns	4.25 B	6.36 A	6.95 A

Legend: Equal lines indicate equality with each other at the significant at 5% probability level; ns = not significant at 5% probability level.

3.4. Correlation and Estimation of Exponential Equation by VIs

Table 4 describes the Spearman correlation coefficients (ρ), determination coefficients (R^2), and the root mean square error (RMSE) for Chl t and LAI data for the three areas for the study period.

Table 4. Spearman correlation coefficients (ρ), determination coefficients (R^2), and the root mean square error (RMSE) for the three study cultivars.

Vis	Chl t			LAI		
	RMSE	R^2	ρ	RMSE	R^2	ρ
Catuaí						
NDVI	26.52	0.06	−0.05	0.07	0.64	0.54
NDRE	26.74	0.01	−0.23	0.10	0.08	0.32
MCARI1	26.32	0.09	−0.09	0.08	0.51	0.68
CI	25.48	0.09	−0.05	0.09	0.47	0.63
GCI	23.32	0.13	−0.09	0.09	0.74	0.72
Catuaí						
NDVI	28.60	0.01	−0.15	0.09	0.56	0.63
NDRE	28.72	0.01	−0.13	0.06	0.77	0.85
MCARI1	28.87	0.01	−0.04	0.07	0.65	0.74
CI	28.84	0.01	−0.08	0.08	0.81	0.87
GCI	28.89	0.01	−0.11	0.05	0.73	0.79
Bourbon						
NDVI	21.79	0.49	−0.18	0.18	0.60	0.66
NDRE	27.85	0.24	−0.48	0.15	0.70	0.77
MCARI1	23.31	0.44	−0.68	0.17	0.64	0.69
CI	25.64	0.26	−0.49	0.15	0.82	0.84
GCI	23.56	0.41	−0.66	0.19	0.60	0.73

Considering the studied cultivars, the models that best represent the relations between LAI and radiometry data expressed by the Vis (Table 4) were selected by observing the highest statistical coefficients of the Spearman correlation (ρ) and determination (R^2), as well as the root mean square error (RMSE). Thus, the exponential regression models of LAI with the GCI for the cultivar Catuaí and of LAI with the CI for the cultivars Catuaí and Bourbon (Figure 13) expressed through the regression equation were proposed, which can estimate the LAI values indirectly by using the VIs.

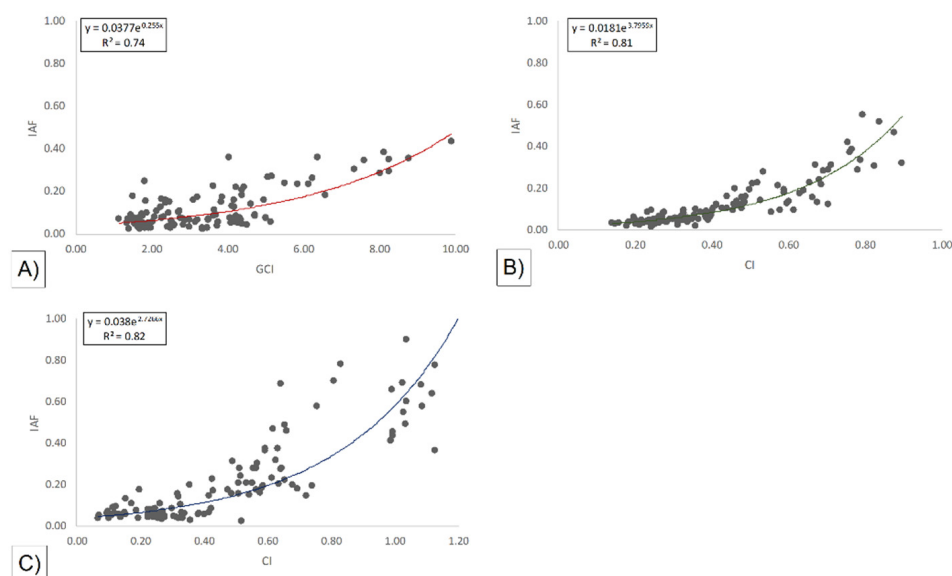


Figure 13. Dispersion graphs, coefficient of determination (R^2), and regression equations between LAI and (A) GCI Catuaí, (B) CI Catuaí, and (C) CI Bourbon.

4. Discussion

According to Table 2, considering the final study period for the variables of height, crown diameter, LAI, and chlorophylls (a, b, and total), the Bourbon coffee cultivar presented higher values, followed by the Catuaí and Catuaí cultivars, respectively. For the studied Vis, the Bourbon coffee cultivar also obtained superior values, followed by the cultivars Catuaí and Catuaí, respectively.

4.1. Temporal Characterization

As shown in Figure 9 regarding the variable of height, it is known that the height of the coffee tree increased with age, and all cultivars showed linear growth, highlighting the Bourbon cultivar (0.93 m), which showed greater height than the cultivars Catuaí (0.70 m) and Catuaí (0.65 m), which are considered medium to small size according to the Embrapa Brazilian Coffee Research Consortium [29], which was also found in this study. However, a growth magnitude reduction was observed for the dry period compared to the rainy period, proving the action of the dry season in reducing the development of plants due to the use of their reserves to maintain the basic activities of survival of the plant, which consequently impact height increase.

Regarding the crown diameter variable (Figure 9), it was noticed that for the initial months of May and July, the growth was linear; however, there was a drop in the value of the variable for September in all cultivars. This fact can be justified by the intense cold action in the region in the previous months, which promoted interruption of the growth of the youngest leaves, chlorosis, burning at the edges and total burning in some leaves, leaf fall, and consequently, reduction in the values of crown diameter. In the following months, due to the reduction from the cold's action, the development of the leaves was resumed, with a noticeable increase in the values of this variable.

In studies by Freitas et al. [30], the influence of local temperature environmental conditions of the cultivation area on the diameter of the crown of coffee cultivars was also observed. The weather conditions that strongly affect the development of Arabica coffee have also been verified in works by Aparecido et al. [31], Oliveira et al. [32], and Camargo [33]. In this study, the Bourbon cultivar presented a larger crown diameter (0.94 m), followed by the cultivars Catuaí (0.82 m) and Catuaí (0.79 m), respectively.

The LAI (Figure 9) behavior over time reflected the canopy processes and general state of the coffee tree [15]. For the cultivars Catuaí and Bourbon, the LAI showed linear growth; however, for the cultivar Catuaí, a slight reduction was observed for September,

followed by an increase in the following months. Thus, it was noticed that the thermal effects that caused a reduction in the canopy diameter in September for all cultivars were not enough to affect the LAI values of the Bourbon and Catucaí cultivars, unlike what was observed for the Catuaí cultivar, which responded with a greater drop in the variable. Consequently, the LAI value reflected a greater sensitivity for this cultivar compared to the others. In the following months, the growth was linear, with higher values of LAI for the cultivars Bourbon (0.64), Catucaí (0.38), and Catuaí (0.32), with values close to and higher than those found in studies by Pereira et al. [34], who observed an LAI value equal to 0.27 in non-irrigated coffee trees for a 15-month analysis after planting.

In general, the growth of lateral branches (plagiotropic) and leaves followed the temperature curves, especially those of medium and minimum temperatures (Figure 4). According to Alégre's [35] study, the average temperature favorable to the growth and development of the coffee tree is between 16 and 23 °C, with an optimum range found from 18 to 21 °C. Therefore, it was verified that the decrease in foliar development and consequently the reduction in the values of the crown diameter of the studied coffee cultivars occurred in the period with a temperature below that considered an optimal value by Alégre [35], reaching average minimum temperature values below 15 °C for the studied area. However, regarding the height of the plants (orthotropic branch), the average temperatures were not enough to explain the decreases in plant height, since the variable remained growing in this study, evidenced mainly by the initial phase of plant development, a phase in which the growth of orthotropic branches is likely in constant development [36].

For the variable Chl *t* (Figure 9), the behavior presented by the Catucaí cultivar was increased considerably in July, decreased in September, increased in November, and decreased in January. The cultivars Catuaí and Bourbon also presented a considerable increase in July, but a decrease in September, November, and January. In March, all the cultivars showed a considerable increase in chlorophyll content, and the cultivar Catucaí presented a higher content of Chl *t* (96.92 µg/cm²), followed by the cultivars Catuaí (89.73 µg/cm²) and Bourbon (71.89 µg/cm²). The higher values of Chl *t* observed for the dry months and with reduced temperature (May, July, and September) for the rainy months and with high temperature (November, January, and March) did not follow the expected pattern for the studied periods. The water and thermal deficit did not significantly affect photosynthetic pigments at the time of evaluation.

The behavior of chloroplast pigments may reflect the state of plant defense, since plants submitted to a water deficit may present a significant increase in the concentration of photosynthetic pigments, demonstrating resistance to a water deficit to enhance the performance of photosynthetic assimilation of CO₂ to maintain growth and development, maintaining normalized physiological activities and favoring metabolic patterns without changes that compromise the species dynamics, with a decrease in the water content in the leaf large enough to promote chlorophyll degradation being necessary [37,38]. This chloroplast pigment behavior may still be related to the leaf sampling for chlorophyll analysis, since the measurement occurred in random and different leaves at each evaluation and with the choice of leaves being more visible and freer from the action of burning and chlorosis due to the action of cold [10] that may have biased the measurement.

However, the data obtained by the chlorophyll measurement methodology by portable chlorophyll meter do not satisfactorily explain the thermal and pluviometric behavior evidenced in the measurements of the other analyzed variables. Therefore, the use of the chlorophyll measurement methodology by portable chlorophyll meter was not efficient to evidence the behavior of the different periods of this study, considering coffee plants in the initial phase of development for the first year of crop formation.

As shown in Figure 10, in this study, the values of the NDVI decreased in the three cultivars for July and September, with an increase observed for the following months of November, January, and March, with higher values for the Bourbon cultivar (0.91), followed by the Catuaí (0.89) and Catucaí (0.87) cultivars. Besides the thermal effects, Braga et al. [39]

have shown in their studies that vegetation takes on average from 30 to 60 days to respond to the effects of rainfall variation. The drop in the index is justified for the dry months (July and September), in which the effects of rainfall and temperature did not affect the values, in contrast to the increase for the rainy months (November, January, and March), in which such variations were reflected in the developmental effects of the crop and consequently increased the NDVI. Results of a reduction in the NDVI by the action of the water deficit were also evidenced in studies by Volpato et al. [40] and Almeida et al. [41].

In the cultivars studied, the NDRE (Figure 10) decreased in the month of July, with an increase observed for the following months. This is indicative of the relation between the stress of the plants and their weakened foliar tissue, both caused by thermal and pluviometric action. The highest value of the index was observed in the Bourbon (0.27) cultivar, followed by Catuaí (0.27) and Catucaí (0.25). Increased sensitivity to a water deficit due to the use of this index (red edge) showed an immediate drop in the values for July and an increase for September, in which the pluviometric action softly influenced the value of the index, highlighting an even higher value for the months of November, January, and March, with greater local pluviometric accumulation. It is noticeable that for March, the values of the NDVI already approached the maximum threshold allowed by the IV of 1. The values of the NDRE presented values that meet the demand for an explanation of the phenomenon but are still far from the maximum threshold of saturation of the index.

In this study, we observed a reduction in MCARI1 (Figure 10) in all study cultivars for July. For September, the value of the index continued to decrease for the Catucaí and Catuaí cultivars, whereas the Bourbon cultivar presented a slight increase. In the following months of November, January, and March, all cultivars showed a considerable increase, with the highest value observed for the Bourbon (0.87), Catuaí (0.85), and Catucaí (0.80) cultivars, respectively. The sensitivity to chlorophyll detection via the use of the green band in this index [42] showed the occurrence of cold nights in July, which led to an immediate drop in the index, since the cold paralyzes the development of leaf tissue and reduces the values of chlorophyll in the leaves. The accumulated rainfall action in November also resulted in a considerable increase in the index values for this month and the following months.

The behavior presented by CI was similar to MCARI1 (Figure 10), and for March the Bourbon (1.04), Catuaí (0.73), and Catucaí (0.61) crops obtained the highest values. When considering the effect of the different levels of chlorophyll on the leaves, the reduction for July in all cultivars is justified by the cold action, which promoted a drop in the chlorophyll values based on the red edge band, which is more sensitive to such variations, and consequently, in the values observed for the index [21]. The sensitivity of the red edge band, however, was not enough in the combination of this IV to detect an increase for the month of September, as detected by the NDRE in the Catucaí and Catuaí cultivars, instead detecting only for the Bourbon cultivar. The temporal behavior of GCI was already similar to the MCARI1 and CI indexes, with higher values observed for March for the Bourbon (8.03), Catuaí (7.74), and Catucaí (7.72) cultivars, respectively.

For the Vis, only the NDRE (Figure 10) detected sensitivity to rain and thermal elevation, showing an increase in all cultivars for September. The NDVI presented itself in a standard way in all cultivars, increasing only in November (the first rainy and hot month). In the other VIs,—MCARI1, CI, and GCI,—the Bourbon cultivar responded more quickly to the accumulation of precipitation and increase in temperature, showing an increase in the value of the IV for September, unlike the other cultivars, which showed an increase only in November.

For the Catuaí cultivar greater care is recommended in the first year after plantation, especially in the period of low rainfall, since the field variables and IVs showed greater oscillations in the amplitude of coverage with difference compared to the other cultivars.

It was observed that the values of Chl *t* did not follow a tendency of behavior like the VIs sensitive to this pigment. These variables (Chl *t* and VIs) captured temporal variations at different hierarchical scales since the VIs measured through the spectral response considered the integration of the plant canopy. The chlorophyll content measured

through the portable chlorophyll meter considered the leaf as an individual study, thus indicating different processes in coffee cultivars, which in young plants show greater effects. Thus, the VIs were more integrative indicators of the canopy, since they identified the burning and defoliation caused by the drop-in temperature and pluviometric action in the action of chloroplast pigment values. Therefore, the behavior presented by the VIs corroborates the vegetative growth of the coffee tree, which is responsive to external environmental conditions due to climatic influence, mainly related to air temperature and atmospheric precipitation, as evidenced in this study.

4.2. Spectral Characterization

Regarding Figure 11, in the green range (580 nm), the Bourbon cultivar presented a higher reflectance value than the other cultivars. This is evidenced by the presence of chloroplast pigments in the plant, with higher levels in the Bourbon cultivar than in the other cultivars. Among the bands of the visible region, this band presented the highest values of reflectance for healthy plants, with the changes of higher reflectance values for the other bands associated with some stress the vegetation was submitted to and, consequently, changes in the levels of chloroplast pigments acting on the behavior and development of the plants.

In the red range (680 nm) (Figure 11), the Bourbon cultivar also presented a higher reflectance value than the other cultivars, a range in which the reflectance was low and affected by chloroplast pigments. However, lower reflectance values were expected in this range compared to the green range. However, when dealing with the study in the dry period, the responses presented by the cultivars by the thermal and pluviometric effects stand out, in which there was a reduction in the content of chloroplast pigments capable of causing burning to the tissues of the leaves, causing the leaves to appear yellowish or chlorotic and leading to total or partial burning [10].

In the ranges of red edge (740 nm) and near-infrared (790 nm) (Figure 11), the behavior of the reflectance values of the cultivars was close to the mean reflectance values, with emphasis again on the Bourbon cultivar, with higher values than the other cultivars, detecting greater sensitivity to the changes previously shown by the VIs.

Regarding Figure 12 in the green (580 nm) and red (680 nm) ranges, there was great similarity between the reflectance of the coffee cultivars, and higher reflectance values than in the dry period. Unlike what was observed for the dry period, it was also observed that the red band presented values slightly lower than the green band values. This is normally observed in healthy plants, since the red region absorbs a greater amount of radiant energy, due to its importance for photosynthesis processes [27].

Higher values of reflectance were also observed for the red edge (740 nm) and near-infrared (790 nm) ranges (Figure 12) compared to the dry period, with the near-infrared range having higher reflected values, showing that healthy plants have little absorption of radiant flux in this range, but an increase in reflectance due to the presence of plant structures and internal leaf morphology [27].

For both periods of study, there was an approximation between the spectral profiles of the coffee cultivars, showing the superposition of values according to the amplitude of distribution of the reflectance values for the different spectral bands, highlighting the lack of possibility of individualization between the coffee cultivars in the initial phase of development and fixation in the field according to the spectral reflectance spectrum. However, describing the spectral signature of cultivars and performing subsequent identification in the field in an agile and precise manner will allow for better monitoring, as well as enable more efficient strategic actions in the production process.

4.3. Statistical Analysis

According to data from Carvalho et al. [29] based on a study developed by the Embrapa Brazilian Coffee Research Consortium, the Bourbon cultivar has a large size and crown diameter, and the Catucaí and Catuaí cultivars have a small size and medium crown

diameter. Concerning these variables, and as shown in Table 3, significant statistical similarities were detected only for the rainy period, as described in the literature regarding height and diameter, between the cultivars Catucaí and Catuaí compared to the Bourbon cultivar, with these variables all considered statistically different (height) and statistically equal (diameter) in the dry period. The same behavior was observed for the LAI in the rainy period, which differed from the dry period when considering statistical similarities between the Catucaí and Bourbon cultivars, a fact that normally does not occur in coffee studies, but that is justified in this study when considering the initial phase of development after planting, in which the plants were still small and close in the values of the variables measured in the field.

For the Chl *t* variable (Table 3), however, regardless of the period, no change in the behavior pattern was observed when contrasting the dry period with the rainy period, which was also observed in studies by *c*, in which it was found that the occurrence of moderate water restriction did not alter the chlorophyll contents in coffee plants.

The detection of similarities and significant statistical differences was similar among the VIs, except for the NDVI and GCI. It should be noted that the pluviometric and thermal action reflects changes in the variables measured in the field, which is reflected in the captured statistical changes. The NDVI and GCI detected statistical differences that did not coincide with any other VI. In the NDRE, MCARI1, and CI the pattern was the same. For the GCI, significant statistical differences were only detected in the second period of study (rainy) of lower water deficit and lower temperatures, with similarities between the Catuaí and Bourbon cultivars.

The results from the VIs show that each cultivar presented distinct behavior, which is related to their morphological characteristics and the initial development of the culture, with greater similarity observed between the Catucaí and Catuaí cultivars, which differed more strongly from the Bourbon cultivar for most of the analyzed variables. It is also worth mentioning that the results did not remain the same throughout the crop development. In this study, this was evidenced by the separation between dry and rainy periods, which can be explained by the beginning of the seedlings' fixation in the field, as well as by the influence of the environment, which can interfere in the values obtained by the VIs.

Thus, regarding the characteristics associated with the studied periods (Table 3), only the plant height in the dry period and the NDVI in the rainy period were efficient in the discrimination and individualization of the studied cultivars. Based on the considerations of similarities regarding the size of the Catucaí and Catuaí cultivars described in the literature, we detected similarities in this study only for the rainy period when the coffee plants were already more developed and with more than 1 year of fixation in the field, with significant statistical similarities observed for the height and diameter of the crown in the NDRE, MCARI1, and CI VIs. Therefore, this shows that the increase in the fixation time in the field, the effects of rainfall, and the increase in the average temperature had a positive influence on the similarities observed between the Catucaí and Catuaí coffee cultivars and the differentiation of the Bourbon cultivar.

4.4. Correlation and Estimation of Exponential Equation by VIs

The correlations between the data of Chl *t* and the VIs were verified, as shown in Table 4, but with weak statistical correlation for all the studied cultivars, as evidenced by the low value of the Spearman correlation coefficient, low determination coefficient, and high RMSE, which does not guarantee the correct estimation of the regression equation.

It was observed in Table 4 for the LAI variable that for the cultivation of Catucaí coffee, the VIs MCARI1, CI, and GCI showed a correlation coefficient considered strong (0.68, 0.63, and 0.72, respectively) and had reduced error (0.07, 0.09, and 0.09, respectively). However, only the GCI showed a moderate and acceptable coefficient of determination (0.74). For the cultivars Catuaí and Bourbon, all of the VIs presented a correlation coefficient from moderate to strong, but only the NDRE and CI VIs presented a coefficient of determination from medium to high (0.85 and 0.87 for Catuaí and 0.77 and 0.84 for Bourbon) and reduced

error (0.06 and 0.08 for Catuaí and 0.15 and 0.15 for Bourbon). Higher values for the CI VI were shown for both cultivars, making it possible to describe equations of exponential function for the estimation of the leaf area index for the studied coffee cultivars and to explain natural phenomena.

5. Conclusions

- The analysis of the temporal behavior of the data measured in the field and the vegetation indexes followed the pattern of the periods (dry and rainy), except for the chlorophyll data, which did not follow the pattern of modification consistent with the periods considered.
- The characterization of the reflectance spectrum allowed for identification between the cultivars for the dry and rainy periods, but it was not possible to differentiate and individualize the study cultivars due to the overlap in the range of the spectral reflectance values.
- For statistical differences, variations between the study periods for coffee cultivars were detected, except for the chlorophyll data. Statistical similarities between the Catucaí and Catuaí cultivars were observed, which differed from the Bourbon cultivar only in the rainy period. It was possible to individualize the cultivars in the dry period for the height variable and the rainy period for the NDVI variable, thus enabling the differentiation of coffee cultivars in the field.
- Low statistical correlation between the radiometric variables obtained through the VIs with the variable Chl *t* was observed, and it was not possible to estimate the equation between such variables.
- Radiometric statistical correlation was observed for the VIs and the LAI, with higher coefficients of correlation and determination and lower RMSE, allowing the generation of exponential regression models of LAI with the GCI for the Catucaí cultivar and the CI for the cultivars Catuaí and Bourbon.

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