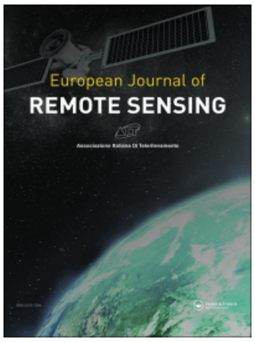

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RESEARCH ARTICLE

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Application of remotely piloted aircraft in the evaluation of the vegetative response of coffee trees affected by frost to sun exposure

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ABSTRACT

The sun exposure on the northern and southern faces of the coffee planting rows may play a key role in recovering of coffee plants affected by frost damage. This study aimed to assess coffee plants with frost damage according to the solar exposure face along the planting rows. Three experimental areas, each with plantations of different ages (one, three and eight years), were used. Evaluations were performed on the northern and southern sides of the planting rows, where the frost damage were measured. The remotely piloted aircraft (RPA) was flown over the three areas to capture multispectral images, and the derived vegetation indices were analysed. Only plants with eight years of age showed differences in frost damage between the sun exposure faces. Greater of damage was observed in the north face, with 48% of plant compromise. For coffee trees of one and three years old, the sun exposure did not exert a significant influence on the levels of damage between the faces of the planting line. The use of remotely piloted aircraft equipped with multispectral cameras demonstrated high efficiency in identifying spatial variations of crop damage. Among the indices evaluated, SAVI and MCARI2 showed a strong correlation with frost damage levels.

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Introduction

Coffee is one of the most widely consumed beverages in the world (Ferreira et al., 2022). Brazil is the largest producer and exporter of coffee; in the 2023/2024 crop year, arabica coffee production totalled 39.6 million bags of processed coffee, a 1.8% increase compared to the previous harvest, while robusta coffee production totalled 14.6 million bags, a 9.6% decrease compared to the previous harvest (CONAB, 2025). However, data from the International Coffee Organization shows a 7.6% decrease in South American production in 2021/24, representing the largest reduction since 2004/05, when there was a 16.6% decrease. According to data from the International Coffee Organization (ICO, 2023), Brazil was the main driver of this decline due to low biennial production and adverse weather conditions. This situation highlights the contribution of Brazilian production to the global coffee industry. This scenario highlights the need to understand the soil and climate factors, such as sun exposure and frost, which directly impact coffee production (Ferreira et al., 2021).

In recent years, the use of remotely piloted aircraft (RPAs) has gained prominence in precision agriculture. These unmanned aerial platforms allow data collection quickly, accurately and with excellent spatial and temporal resolution. RPAs equipped with multispectral, thermal or RGB cameras have been widely used for crop monitoring, detection of biotic and abiotic stresses, evaluation of vegetative vigour and yield estimates (Marin et al., 2019). In coffee growing, the use of RPA is consolidated as an efficient

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tools to map areas affected by frost, diseases or nutritional deficiencies, providing information for more assertive and sustainable agronomic decisions (Bento et al., 2022; Martello et al., 2022).

In this context, several studies highlight the applicability of RPAs in coffee cultivation, with different approaches. Martello et al. (2022) used RGB images for temporal and spatial analysis of coffee crops, Da Cunha et al. (2019) estimated the volume of vegetation of coffee crops from images of unmanned aerial vehicles. Multispectral images obtained by RPAs were also used by Rosas et al. (2022) for the monitoring of coffee maturation and Martins et al. (2021) proposed a new vegetation index to monitor the ripening of coffee by aerial images. Based on these technological applications, it is essential to understand how environmental factors, such as the arrangement of planting lines and solar incidence, directly affect the physiology of coffee trees and their response to stresses, such as frost.

In general, coffee plantations in Brazil are grown almost exclusively in full sun, and they are commonly planted in rows or open rows (Fernandes et al., 2012; Matiello et al., 2010; Ronchi et al., 2015). The exposure of coffee plants to solar radiation plays a crucial role in the physiology of the plants, influencing factors such as leaf temperature and humidity. The exposure of the plants to solar radiation and the arrangement of the planting rows can significantly impact the absorption of solar radiation between the sides of the plant rows (Alves et al., 1983; Ferreira et al., 2022). A lower exposure to solar radiation due to the arrangement of crop rows is associated with a marked reduction in temperature and an increase in leaf moisture (Bosselmann et al., 2009; Ferreira et al., 2022), conditions that may increase the vulnerability of plants to adverse weather events such as frost (Chaves et al., 2012).

The absorption of solar radiation is essential for determining leaf and air temperatures, as it affects the vapour pressure, water status maintenance and oxidative stress in plants (Holmgren, 2003). However, studies on the influence of sun exposure in planting rows and frost damage in coffee plants are rare. Ferraz et al. (2014) evaluated the spatial dependence of the detachment force of unripe fruits based on the side exposed to the sun (east and west). Chaves et al. (2012) reported that the magnitude of fruit production may vary between the opposite sides of coffee trees grown in rows. These findings highlight the importance of a north-south orientation in coffee planting lines to optimize sun exposure and create ideal conditions for the growth and development of crops. However, the extent to which the exposure face influences frost damage is not known.

Frost is a microclimatic phenomenon characterized by temperatures below 2 °C in sheltered areas and ranging from −2 °C to −3 °C at ground level (Caramori et al., 2001). It has devastating effects on plants. This extreme weather event causes water to freeze within plant tissues, leading to the formation of ice inside the cells, which results in the rupture of cell walls and necrosis of plant tissue (Morais et al., 2009). Studies on the impacts of frost on agronomic characteristics demonstrate that foliar damage in *Coffea arabica* L. cultivars can be severe, potentially leading to plant death and total yield loss (Júnior & Menechini, 2021). Leaves, which play an important role in interaction with electromagnetic radiation, may exhibit significant changes in their spectral behaviour when damaged (Morais et al., 2009). This can impair the plant's ability to recover and maintain its productivity.

This contextualization of the effects of frost reinforces the need to understand how sun exposure, especially on the north and south faces of plants, can influence the severity of damage and recovery after frost. Although it is known that the north and south faces receive different amounts of sunlight throughout the day, creating microclimates that affect the physiology and resistance of plants, there is still a gap in understanding how these differences impact the resilience of cultures to extreme weather events. Thus, this study aims to evaluate how sun exposure influences phenology and the damage caused by frost in coffee plantations, using remotely piloted aircraft (RPAs) as a tool for data collection, contributing to a better understanding of the interactions between soil and climate factors and crop resilience.

Materials and methods

Description of the area

The study was carried out at Fazenda Bom Jardim (Figure 1), situated in Santo Antônio do Amparo, in the western region of Minas Gerais, Brazil, at the geographical coordinates 21°00′58.9″S and 44°55′24.9″W and an elevation of 950 m above sea level.

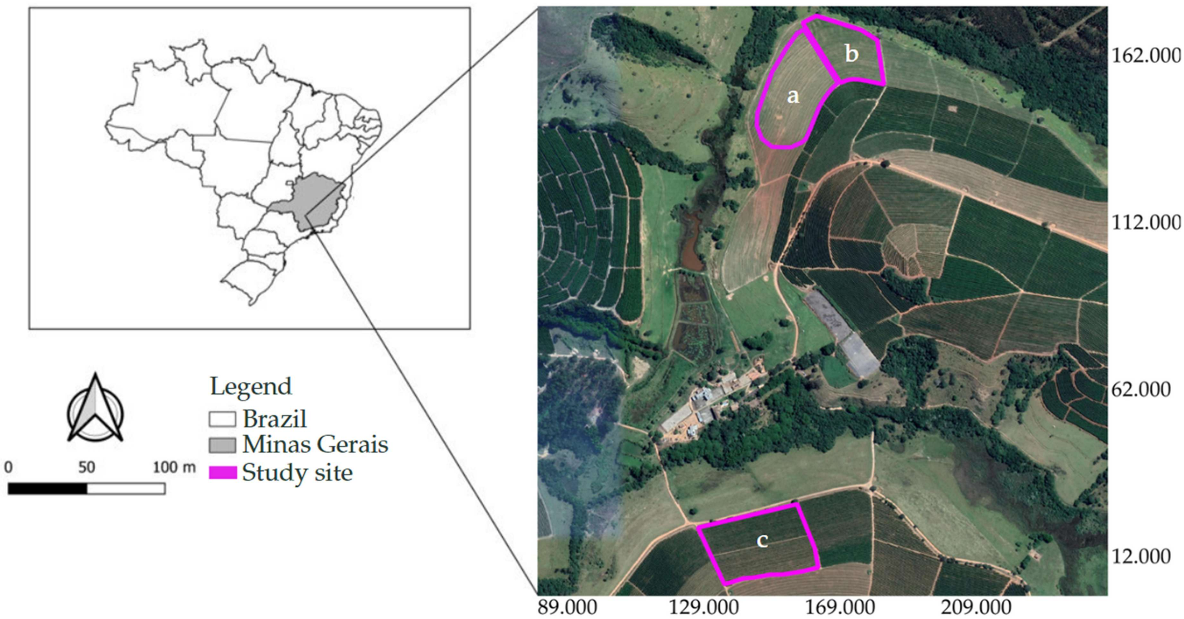

Figure 1. Geographical location of the study area. Areas used in the experiment with one year of age (a), two years of age (b) and eight years of age (c).

Frost event was recorded on July 19, 2021, when minimum temperatures reached −1.7 °C. Temperature data were obtained from an automatic weather station installed within the experimental area. The climate of the region is classified as Cwa with humid subtropical conditions according to the Köppen–Geiser classification. The area has hot and humid summers and cold, dry winters, with average, minimum and maximum temperatures of 20 °C, 14 °C and 26 °C, respectively. The mean annual minimum rainfall is 1400 mm and the mean annual maximum rainfall is 1670 mm (Alvares et al., 2013).

Experimental design

Three experimental coffee plantation areas (*Coffea arabica* L.) with distinct characteristics, including planting seasons and specific varieties, were used. Figure 2 shows the different planting areas within the experimental areas.

The areas were designated as the 1-year area, 2-year area and 8-year area, and the age of the plants was determined based on the interval between planting and the occurrence of frost. The 1-year area covered 31,966 m^2 and was planted with coffee plants of the cultivars Catucaí and Arara; the 2-year area had 19,546 m^2 of coffee plants of the Catuaí Amarelo cultivar; and the 8-year-old area was planted with coffee plants of the cultivar Catucaí Vermelha IAC 144 and covered 35,176 m^2. All three areas were planted with a spacing of 0.5 m between plants and 3.5 m between rows.

Aerial imagery and image processing

The first step involved generating a database containing digital images. A remotely piloted aircraft (RPA) and an attached multispectral camera were utilized to obtain the images. The RPA used was a commercial 3DR Solo (3D Robotics, 2024) with four engines (quadricopter).

The images were captured by a Parrot Sequoia multispectral camera that has an RGB sensor with a resolution of 16 megapixels (4608 × 3456) and four extra sensors with a resolution of 1.5 megapixels (1280 × 960) in the green (550 nm BP 40), red (660 nm BP 40), red border (735 nm BP 10) and near infrared (790 nm BP 40) spectral bands. The ground has a pixel size of about 0.8 cm per pixel. To mitigate atmospheric interference effects, a radiometric correction plate was employed during the flights. Image acquisition was conducted with 80% overlap, at a flight altitude of 30 m and a speed of 30 m/s. The image

(a) (b) (c)

Figure 2. Coffee plants and their structural characteristics in: (a) One-year area; (b) two-year area; (c). eight-year area.

Table 1. Vegetation indices calculated from the reflectance of the multispectral bands of the images.

Vegetation index	Formula	References
NDVI (normalized difference vegetation index)	(Nir–Red)/(Nir + Red)	Rouse et al. (1974)
MCARI2 (modified chlorophyll absorption ratio index)	1.5 (2.5 (Nir–Red)–1.3 (Nir–Green)) (Nir/Red)/√(2Nir + 1) 2–(6Nir–5√Red)–0.5	Haboudane et al. (2004)
SAVI (soil adjusted difference vegetation index)	(1 + 0.5) * ((Nir–Red)/(Nir + Red + 0.5)	Huete (1988)
CIrededge (chlorophyll index red edge)	(Nir/Red edge)–1	Ahamed et al. (2011)

Note: Reflectance in the bands (RedEd) between red and infrared (borderline red); (Red) red; (Nir) near infrared; (Green) green. Source: From the Author (2025).

dataset was processed using the student version of Pix4Dmapper software, with parameters configured at the highest precision level. The images were merged to generate orthomosaics, which served as the basis for vegetation index calculations. Pix4Dmapper, specifically designed for processing datasets from remotely piloted aerial surveys, automatically determines the positions and orientations of the original images through Aerial Triangulation (AT) and Bundle Block Adjustment (BBA). From the three-dimensional point cloud obtained during AT and BBA, a Digital Surface Model (DSM) is constructed by connecting the points. The orthomosaic is subsequently generated by projecting and integrating the original images with the DSM. The default "Ag Multispectral" model was applied to produce orthomosaics from the individual spectral bands (green, red, red edge and near-infrared). Image reflectance was corrected using a calibrated reflectance panel. Following orthomosaic generation, vegetation indices were computed in QGIS and exported in TIFF format for subsequent analysis.

The selection of vegetation indices was based on a study by Marin et al. (2021), who evaluated and identified indices that can be used to evaluate the spectral response of plants to frost damage. The selected vegetation indices are shown in Table 1. The areas of interest for vegetation indices were cropped after processing the orthomosaics.

Using the Raster Calculator tool in the Raster menu of QGIS 3.4.14-Madeira software (QGIS Development Team, 2018), the vegetation indices of the images were measured. After preparing the vegetation indices, *buffers* were created for the georeferenced field sampling points. The average values of the *pixels* of the image corresponding to each plant were extracted using the Zonal Statistics tool in QGIS 3.4.14-Madeira software (QGIS Development Team, 2018). The average values were analysed statistically. The performance of vegetation indices in estimating frost damage on the north and south faces of coffee plants was assessed by exporting pixel values in XLSX format.

Damage assessment

The methodology described by Soderholm and Gaskins (1960), Androcioli Filho et al. (1986) and Morais et al. (2009) was used to perform a visual evaluation of frost damage to coffee plants. In this evaluation system, three independent evaluators visually assess three sections of each plant (upper, middle and lower third), considering leaves and branches. They assign scores from 0 to 10, calculate an average score for each plant, and convert the scores into percentages. Plant parts exhibiting brown coloration and necrosis, physical characteristics resulting from cell death due to freezing, were classified as damaged. The average values obtained by each evaluator were grouped into damage classes, with scores ranging from one to ten corresponding to damage percentages from 0% to 100%, as outlined in the table described in the article by Marin et al. (2021).

Evaluation of recovery and vegetative growth

The coffee plants were evaluated by measuring the following variables: leaf number (NL), number of nodes per branch (NN) and frost damage (FD). Eighteen plants were evaluated in each climatic risk area (low risk and high risk), and the evaluated plants were distributed in the production area to evaluate the spatial distribution of plant responses. In each climate-risk area, nine plants were evaluated on each face; a total of 36 plants were used, covering the three plant ages. The plants on the southern and northern sides of the planting row were evaluated to determine the influence of sun exposure. Two branches (upper and lower) from the middle third of each evaluated plant were collected to assess the variables. Figure 3 shows the evaluations performed in the study area. Evaluations were performed in the area three days after the frost event (3 DAF) on 7/22/21 and one hundred three days after the frost event (103 DAF) on 10/29/21.

Statistical analyses

To assess the mean differences in frost damage and vegetative responses in different climate risk zones and the southern and northern faces of the plants, a 2×2 factorial statistical analysis was conducted using SISVAR software (Ferreira, 2019). To evaluate the mean differences in frost damage and vegetative responses as a function of plant orientation and climatic risk zones, a factorial analysis of variance (ANOVA) was conducted in a 2×2 design. The design considered two factors, each with two levels:

(a) (b) (c)

Figure 3. Evaluation of coffee plants and their structural characteristics at 103 days after frost (DAF) in: (a) one-year-old plants, (b) two-year-old and (c) eight-year-old.

- Climatic risk zone: high-risk zone and low-risk zone;
- Plant face: south face and north face

The combination of these factors resulted in four experimental groups: High risk (HR)—south face; High risk—north face; Low risk (LR)—south face; and Low risk—north face. This arrangement allowed for the evaluation of both the main effects of each factor individually and the interaction between them, making it possible to identify mean differences in frost damage and vegetative response among the groups.

For data analysis using the multiple linear regression model, all vegetation indices presented in this study (NDVI, MCARI2, SAVI, CIRededge) were included. The model was adjusted to explain the damage, identifying significant variables at the 5% significance level and estimating parameter values. The stepwise computational method was used for variable selection, a procedure that iteratively includes or excludes variables based on an algorithm that evaluates their importance, following a predefined decision rule.

Residual analysis was conducted to check for any violations of the model assumptions. Residue analysis was conducted using the following graphic techniques: Residuals versus fitted values plot, histogram plot, studentized residuals versus fitted values plot, and residuals normality plot for the model 1 (Appendix: Figure A1) and model 2 (Appendix: Figure A2). In addition to graphical analysis, normality will be confirmed by the Shapiro-Wilk test at a 5% significance level All computational aspects were carried out using the open-access software R (R Core Team, 2023).

It can be observed in Figures A1 and A2 (Appendix A) that the histogram and normal probability graph of the residues, which assumption of random errors have a normal distribution. The random errors have a normal distribution. However, this hypothesis was confirmed by the Normality test of Shapiro Wilk, we have:

Hypotheses that were tested:

H_0: Random errors follow a Normal Distribution;

H_1: Random errors do not follow a Normal Distribution.

As by the Shapiro–Wilk test the p-value was equal to 0.9524 for model (1) and 0.8517 for model (2), that is, at 5% of significance, H is not rejected lower than line 0, so errors follow the normal distribution. The focus of the investigation was to evaluate possible differences in frost damage, vegetation indices and vegetative response between the southern and northern faces of the plants.

Results

Statistical analysis of southern and northern faces

Table 2 shows the results of the variance analysis and the average test for frost damage (FD). For the plants of one and two years, it is noticed that FD does not present remarkable differences between the faces

Table 2. Frost damage (FD) in one-, two- and eight-year-old coffee plants in different zones of climatic favourability in the study areas and the southern and northern faces.

	Low risk (LR)		High risk (HR)	
Climatic zones	North	South	North	South
One-year-old FD (%)	9.72 Ba	12.50 Ba	64.38 Aa	62.27 Aa
Two-year-old FD (%)	14.44 Ba	8.88 Ba	48.88 Aa	50.55 Aa
Eight-year-old FD (%)	5.70 Ba	2.37 Ba	48.00 Aa	32.88 Ab

Note: Means followed by the same uppercase letter in the row do not differ between LR and HR, and means followed by the same lowercase letter in the row do not differ between the North and South faces, according to Tukey's test ($p < 0.05$). From the Author (2025).

(south and north) observed. In the eight-year-old coffee plantation (Table 2), it was noted that in the sample analysed, the north face showed higher values of FD (48.00%).

In relation to the climatic zones Low risk and High risk (Table 2), the south and north faces presented a higher percentage of frost damage in High risk at all planting ages, with FD exceeding 30%. The plants located on the northern face and climatic zones High risk experienced greater damage after frost.

Table 3 shows the results from the analysis of variance and mean test for the number of leaves (NL) and the number of nodes per branch (NN).

The quantities of NL and NN were recorded on two specific dates (3 DAF and 103 DAF). There were no visually significant disparities between the NL and NN, on the observed southern or northern sides at 3 DAF. In the case of one-year-old plants (Table 3), there were visually significant disparities between the NN on the observed southern or northern sides at 103 DAF in the Low risk climate zone.

There was a difference in NL and NN between the solar exposure faces to 103 DAF, in the high-risk climate zone (Table 3). In the high-risk climate area with eight-year-old plants, there were differences in the incidence of leaf damage (Table 2) and in the number of leaves and between the sun exposure faces.

Inferential analyses of vegetation index

Table 4 shows the results that provide information on the median and the interquartile range (IQR), which are central and dispersion statistical measures used to characterize the data distribution. The interquartile range is not sensitive to outliers because it eliminates some of the major and minor values and calculates the range using only the remaining the remaining values. Interquartile range = 3rd quartile—1st quartile = Q3—Q1.

Table 5 shows the findings from the vegetation index analysis conducted on one-, two- and eight-year-old plants. There is a difference only concerning the damage, as the plants located on the north face showed greater damage after frost.

Vegetation indices showed differences between the northern and southern faces in different ways for each planting age (Table 5). However, among the vegetation indices, only the SAVI (Table 5) presented results similar to those collected in the field of FD, as shown in Table 2. The SAVI showed a difference between the northern and southern faces in the high climate risk zone for plants that were eight years old,

Table 3. Analysis of variance and mean test for the number of leaves (NL) and the number of nodes per branch (NN) in one-, two- and eight-year-old coffee plants in different zones of climatic favourability in the study areas and the southern and northern faces, at 3 days after frost (DAF) and 103 days after frost (DAF).

	Climatic zones			
	Low risk (LR)		High risk (HR)	
Variables	North	South	North	South
	One-year-old (3 DAF)			
NL	4.72 Ba	5.89 Ba	9.00 Aa	9.44 Aa
NN	5.44 Aa	5.67 Aa	5.39 Aa	5.61 Aa
	Two-year-old (3 DAF)			
NL	4.39 Ba	5.06 Ba	11.11 Aa	11.56 Aa
NN	11.78 Aa	12.11 Aa	10.72 Aa	10.72 Aa
	Eight-year-old (3 DAF)			
NL	1.67 Ba	2.06 Ba	7.33 Ab	4.72 Ab
NN	6.39 Ba	4.83 Ba	8.50 Ab	8.39 Ab
	One-year-old (103 DAF)			
NL	7.77 Aa	7.66 Aa	3.55 Aa	3.88 Ba
NN	7.11 Aa	5.00 Ab	5.66 Aa	4.77 Aa
	Two-year-old (103 DAF)			
NL	8.33 Ba	12.55 Aa	1.11 Aa	8.22 Ab
NN	12.22 Aa	11.22 Aa	4.33 Ba	6.22 Ba
	Eight-year-old (103 DAF)			
NL	18.56 Aa	14.00 Aa	18.33 Aa	1 Bb
NN	9.66 Ba	8.77 Aa	14.66 Aa	9.55 Ab

Note: The capital letters indicate differences between the LR and HR climate zones on the North and South faces. The lower-case letters differ horizontally between the North and South faces within each climate zone. From the Author (2025).

Table 4. Results of the distribution analysis using measures of central tendency and dispersion were analysed for vegetation indices between the southern and northern faces.

Vegetation index	Min	1st Qu.	Median	Mean	3rd Qu.	Max
			North			
NDVI	0.22	0.45	0.49	0.47	0.53	0.65
MCARI2	0.08	0.21	0.25	0.25	0.29	0.48
CiredEdge	0.18	0.41	0.45	0.41	0.49	0.52
SAVI	0.19	0.34	0.38	0.37	0.42	0.58
			South			
NDVI	0.29	0.39	0.49	0.46	0.53	0.55
MCARI2	0.11	0.17	0.25	0.23	0.29	0.33
CiredEdge	0.26	0.36	0.43	0.41	0.46	0.52
SAVI	0.23	0.29	0.38	0.36	0.41	0.45

Note: Min: minimum; 1st Qu.: first quartile; Median: median; 3rd Qu.: third quartile; Max: maximum.

Table 5. Results of the variance analysis of vegetation indices between the southern and northern faces in climate risk areas for vegetation at 3 days after frost (DAF) and 103 days after frost (DAF).

	Low risk		High risk	
Vegetation index	North	South	North	South
		One-year-old (3DAF)		
NDVI	0.53 A	0.49 A	0.28 A	0.34 B
MCARI2	0.30 B	0.26 A	0.13 A	0.16 B
CIREDEDGE	0.45 A	0.43 A	0.24 A	0.31 B
SAVI	0.43 B	0.39 A	0.24 A	0.28 B
		Two-year-old (3DAF)		
NDVI	0.81 B	0.76 A	0.70 A	0.69 A
MCARI2	0.53 B	0.48 A	0.43 A	0.43 A
CIREDEDGE	8.71 B	6.82 A	4.84 A	4.63 A
SAVI	0.80 B	0.76 A	0.70 A	0.69 A
		Eight-year-old (3DAF)		
NDVI	0.83 A	0.80 B	0.79 B	0.81 A
MCARI2	0.31 A	0.15 B	0.12 B	0.08 A
CIREDEDGE	0.84 B	1.15 A	1.15 B	1.34 A
SAVI	0.44 A	0.25 B	0.24 A	0.15 B
		One-year-old (103 DAF)		
NDVI	0.59 A	0.58 A	0.28 A	0.29 A
MCARI2	0.32 A	0.31 A	0.09 A	0.09 A
CIREDEDGE	0.42 A	0.42 A	0.22 A	0.21 A
SAVI	0.46 A	0.44 A	0.21 A	0.20 A
		Two-year-old (103 DAF)		
NDVI	0.87 B	0.84 A	0.85 A	0.84 A
MCARI2	0.64 B	0.61 A	0.61 A	0.60 A
CIREDEDGE	0.55 B	0.51 A	0.49 A	0.49 A
SAVI	0.71 B	0.68 A	0.68 A	0.67 A
		Eight-year-old (103 DAF)		
NDVI	0.87 A	0.86 A	0.76 B	0.72 A
MCARI2	0.65 A	0.57 B	0.42 B	0.37 A
CIREDEDGE	0.59 A	0.64 B	0.47 A	0.49 A
SAVI	0.71 B	0.65 A	0.52 B	0.48 A

Note: Means followed by the same uppercase letter in the row do not differ from faces North e South.

three days after the frost (Table 5). On the date 103 DAF the MCARI2 and SAVI showed the difference between the faces in eight-year planting in high and low climate risk areas.

To improve the accuracy of frost damage (FD) estimates using vegetation indices as independent variables, a Multiple Linear Regression model was applied, incorporating all indices. The stepwise computational approach was utilized, and the selected models are presented below:

Estimate of frost damage generated by vegetation indices faces the north:

$$\begin{aligned} FD &= -225.9 - 3112.7 * MCARI2 - 614.7 * CiredEdge + 3495.0 * SAVI \\ R^2 &= 43.31\% \end{aligned} \quad (1)$$

Estimate of frost damage generated by vegetation indices facing south:

$$\begin{array}{l} FD = -472.8 - 5853.6 * MCARI2 - 580.7 * CiredEdge + 5952.8 * SAVI \\ R^2 = 65.72\% \end{array} . \qquad (2)$$

In the adjusted model (1) for the north and south faces of the plants, the MCARI2, CireEdge and SAVI indices were identified as the most effective in describing frost damage, with the model achieving a coefficient of determination (R^2) of 43.31%. For the adjusted model (2), developed specifically for plants on the south side, the coefficient of determination (R^2) accounts for 76.44% of the data variability.

Discussion

Frost damage and relationship between vegetative growth and faces of the plant

A few published studies on this topic show that coffee trees are highly influenced by sun exposure. Both light and temperature affect bud differentiation, fruit ripening speed, vegetative growth and injuries (Santinato et al., 2020). Leaf damage is directly related to decreases in temperature and sun exposure time. Mariucci Junior et al. (2022) reported that the effect of freezing temperature increases with increasing exposure time.

However, the present study showed that, in younger plants, direct sunlight exposure on a given face does not seem to have a significant impact on frost damage. This can be attributed to the specific characteristics of plants in the early stages of development, such as height and foliage. Specifically, height and foliage do not provide shade for plants, which can delay the effect of sunlight on their leaves. Fahl et al. (2000) evaluated the microclimatic variations after a frost event in a 3-year-old coffee plantation and reported that two weeks after the event, the plants had fully recovered. In summary, in plantations with young plants, the conditions needed for severe damage to occur on each face in the planting row may not exist.

In the first visit after the frost, a greater percentage of leaf damage was observed on the northern face of the planting row, where there was no sunlight early in the morning. In the second visit, these results were confirmed by the greater leaf density on this side of the planting row. Consequently, the southern face had a larger number of leaves. As indicated by Camargo and Camargo (2004), although frost damage is commonly associated with "morning sunshine", observations of frost-affected coffee plants showed that no significant damage occurred on the face exposed to the first warm rays of the morning sun.

A notable difference was observed between the southern and northern sides of the eight-year-old plants relative to date 103 DAF, on the second visit (103 DAF). In the analysed sample, the southern face exhibited higher values of NFL and NFR. Beginning at the second field visit, three months after the frost, the plants started to defoliate in areas affected by the frost. This finding helps to explain the results obtained.

According to Santinato et al. (2020) and Cassia et al. (2013) the disparity between solar exposure faces is remarkable. The southern face of coffee plants, which receives sunlight in the morning, has larger leaves and a darker green colour. Therefore, the opposite face, to the north, receives the sun's rays hours later, resulting in prolonged shading. The northern face is also impacted by more intense sunlight in the afternoon. These results consistently show that the side of the plant exposed to morning sunlight is linked to a lower occurrence of disease and defoliation.

On the other hand, on the face where solar incidence occurs later, greater defoliation occurs. This finding can be explained by the fact that on this face, the foliage does not dry quickly in the morning; thus, greater humidity is maintained. This difference in sunlight exposure contributes significantly to the patterns observed in plants.

The results shown in Tables 2 and 3 emphasize the strong correlation between frost damage and the topographic features of the coffee plantation. Specifically, in the eight-year-old planting area, which is identified as having a high climate risk, the damage was more evident on the northern and southern faces of the plants in each planting row.

As noted in Camargo and Camargo (2004), topographic factors play a critical role in air circulation and movement. Cold air, being denser than warm air, accumulates on the soil surface overnight due to heat loss. On sloping terrains, this cold air tends to flow downward and gather in depressions or valleys.

Therefore, it is reasonable to anticipate more frequent frosts in these lower areas, resulting in more severe leaf damage to plants located in this zone.

Vegetation index in relation to frost leaf damage on the north and south sides of the plant

The results of vegetation indices are directly related to plant vigour, with frost damage, number of leaves and sunlight incidence being factors that lead to different values in these indices. These findings demonstrate a strong and proportional relationship between these vegetation indices and the occurrence of frost damage. They provide valuable insights into the response patterns of plantations to frost phenomena across different ages of coffee plantations and various aspects of the plant. This study reinforces the essential role of remotely piloted aircraft in field damage identification and quantification. The use of multispectral images obtained by RPA allowed the generation of vegetation indices highly sensitive to physiological changes in coffee plants, being key to estimating frost damage with greater precision and spatial coverage than traditional visual assessment methods.

From field observations, it is known that the side of a plant receiving sunlight in the morning has larger, more flaccid leaves with a more saturated green colour than does the side that receives sun in the afternoon; these leaves are characterized by being smaller and yellowish-green. Several investigative studies involving plants in shade and full sun can be found in the literature (Carelli et al., 2000). Cassia et al. (2013) suggested that one plant shades another, depending on the planting direction, in addition to self-shading and the "umbrella" effect, where the branches of the upper third of the plant overlap those of the lower two-thirds. Bicalho et al. (2005), reported that parts of plants exposed to afternoon sunlight had lower branch and leaf growth, higher temperatures and lower photosynthesis and transpiration rates.

These conditions result in endogenous control influenced by climate, leading to asynchronous growth, where some plant parts grow while others undergo defoliation due to leaf damage. Based on these findings, it can be inferred that the coffee plants in a row associated with the north and southern faces of sun exposure will exhibit distinct behaviours in response to frost, with a greater percentage of damage on the northern side of the planting line.

Because there was a significant difference in the damage observed on the eight-year-old plants, the effect was verified in the different risk zones (high and low risk) (Table 2). In the eight-year area with high climate risk, there was a difference in the incidence of leaf damage and in the number of leaves on the northern and southern sides of the plants.

As the air descends, the temperature decreases. Physical barriers can efficiently stop this downwards flow of cold air. In the study area, topographic features were observed around the plantation that may have contributed to the damming of cold air in the lower part of the slope. In addition, sun exposure to the planting rows played a significant role in increasing damage to the northern face, which does not receive direct solar radiation in the morning, thus creating a microclimate conducive to more intense leaf damage.

When plants are exposed to prolonged freezing temperatures, the formation of ice crystals in the extracellular space leads to a steady movement of water from inside the cells to the extracellular area. This process causes the protoplast to dehydrate and results in the freezing of the intracellular contents. The formation of intracellular ice crystals leads to severe and often fatal damage to cells (Taiz & Zeiger, 2009). Several studies, mainly those focused on microclimatic factors, have recommended several methods for improving cultivation outcomes, especially for locations with appropriate microclimates, such as exposed faces, slopes and topographic configurations (Caramori & Manetti Filho, 1993; Fahl et al., 2000).

Extracellular liquids are poorer in solid solubility than intracellular liquids and therefore tend to freeze more easily. Intracellular fluids may leak and form extracellular ice crystals. The cytoplasm can shrink and move away from the cell wall; this phenomenon, known as plasmolysis, is irreversible and leads to cell death. In severe cases, cells can be crushed by the pressure of extracellular ice crystals (Camargo, 2010).

In summary, the results highlight the importance of topographic characteristics and solar exposure in the manifestation and intensity of frost damage in coffee plantations, especially in areas with high climatic risk. The relationship between the orientation of sun exposure and the age of the plants was crucial, with more pronounced damage on the northern faces of eight-year-old plants.

The presence of topographic features around the plantation and sunlight exposure played essential roles in creating microclimates conducive to more intense damage, especially on the northern face, which does not receive direct morning sun. Therefore, a judicious selection of planting sites is recommended, considering the orientation and slope of the soil. The results of this study provide a basis for understanding the factors that influence the susceptibility of coffee plantations to frost, providing valuable information for management practices and selecting locations that are conducive to planting, to mitigate the impacts caused by frost events.

Conclusions

This study showed that, in coffee trees with eight years of age, the north face presented a higher incidence of frost damage, reflecting a significant reduction in the number of leaves, nodes and, potentially, flowers and fruits. In contrast, one and two-year-old plants did not show significant differences of damage between the north and south faces, possibly due to their smaller height and the absence of shading between plants, which allows a more uniform distribution of solar radiation.

The vegetation indices SAVI and MCARI2 showed strong correlation with frost damage levels, reinforcing the potential of remote sensing as an efficient tool for diagnosis and real-time monitoring. The use of remotely piloted aircraft (RPAs) equipped with multispectral cameras proved to be an effective strategy for detecting spatial variations in damage and assessing vegetative response, supporting the application of precision agriculture in coffee plantations.

In addition, the topography of the terrain and the sun exposure of the plants are determinants in the creation of differentiated microclimates that directly influence the severity of the damage. To reduce the impacts of frost on coffee plantations, future studies should explore management strategies considering the sun exposure of plants throughout the day. The incorporation of predictive models based on multispectral images can also assist in agricultural planning and decision-making, especially in regions with greater climate risk.

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Author contributions

None.

Disclosure statement

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Appendices

Appendix A

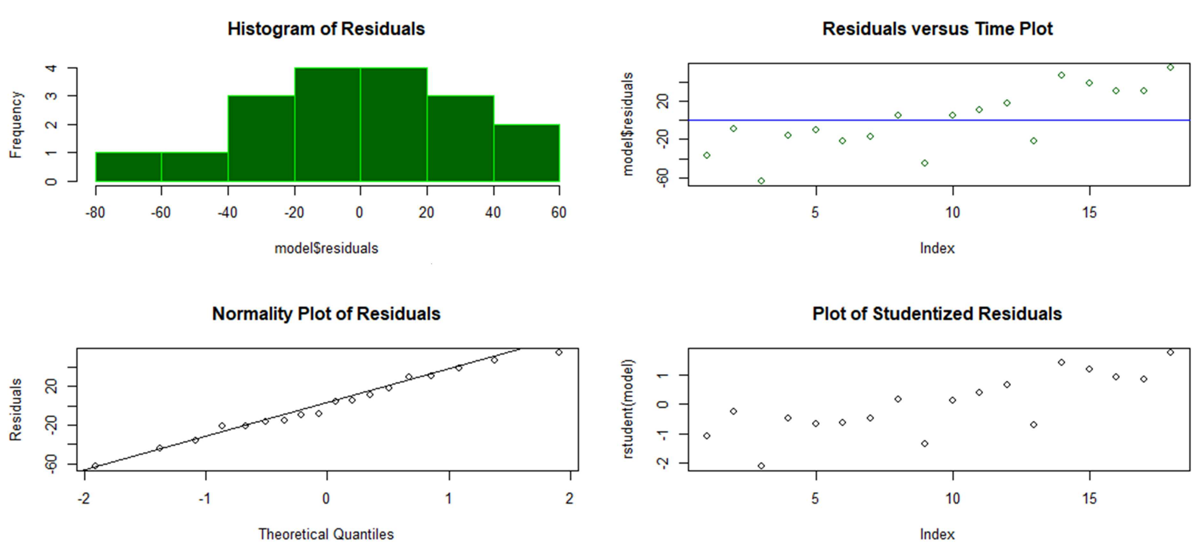

Figure A1. Residue chart for the model (1).

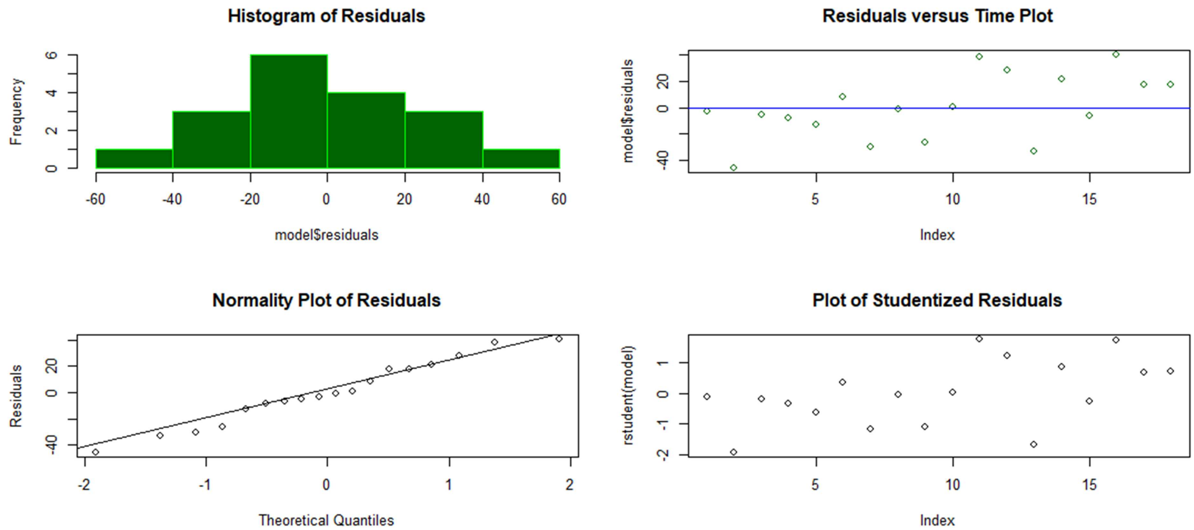

Figure A2. Residue chart for the model (2).