Agronomy Research **21**(S3), 1555–1566, 2023
https://doi.org/10.15159/AR.23.084

Preliminary study on the potential use of RPA images to quantify the influence of the defoliation after coffee harvesting to its yield

L.M. dos Santos[1,*], G.A.S. Ferraz[1], M.A.F. Carvalho[2], M.S. Vilela[3] and P.H.O. Estima[1]

[1]Federal University of Lavras, Department of Agricultural Engineering, University Campus, BR37.200-000 Lavras-MG, Brazil
[2]Embrapa Café, Brasília BR70770-901, Distrito Federal, Brazil
[3]Federal University of Lavras, Department of Agronomy/ Phytotechnics, University Campus, BR37.200-000 Lavras-MG, Brazil
[*]Correspondence: luanna_mendess@yahoo.com.br

Received: January 24th, 2023; Accepted: May 22nd, 2023; Published: September 18th, 2023

Abstract. Coffee is an agricultural commodity with global commercial importance capable of impacting the production chain. The quantification of defoliation at harvest is important for monitoring crop yield because defoliation is one of the main types of damage caused by this agricultural operation in coffee crops. Thus, the objective of this study was to evaluate the relationship between yield and defoliation obtained in the field and obtained through remotely piloted aircraft (RPA) images. The experiment was conducted in a coffee plantation belonging to the Federal University of Lavras (UFLA), Lavras, Minas Gerais state, Brazil. An RPA with a rotary wing containing a multispectral camera was used in autonomous flight mode with a height of 30 m, an image overlap of 80%, and a speed of 3 m s^{-1}. The images were collected before and after the 2020 and 2021 harvest, defoliation data obtained in the field were measured in 2020 and 2021, and the yield was measured from 2019 to 2021. Image processing was performed in the software PhotoScan, postimage processing was performed in QGIS, and statistical analyses were performed using the software R. With the processing of the images in 2020, the crop showed reductions of 17.3% and 18.4% in leaf area and volume, respectively, after harvest. In 2021, the crop showed reductions of 12.8% and 9.8% in leaf area and volume, respectively, after harvest. The leaf area and leaf volume of the coffee plantation after harvest could be quantified by means of images obtained by RPA, which allowed the observation of the loss of area and volume of the coffee plantation. Furthermore, it was possible to analyse the interactions between field data and the yield of the same harvest year, which were directly proportional, and the interaction of image data from one year with the previous yield, which were inversely proportional. In the year 2020, there was a reduction of 17.3% in leaf area after harvest, and a reduction of 18.4% in leaf volume after harvest in the plots under study.In the processing carried out in 2021, there was a 12.8% reduction in leaf area after harvest, and a 9.8% decrease in leaf volume after harvest in the plots under study.

Key words: canopy volume, coffea arabica l., digital image processing, harvest, systems of unmanned aircraft.

INTRODUCTION

Coffee is an agricultural commodity of global importance with the ability to impact the production chain. The estimated global coffee production for the 2020/2021 harvest was 175.5 million bags (60 kg). Brazil significantly participates in this sector; it contributes the greatest proportion at approximately 38.6% of the world coffee production (USDA, 2021). This makes Brazil the largest producer and exporter of Coffea arabica and the second largest producer of Coffea canephora of the global production of this cultivar.

These data reflect the significant economic and social importance of this culture for Brazil. In addition, due to the growing global demand for specialty coffees, it is necessary to develop productive techniques and culture monitoring to differentiate Brazilian producers. However, this culture undergoes oscillations such as those cited by Silva et al. (2010), in which factors such as crop management can also cause spatial and temporal variations in the crop.

The quantification of defoliation at harvest is important for monitoring crop yield because it is one of the main types of damage caused by this agricultural operation in the coffee crop. Defoliation causes the plant to produce less in the following year because it uses its reserves to recompose its vegetation, which results in less fruit (Silva et al., 2010). Thus, frequent defoliation induces plant stress and reduces plant longevity (Bártholo & Guimarães, 1997; Oliveira et al., 2007).

Precision agriculture combined with computational tools has been studied and widely disseminated in terms of coffee crops. According to Amaral et al. (2020), sensors and applications in remote sensing (RS) at all levels (orbital, aerial and terrestrial) have significantly evolved; however, at the aerial level, remotely piloted aircraft (RPA) were one of the most developed tools in recent years. This tool captures images with high spatial resolution (with a spatial resolution on the order of mm, depending on the flight height) and high temporal resolution (it is possible to use RPA whenever there are good climatic conditions and sufficient battery life) that can be processed by using the Structure from Motion (SfM) algorithm.

SfM is based on the principles of traditional stereoscopic photogrammetry, using the overlapping of multiple images obtained by conventional cameras to obtain geometric characteristics and generating a 2D and 3D point cloud (Martínez-Carricondo et al., 2018; Santos et al., 2020a). The point cloud facilitates the generation of a digital surface model (DSM) and digital elevation model (DEM); these products can be used for the production of orthophoto mosaics, 3D modelling, and metric information such as area, volume, and height (Nex & Remondino, 2014; Santos et al., 2020a).

In this context, the use of RPA has enabled the collection of data for estimating morphological parameters (Santos et al., 2020a; Barbosa et al., 2021), crop coefficients (Kc) (Santos et al., 2020b), and leaf area indexes (Santos et al., 2020c), volume (Cunha et al., 2019) and for monitoring leaf nitrogen (Parreiras et al., 2020; MARIN et al., 2021b), frost damage (MARIN et al., 2021a), and fruit ripening (Martins et al., 2021).

Cunha et al. (2019) developed a methodology to determine the vegetation volume of coffee crops from RPA images and compared this approach with the traditional estimate of vegetation volume (the tree row volume (TRV) method). The authors studied this method under normal crop conditions to obtain the volume for defining pesticide application techniques. These authors concluded that the vegetation volume of coffee plants can be determined in a practical and accurate manner by digital processing of the images captured by RPA because it is a fast method that allows the evaluation of large areas.

However, the quantification of the area and volume of coffee crops after harvest using images obtained by RPA to obtain defoliation have not been explored. Based on this, we hypothesize that it is possible to quantify the area and volume of coffee crops before and after harvest to obtain defoliation by using RPA; this would be useful for supporting studies on the biennial production and yield of crops that undergo this agricultural operation. In this sense, the objective was to evaluate the relationship between yield and defoliation obtained in the field and obtained through RPA images.

MATERIALS AND METHODS

Study area

We conducted the experiment in an area of 0.48 ha in an experimental coffee plantation (Coffea arabica L.) belonging to the Coffee Plant Sector of the Department of Agriculture (DAG, for its acronym in Portuguese) of the Federal University of Lavras (UFLA), in Lavras - MG. We used the cultivar 'Mundo Novo 379-19'; this cultivar was planted in January 2016, with a spacing of 3.6 metres between the planting rows and 0.75 metres between the plants, and its treatments are described by Castanheira et al. (2019) and Alecrim et al. (2020).

The geographic coordinates of the area are 21°13'36.47" South latitude and 44°57'40.35 West longitude, with a mean altitude of 975 metres, the terrain under study has a 2% slope (Fig. 1).

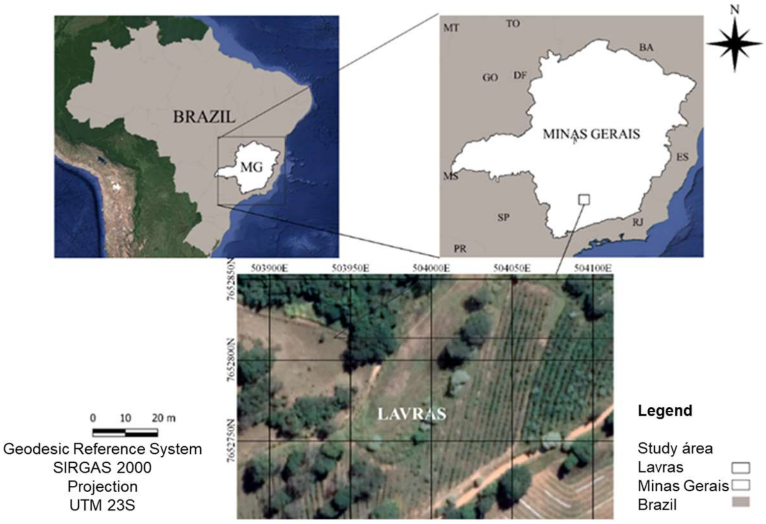

Figure 1. Delimitations of the state of Minas Gerais, the municipality of Lavras, and the study plot.

We used a total of 90 experimental plots, in which each experimental plot consisted of six plants, with four central plants being considered useful plants. We used a border row between the treatment rows to avoid interference. We georeferenced the study area, the sampled plots, and control points with the aid of a differential global positioning system (DGPS) (Trimble Navigation Limited, Sunnyvale, California, USA) with horizontal and vertical accuracy of 0.007 m.

Acquisition and processing of RPA images

In this study, we used a quadcopter (Matrice 100, DJI) equipped with a high spatial resolution multispectral camera (Parrot SEQUOIA) carrying a payload of 72 g as the RPA platform to capture images in the visible range of the RGB spectrum (red - R, green - G and blue - B) and images in nonvisible spectral ranges such as red edge (REG) and near infrared (NIR).

The RGB camera had a resolution of 16 megapixels with a lens focal length of 5 mm. In addition, the camera had another 1.2-megapixel sensor with a focal length of 4 mm and captured the four spectral bands of G (wavelength of 530–570 nm), R (wavelength of 640–680 nm), REG (wavelength of 730–740 nm), and NIR (wavelength of 770–810 nm), which were not used in the present study.

We collected images simultaneously from a flight altitude of 30 m above ground level, with 80% frontal and lateral overlap, at speeds of 3 m s^{-1}, according to the methodology of Santos et al. (2020a), and obtained a spatial resolution of 0.86 cm with the RGB camera.

Four flights were performed, the first before harvest on 1st of May 2020, the second after harvest on 8th of May 2020, the third before harvest on 1st of May 2021, and the fourth after harvest on 12th of May 2021. The images were collected around noon, with clear and sunny skies, to minimize the effects of clouds and the generation of shadows in the images.

The images were processed in PhotoScan Professional 1.4.0 software (Agisoft LLC, St. Petersburg, Russia) (Table 1), following the available processing workflow, in which the photos were geometrically aligned to build the point cloud, 3D model, digital terrain model (DTM), DSM, and orthomosaic.

Table 1. Data of RPA image processing

Information	Preharvest	Postharvest	Preharvest	Postharvest
Date (dd/mm/yy)	01/05/2020	08/05/2020	01/05/2021	12/05/2021
Time (duration)	8 min 52 s			
Number of images	120	121	119	120
Flight height (m)	30			
Data size (GB)	1.03	1.08	1.08	1.02
Processing time (h)	5.47	6.14	4.88	5.44
Software platform	Microsoft Windows 7 (64 -bit)			
Spatial resolution (cm/pixel)	1.03	1.13	1.04	1.01
Reprojection error (RMS) (pixel)	1.34	1.43	1.81	1.84

We georeferenced the orthomosaics using the second-order polynomial transformation with the nearest neighbour resampling method, using 6 control points (CPs) distributed in the area. We adopted the Geocentric Reference System for the Americas (SIRGAS 2000) and the Universal Transverse Mercator (UTM) projection (zone 23S). We used the software QGIS version 3.10 (Quantum GIs) for preprocessing and map preparation.

We determined the plant height by using a raster calculator in QGIS, in which we obtained a canopy height model (CHM) by subtracting the DTM from the DSM according to the methodology used by Santos et al. (2020a), Panagiotidis et al. (2017), and Iizuka et al. (2017).

We used the raster volume surface plugin in the QGIS to obtain the area and volume of the crop in each of the 90 experimental plots under study. This algorithm calculates the volume above the base level of the CHM surface. The algorithm generates the calculated volume, the total area, and the total number of pixels analysed. The plots of the area and the calculated volume depend on the coordinate reference system of the input raster file. Thus, as the projection system used was UTM (in metres), we present the CHM height (in metres) and the calculated values for the area and for the volume in m^2 and m^3, respectively.

We obtained the defoliation data of the aircraft in area (DAA) (m^2/plant) and the defoliation data of the aircraft in volume (DAV) (m^3/plant) by subtracting the data obtained for area and volume before and after harvest and dividing it by the number of useful plants in each experimental plot, using an Excel spreadsheet.

Field data collection

We collected coffee production data from each experimental plot (L/plot) in 2019 and 2020. We obtained these data by manual harvesting onto a canvas; after the removal of twigs and leaves, we performed shaking and collected the fruits in a container graduated in litres. With this measurement, we obtained the yield (L/plant) (Y-2019 and Y-2020) as the mean of the useful plants of each experimental plot.

When harvesting onto a canvas, we removed and weighed the leaves that fell on the canvas due to this process. We obtained the field defoliation based on the leaf fresh weight (FDW) (kg) after manual harvest using a portable scale up to 12 kg, following the methodology of Silva et al. (2010). With this measurement, we obtained the defoliation (kg/plant) as the mean defoliation of the useful plants of each experimental plot. We obtained the yield and defoliation samples on 7th of May 2020.

We obtained the coffee production of each experimental plot (L/plot) of the harvest performed in 2021 by semimechanized harvesting using portable harvesters. When harvesting onto the canvas, we removed and weighed the leaves and twigs that fell on the canvas due to this process. With this measurement, the yield of useful plants (L/plant) was obtained (Y-2021). We obtained field defoliation was obtained based on the fresh weight of leaves and twigs (FDW) (kg) using a portable scale up to 12 kg following the methodology of Bordin et al. (2019). We measured the field defoliation based on the volume of fresh leaves and twigs (FDV) (L) in a 14 L bucket. We adopted this methodology to evaluate the correlation between the defoliation data in the field and the data obtained from the RPA images. With these measurements, we obtained defoliation (kg/plant and L/plant). We obtained the yield and defoliation samples on 11th of May 2021.

The Pearson correlation was applied to all variables studied, Y-2019, DAA-2020, DAV-2020, FDW-2020, Y-2020, DAA-2021, DAV-2021, FDW-2021, FDV-2021, and Y-2021, to evaluate the relationships between them. To verify the significance, we adopted $\alpha = 5\%$ (correlation coefficient). We calculated the residuals as the difference between defoliation and yield and calculated the mean absolute error (MAE), as well as the root mean square error (RMSE). We performed descriptive statistical analyses using the statistical software R (R Core Team, Vienna, Austria).

RESULTS AND DISCUSSION

There were significant ($p \leq 0.05$) and insignificant ($p > 0.05$) variations between the variables studied. Given this result, this study considered only the analyses with positive and/or negative significant variations, which are highlighted in bold in Table 2.

Table 2. Pearson correlation coefficients of the study variables; the significant relationships are in bold

	Y-2019	DAA-2020	DAV-2020	FDW - 2020	Y-2020	DAA-2021	DAV-2021	FDW - 2021	FDV - 2021	Y-2021
Y-2019	- -									
DAA -2020	-0.25	- -								
DAV-2020	-0.10	0.63	- -							
FDW-2020	0.04	-0.13	0.00	- -						
Y-2020	0.15	-0.14	-0.06	0.56	- -					
DAA-2021	-0.11	0.17	0.13	-0.25	-0.17	- -				
DAV-2021	-0.15	0.16	0.15	-0.19	-0.19	0.87	- -			
FDW-2021	0.01	0.13	0.15	0.41	0.12	0.15	0.14	- -		
FDV-2021	0.13	0.09	0.19	0.34	0.15	0.20	0.18	0.70	- -	
Y-2021	0.14	-0.02	0.16	0.06	-0.25	0.28	0.21	0.54	0.72	- -

Defoliation data of the aircraft in area (DAA) (m^2/plant); defoliation data of the aircraft in volume (DAV) (m^3/plant); field defoliation obtained based on leaf fresh weight (FDW-2020) (kg/plant); field defoliation obtained based on the fresh weight of leaves and twigs (FDW-2021) (kg/plant); field defoliation obtained based on the volume of fresh leaves and twigs (FDV-2021) (L/plant), and Y-yield (L/plant).

Therefore, we analysed the relationships between Y-2020 and FDW-2020; Y-2021 and FDW-2021; and Y-2021 and FDV-2021, and these correlations were statistically adequate for analysing the relationships between field defoliation and yield. We used the relationships between Y-2019 and DAA-2020; Y-2020 and DAA-2021; and Y-2020 and DAV-2021 to analyse the defoliation obtained by the aircraft and yield. Notably, there were no significant correlations between the defoliation obtained in the field and the defoliation obtained by the aircraft, this result can be attributed to the fact that the field methodology is not ideal for quantifying defoliation, as recent RPA research shows the potential of this type of data collection capable of estimating the entire area and not just the sampled plants as in the field methodology.

The study developed by Cunha et al. (2019), in which the authors state that the use of manual methods in large areas becomes costly, time-consuming and may possibly generate inaccurate data. In addition to the samples being random, the number may not be representative, unlike the digital image processing method, the sample sizes can vary and the results are more accurate. In addition, the correlation between DAV-2020 and DAA-2020 showed strong and positive correlations ($R = 0.63$) and the relationships between DAV-2021 and DAA-2021 ($R = 0.87$) were expected as the methodology uses the CHM to obtain the area and volume of the processed images (Santos, et al., 2020a). The relationship between FDV-2021 and FDW-2021 ($R = 0.70$) was another expected result because these variables represent field data from the same year measured differently.

Analysis of field defoliation and yield

After manual harvesting, FDW-2020 showed values from 0 to 0.64 kg/plant, as shown in Table 3. The defoliation values observed in the present study were close to those found by Silva et al. (2000), approximately 0.64 kg/plant. Silva et al. (2010) found plant defoliation values caused by manual harvesting from 0 to 0.9 kg/plant.

After the semimechanized harvest, FDW-2021 showed values from 0 to 4 kg/plant, as shown in Table 3. Notably, FDW-2021 was higher than FDW-2020 due to the amount of twigs and leaves that fell on the canvas due to the harvesting process. However, these measurements cannot be compared because they were obtained at different time points and used different methodologies.

Table 3. Exploratory data analysis

	2020		2021	
Statistics	FDW (kg/plant)	Yield (L/plant)	FDW (kg/plant)	Yield (L/plant)
Minimum	0	0	0	0
1st Quartile	0.01	2.38	0.1	0.1
Median	0.06	4.67	0.38	1.71
Mean	**0.08**	**4.59**	**0.45**	**3.64**
3rd Quartile	0.13	6.71	0.72	5.67
Maximum	0.64	13	4	26

Field defoliation obtained based on leaf fresh weight (FDW-2020) (kg/plant); field defoliation obtained based on the fresh weight of leaves and twigs (FDW-2021).

Y-2020 showed values ranging from 0 to 13 L/plant, and Y-2021 showed values ranging from 0 to 26 L/plant (Table 3). When observing the two harvests, we noted that 2020 had a high crop yield, and the mean yield was higher than that in 2021. In 2021, the crop had a 20% lower yield than that of the previous year, and low crop yield was attributed to 2021.

The yield values found in this study were consistent with the study conducted by Ferraz et al. (2012), who studied a crop 2 years and seven months in age and found yield values from 0.025 to 3.95 L/plant. Conversely, the study by Silva et al. (2010) found yield values from 0 to 11.8 L/plant in a 16-year-old crop.

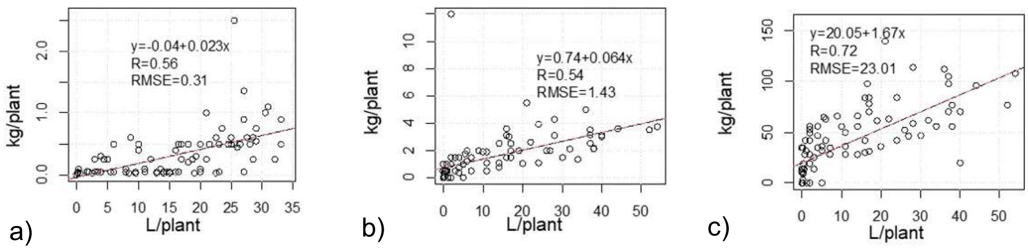

Figure 2. Regression and correlation: a) Y-2020 and FDW-2020; b) Y-2021 and FDW-2021, and c) Y-2021 and FDV-2021.

The interaction between Y-2020 and FDW-2020 was moderate and positive at 56% (Fig. 2, a), as well as the interaction between Y-2021 and FDW-2021 at 54% (Fig. 2, b) and the interaction between Y-2021 and FDV-2021 at 73% (Fig. 2, c). Such positive correlation results indicate that the yield is directly proportional to the defoliation of the same year; thus, the higher the yield is, the greater the defoliation as a function of the harvest. These results corroborate the study conducted by Oliveira et al. (2007), in which the authors concluded that an increase in the volume of harvested grains was proportional to an increase in defoliation.

Defoliation is the main type of damage caused in coffee plants by the action of harvesting. With defoliation, the plant produces less in the following year since it uses its reserves for the restoration of vegetation and, consequently, produces less fruit (OLIVEIRA et al., 2007). Studies performed by Silva et al. (2010) found that manual harvesting resulted in more defoliation in places of higher yield and reduced yield in the subsequent year, as also observed in this study. This is due to the loss of leaf area and the reduction in the photosynthetically active area characteristic of the crop.

Analysis of defoliation obtained by aircraft and yield

We found significant correlations at the 5% significance level. The correlation between Y-2019 and DAA-2020 (Fig. 3, a) presented a weak and negative interaction of 25%. The results of the negative correlation indicate that the yield of one year is inversely proportional to the defoliation of the following year; thus, negative correlations imply that the higher the yield of one year is, the lower the defoliation of the following year, to which it is correlated because of the biennial characteristics of the coffee plant. We found a similar result for the correlation between Y-2020 and DAA-2021 of -17% (Fig. 3, b) and for Y-2020 and DAV-2021 of -19% (Fig. 3, c).

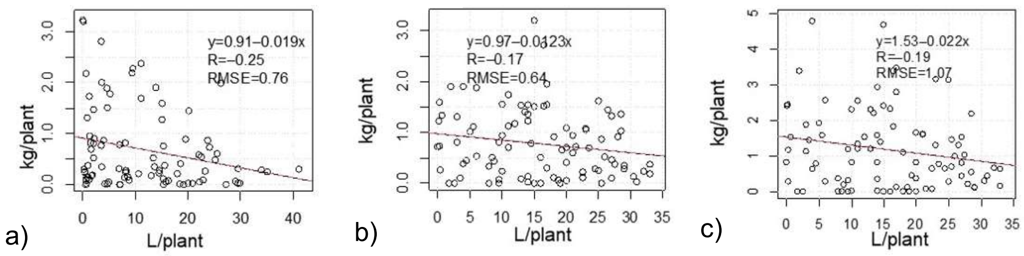

Figure 3. Regression and correlation. a) Y-2019 and DAA-2020; b) Y-2020 and DAA-2021, and c) Y-2020 and DAV-2021.

By comparing the data obtained from the crop images after the 2020 harvest with the data obtained from the crop images before the 2021 harvest, we could quantify the recovery of the crop from one year to the other, in which there was a 22.8% increase in leaf area and a 19.6% volume increase in the crop. This result expresses the physiological characteristics of coffee plants and their biennial nature, and it is possible to observe the losses caused by harvest.

This study reflects the importance of loss of leaf area. Any factor that reduces leaf area negatively influences the photosynthetic capacity of the plant (Magalhães, 1964). This loss of leaf area should be considered given the biennial nature of coffee plants, as the alternation of defoliation patterns tends to be reflected in yield. Similar to the study conducted by Magalhães (1964), the effect of the 25% reduction in leaf area resulted in a 32.6% delay in leaf development and a 10.5% decrease in the development of the plant shoots. In this study, this loss of leaf area was below 20%, and it was possible to observe the recovery of the plant in the subsequent year. This further reinforces the need to perform samplings such as these so that actions can be taken quickly and accurately.

With the processing of images from 2020, the obtained crop areas were 354.6 m^2 (Fig. 4, a) and 293.1 m2 (Fig. 4, b) before and after harvest, respectively. This result demonstrates a reduction of 17.3% in leaf area after harvest. The crop volumes before and after harvest were 505.6 m^3 and 412.7 m^3, respectively, with an 18.4% reduction in leaf volume after harvest in the plots under study.

The crop area obtained in 2021 was 379.9 m^2 before harvest (Fig. 4, c) and 331.2 m^2 (Fig. 4, d) after harvest. This result reflects a 12.8% reduction in leaf area after harvest. The crop volumes were 524.9 m^3 and 473.4 m^3 before and after harvest, respectively, which resulted in a 9.8% decrease in leaf volume after harvest in the plots under study.

Figure 4. Leaf area of coffee plants a) before the 2020 harvest, b) after the 2020 harvest, c) before the 2021 harvest, and d) after the 2021 harvest.

The results of the analyses of the relationship between yield and defoliation obtained in the field and the relationship between yield and defoliation obtained through the RPA images were complementary. It is noteworthy that in 2020, the crop showed a greater reduction in leaf area after harvest obtained by the RPA and a higher yield than the year 2021. These results agree with the defoliation obtained in the field with the yield of 2020 and the lower yield in the following year and validate what was observed when using both methodologies. Thus, we observed that high yield combined with high defoliation in the same year is complementary to high yield in the year combined with the low defoliation in the following year (due to the lower yield of the following year). We recommend that these analyses be performed in a consecutive period of four years to obtain relevant and repeated data in a biennial coffee cycle for both methods.

Otsu et al. (2019) studied a combined random forest classification for the detection of defoliation in a forest area by means of histogram threshold analysis with four vegetation indices obtained from RPA images. The authors obtained good results; however, this methodology for obtaining defoliation of a given vegetation requires multispectral cameras to calculate vegetation indices that use spectral bands in the NIR range, and it is a more costly methodology than that of this study, which, although it uses a multispectral camera, does not use the nonvisible bands of the spectrum. Thus, it was not necessary to perform the calibration in the data processing, as in the studies performed by Cunha et al. (2019), in which the authors used an RGB camera to conduct their study. Thus, the proposed methodology is accessible to small coffee producers who want to obtain morphological parameters of their crop, such as height, crown diameter, plant area, plant volume, and crop defoliation using an accessible camera that is easy to handle and process.

This study is relevant because it quantifies the areas and volume of coffee plants without the need for direct sampling in the field, where data are obtained remotely, which facilitates quicker and more accurate interventions in the crop. Cunha et al. (2019) developed a method to determine the vegetation volume of coffee crops from images obtained by RPA; however, the authors used a computational routine implemented in the software Pix4D that allows the volume of the target to be estimated. This difference in processing may lead to an underestimation or overestimation of the canopy volume because the authors did not individualize the plants.

The advantage of this study is that it considers the height of the plants obtained by the CHM and is an agile methodology for obtaining this information from the entire area under study without having to perform field measurements. In addition, it allows us to remotely obtain the morphological parameters of the crop, favouring the more efficient identification of anomalies in the crop and streamlining necessary crop treatment procedures in the field.

Some additional aspects should be considered for this methodology, such as the effect of the flight overlap parameters on the quality of the images, terrain topography, and ground control points (GCPs) with georeferencing obtained with a global navigation satellite system (GNSS) receiver, to improve the accuracy and processing of the images.

For future studies, we suggest testing the methodology on different terrains and developing plugins that automate and standardize this processing and technologies that allow obtaining this information in real time. In addition, the use of unmanned aerial vehicle laser scanning (UAV-LS) technology (Brede et al., 2019) in coffee crops has been suggested.

CONCLUSIONS

It was possible to analyse and correlate the relationship between yield and defoliation obtained in the field and obtained through RPA images.

The non-significance between the defoliation obtained in the field and the defoliation obtained by the aircraft should be highlighted, for this result reinforces the need for complementary studies and investigations longer than 2 years.

The interactions between the defoliation data obtained in the field and the yield of the same harvest year showed a directly proportional relationship, and the interaction of yield with the defoliation data obtained by the RPA in the subsequent year showed an inversely proportional relationship.

ACKNOWLEDGEMENTS. We acknowledge the Federal University of Lavras (UFLA) and the Graduate Program in Agricultural Engineering (PPGEA, for its acronym in Portuguese) for supporting the study, the Research Coffee Consortium (project approved in call no. 20/2018) - Embrapa Coffee for funding the research, the National Council for Scientific and Technological Development (CNPq), the Minas Gerais Research Foundation (FAPEMIG), and the Brazilian Federal Agency for the Support and Evaluation of Graduate Education (CAPES) for financial support, and the Coffee Sector of UFLA, Centre for Agricultural Systems Studies (NESA, for its acronym in Portuguese), and Centre for Coffee Culture Studies (NECAF, for its acronym in Portuguese) for the support and development of the research.

REFERENCES

Alecrim, A.O., Castanheira, D.T., Voltolini, G.B., Netto, P.M., Guimarães, R.J. & Gonçalves, A.H. 2020. Phytosociology of weeds in coffee plants with different soil management techniques. *Scientia Agraria Paranaensis* **19**(3), 270–279.

Amaral, L.R.D., Zerbato, C., Freitas, R.G.D., Barbosa Júnior, M.R. & Simões, I.O.P.D.S. 2020. UAV applications in Agriculture 4.0. *Revista Ciência Agronômica* **51**, e20207748. https://doi.org/10.5935/1806-6690.20200091

Barbosa, B.D.S., Ferraz, G.A.S., Santos, L.M.D., Santana, L.S., Marin, D.B., Rossi, G. & Conti,L. 2021. Application of RGB Images Obtained by UAV in Coffee Farming. *Remote Sensing* **13**, 2397, 2021.

Bártholo, G.F. & Guimarães, P.T.G. 1997. Care in harvesting and preparing coffee. *Informe Agropecuário* **18**(187), 33–42. (in Portuguese).

Bordin, B.C.D.M., Ronchi, C.P., Campos, A.A.V., Miranda, F.R., Batista, L.B., Ribeiro, A.J. & Mewes, W.L.C. 2019. Productive responses of first-crop crops to manual and mechanized harvesting. X Simpósio de Pesquisa dos Cafés do Brasil. (in Portuguese).

Brede, B., Calders, K., Lau, A., Raumonen, P., Bartholomeus, H.M., Herold, M. & Kooistra, L. 2019. Non-destructive tree volume estimation through quantitative structure modelling: Comparing UAV laser scanning with terrestrial LIDAR. *Remote Sensing of Environment* **233**, 111355. doi: 10.1016/j.rse.2019.111355

Castanheira, D.T., Barcelos, T.R., Guimarães, R.J., Carvalho, M.A.D.F., Rezende, T.T., Bastos, I.D.S. & Cruvinel, A.H. 2019. Agronomic techniques for mitigating the effects of water restriction on coffee crops. *Coffee Science* **14(**1), 104–115.

Cunha, J.P., Neto, M.A.S. & Hurtado, S. 2019. Estimating vegetation volume of coffee crops using images from unmanned aerial vehicles. *Engenharia Agrícola* **39**(SPE), 41–47.

Ferraz, G.A., Silva, F.M.D., Costa, P.A.N.D., Silva, A.C. & Carvalho, F.D.M. 2012. Precision agriculture to study soil chemical properties and the yield of a coffee field. *Coffee Science* **7**(1), 59–67 (in Portuguese).

Iizuka, K., Yonehara, T., Itoh, M. & Kosugi, Y. 2017. Estimating tree height and diameter at breast height (DBH) from digital surface models and orthophotos obtained with an unmanned aerial system for a Japanese cypress (Chamaecyparis obtusa) forest. *Remote Sensing* **10**(13), 1–14. doi: 10.3390/rs10010013

Magalhães, A.C.N. 1964. Effect of leaf surface reduction on coffee plant development. *Bragantia* **23**, 337–342 (in Portuguese).

Martins, R.N; Pinto, F. De A. De C., Queiroz, D.M. De, Valente, D.S.M. & Rosas, J.T.F. 2021. A Novel Vegetation Index for Coffee Ripeness Monitoring Using Aerial Imagery. *Remote Sensing* **13**(2), 263–273. doi: 10.3390/rs13020263

Martínez-Carricondo, P., Agüera-Vega, F., Carvajal-Ramírez, F., Mesas-Carrascosa, F.J., García-Ferrer, A. & Pérez-Porras, F.J. 2018. Assessment of UAV-photogrammetric mapping accuracy based on variation of ground control points. *International Journal of Applied Earth Observation and Geoinformation* **72**, 1–10.

Nex, F. & Remondino, F. 2014. UAV for 3D mapping applications: a review. *Applied Geomatics* **6**(1), 1–15.

Oliveira, E. De, Silva, F.M. Da, Salvador, N. & Figueiredo, C.A.P. 2007. The influence of the sticks vibration and the speed in the displacement of the harvester machine on mechanized coffee harvest process. *Engenharia Agrícola* **27**(3), 714–721 (in Portuguese).

Otsu, K., Pla, M., Duane, A., Cardil, A. & Brotons, L. 2019. Estimating the threshold of detection on tree crown defoliation using vegetation indices from UAS multispectral imagery. *Drones* **3**(4), 80–90.

Panagiotidis, D., Abdollahnejad, A., Surový, P. & Chiteculo, V. 2017. Determining tree height and crown diameter from high-resolution UAV imagery. *International Journal of Remote Sensing* **38**(8–10), 2392–2410.

Parreiras, T.C., Lense, G.H.E., Moreira, R.S., Santana, D.B. & Mincato, R.L. 2020. Using unmanned aerial vehicle and machine learning algorithm to monitor leaf nitrogen in coffee. *Coffee Science* **15**(1), 1–9.

Santos, L.M. Dos; Barbosa, B.D. De S., Diotto, A.V., Maciel, D.T. & Xavier, L.A.G. 2020a. Biophysical parameters of coffee crop estimated by UAV RGB images. *Precision Agriculture* **21**(6), 1227–1241.

Santos, L.M., Ferraz, G.A.S., Barbosa, B.D.S., Diotto, A.V., Andrade, M.T., Conti, L. & Rossi, G. 2020b. Determining the Leaf Area Index and Percentage of Area Covered by Coffee Crops Using UAV RGB Images. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **13**(1), 6401–6409.

Santos, L.M, Ferraz, G.A.S., Diotto, A.V., Barbosa, B.D.S., Maciel, D.T., Andrade, M.T. & Rossi, G. 2020c. Coffee crop coefficient prediction as a function of biophysical variables identified from RGB UAS images. *Agronomy Research* **18(**2), 1463–1471.

Silva, F.M.D., Alves, M.D.C., Souza, J.C.S. & Oliveira, M.S.D. 2010. Effects of manual harvesting on coffee (Coffea arabica L.) crop biannuality in Ijaci, Minas Gerais. *Ciência e Agrotecnologia* **34**(3), 625–632 (in Portuguese).

Silva, F.M., Rodrigues, R.F., Salvador, N., Tourino, E.S. & Silva, S.S.S. 2000. Cost of mechanized coffee harvesting with self-propelled harvesters in Sul de Minas. *Engenharia na Agricultura* **8**(1), 54–60 (in Portuguese).

United States Department of Agriculture (USDA). Avaible in:< http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1801> Access in: February 2023.