Multispectral images for discrimination of sources and doses of fertilizer in coffee plants[1]

Camila Isabel Pereira Rezende[2], Gleice Aparecida de Assis[2], George Deroco Martins[3], Fábio Janoni Carvalho[4], Miguel Henrique Rosa Franco[5], Nathalia Oliveira de Araújo[2]*

10.1590/0034-737X202370030006

ABSTRACT

Remote monitoring of the management of coffee crops is necessary as the demand in decision-making, where the aim is to rise production based on sustainable management is in a constant growth. In this work, it was evaluated the potential of images obtained by low-cost sensors in the discrimination of sources and doses of mineral and organomineral fertilizers in coffee. The experimental design was in randomized blocks, with five blocks and six treatments, as follows: (T1) - 100% of the organomineral treatment; (T2) - 70% of the organomineral treatment; (T3) - 50% of the organomineral treatment; (T4) - 100% of mineral fertilization; (T5) - standard treatment of the farm and (T6) - 70% of mineral fertilization. After management, we used the Mapir 3 Survey3W camera coupled to an ARP drone – Phantom4 to take images of the experiment over a 12-month vegetative period. Combined with image taking, it was collected agronomic parameters of coffee growth and productivity for two crops and concluded that different fertilization doses did not significantly affect the analyzed parameters. Based on the supervised classification of multispectral images, it was possible to discriminate treatments with a higher degree of accuracy (86.66% accuracy) than when analyzing coffee growth parameters.

Keywords: *Coffea arabica* L.; fertilization management; low-cost remote monitoring; treatment discrimination

INTRODUCTION

Coffee fertilization is a key for the entire plant development and must be managed according to the phenological stage of the crop. The source, dose and also the moment of application of the fertilizer to be used is an important choice, as it affects not only productivity but also the chemical and biological properties of the soil. Mineral fertilizer sources provide rapid availability of nutrients, however, over time, depending on the applied dose, they may cause soil acidification, especially in the case of nitrogen (Francioli *et al.*, 2016).

On the other hand, organomineral fertilizers, in addition to providing organic matter, are a way of reusing the organic waste from different agribusiness sectors (Almeida *et al.*, 2020). The organic matter provided by organomineral fertilizers improves soil quality, improving physical, chemical, and biological properties, as all these attributes are essential for fertility (Souza *et al.*, 2018).

Innovations such as precision agriculture (PA) collect highly accurate and reliable information that helps in crop management, reducing field inputs and manual processes, resulting in better use of time and financial resources. Technologies such as Unmanned Aerial Vehicles (UAVs) for image capture and artificial intelligence are capable of identifying anomalies in crops, being able to discriminate

Submitted on February 08th, 2022 and accepted on October 24th, 2022.
[1] This work is part of the first author's Master Dissertation.
[2] Universidade Federal de Uberlândia, Instituto de Ciências Agrárias, Monte Carmelo, Minas Gerais, Brazil. camilaisabel36@hotmail.com; gleice@ufu.br; natyaraujo2008@hotmail.com
[3] Universidade Federal de Uberlândia, Faculdade de Engenharia Civil, Monte Carmelo, Minas Gerais, Brazil. deroco@ufu.br
[4] Instituto Federal do Triângulo Mineiro, Uberlândia, Minas Gerais, Brazil. fabiojanoni@iftm.edu.br
[5] Universidade Federal de Uberlândia, Instituto de Ciências Agrárias, Uberlândia, Minas Gerais, Brazil. miguelmhrf@yahoo.com.br.
*Corresponding author: gleice@ufu.br

areas in different situations (Santos *et al.*, 2018, Pereira *et al.*, 2022).

One of the tools used with some frequency in several sectors of agriculture is Machine Learning (ML), which is considered an artificial intelligence that identifies similar patterns of the object of study, consisting in the automation of data analysis, without the demand for new continuous programming in the equipment or software (Pinheiro *et al.*, 2021). ML is used in conjunction with remote sensing data, which has enabled the application in new areas and methodologies for both tools (Scheunders *et al.*, 2018).

Applications of ML in the agricultural area have been detected in several studies. One of them is the aid in the identification of biotic and abiotic stresses (Liakos *et al.*, 2018), productivity estimates, and mapping of plant nutritional deficiencies (Barbedo, 2019), which helps in the understanding and forming management zones with different levels of fertility.

Given the above, we understand that there is a need to evaluate the viability of image-provider remote sensors that are now easily accessible to the scientific community and professionals working in the coffee field in the monitoring of management related to fertilization. Thus, employing classic field analyses of monitoring of agronomic parameters of coffee allowed us to evaluated the potential of multispectral images taken by low-cost sensors to discriminate sources and doses of mineral and organomineral fertilizers in coffee crops.

MATERIAL AND METHODS

For the execution of this experiment, we assumed that image monitoring would only be usual for the evaluation of different treatments if the spectral bands were able to discriminate the different management conditions with a degree of accuracy close to the classical techniques of in vitro evaluation of coffee growth parameters.

The experiment was carried out on Araras Farm, located in Monte Carmelo, state of Minas Gerais. The geographical coordinates of the experimental area are 18°43’ 19.5’’ S and 47°32’16.1’’ W, located at an altitude of 898 m. The crop was planted in December 2016, using seedlings of the cultivar MGS Paraíso 2, with a spacing of 3.8 m between rows and 0.6 m between plants. The fertilization of the furrows was carried out by applying 2.5 kg of organic matter, 400 g of gypsum, 350 g of the formulated 05-37-00 (N - P_2O_5 - K_2O), and 300 g of limestone with 95% Relative Power of Total Neutralization (PRNT) per linear meter. The cultivated area was irrigated using a drip system, with a spacing between the drippers of 0.6 m and a flow rate of 2.3 L h^{-1}. The soil of the experimental area is classified as Red Clayey Latosol.

Soil chemical characterization in July 2019, before differentiation of the treatments, at a depth of 0-20 cm, showed the following results: pH H_2O = 6.1; P and K (Mehlich^{-1} method) = 36.2 and 330.0 mg kg^{-1}, respectively; Ca^{2+}, Mg^{2+} and Al^{3+} (KCl 1 mol L^{-1} method) = 2.7; 0.8 and 0.0 cmolc kg^{-1}, respectively; H+Al (Buffer solution SMP pH 7.5) = 1.7 cmolc kg^{-1}, S-SO_4^{-2} (Calcium Phosphate Monobasic 0.01 mol L^{-1}) = 9.0 mg kg^{-1}, potential cation exchange capacity = 6.0 cmolc kg^{-1}, effective cation exchange capacity and sum of bases = 4.3 cmolc kg^{-1}, base saturation = 72% and organic matter = 27 g kg^{-1}.

The experimental design used was the randomized blocks, with five blocks and six treatments, as follows: (T1) - 100% of the organomineral treatment; (T2) - 70% of the organomineral treatment; (T3) - 50% of the organomineral treatment; (T4) - 100% of mineral fertilization; (T5) - farm standard treatment and (T6) 70% of mineral fertilization. Each experimental plot consisted of a row with 16 plants, the eight central plants considered useful.

Doses of fertilizer applied in 2019 at treatment differentiation, were: 250 kg ha^{-1} N (T1 and T4); 175 kg ha^{-1} N (T2 and T6); 125 kg ha^{-1} N (T3); 94 kg ha^{-1} N; 7 kg P_2O_5 and 53 kg ha^{-1} K_2O (T5). In 2020, the applied doses were 450 kg ha^{-1} N; 80 kg ha^{-1} P_2O_5 and 340 kg ha^{-1} K_2O (T1 and T4); 315 kg ha^{-1} N; 56 kg ha^{-1} P_2O_5 and 238 kg ha^{-1} K_2O (T2 and T6); 225 kg ha^{-1} N; 40 kg ha^{-1} P_2O_5 and 170 kg ha^{-1} K_2O (T3); 190 kg ha^{-1} N; 55 kg P_2O_5 and 310 kg ha^{-1} K_2O (T5). The recommendations were based on the proposal by Guimarães *et al.* (1999).

Evaluations on growth, chlorophyll index, and drone image capture were performed bimonthly from April 2020 to May 2021. The evaluated growth parameters were canopy diameter, plant height, length of plagiotropic branches, and number of nodes per plagiotropic branch.

To determine the Falker Chlorophyll Index, an electronic chlorophyll content meter model CFL 1030 was used, following the methodology of Falker (2008). From each useful plant in the experimental plot, the reading of the third or fourth pair of leaves of the plagiotropic branch located in the middle-third of the coffee tree on the upper side of the planting lines was performed. All collections were performed in the morning starting at 08:00 a.m.

Soil samples for chemical characterization (pH in water, potential acidity, calcium, magnesium, potassium, Mehlich^{-1} phosphorus, organic matter, sum of bases, potential cation exchange capacity and base saturation) were collected in August 2020 at a depth of 0 to 20 cm in each experimental plot, in the region of the wet bulb. The samples were collected with the aid of an auger and were subsequently homogenized in a bucket to compose a sample composed of each experimental unit. For leaf analysis, a pair of leaves located at the third or fourth node of a plagiotropic branch located in the middle third of each quadrant of the useful plants of the experimental plot were collected, totaling 64 leaves per experimental unit (Guimarães *et al.*, 1999). The levels of the macronutrients nitrogen, phosphorus, and potassium were determined in January 2021, when the fruits were at the small green phase.

In June 2020 and July 2021, the experimental area was harvested through harvesting the fruits belonging to the eight useful plants in the plot. Harvesting was started when the percentage of green fruits was below 20%.

For growth and chlorophyll parameters, the split-plot in time scheme was used. The data obtained were subjected to analysis of variance with the application of the F test, at 5% probability, after meeting the assumptions of residuals normality by the Kolmogorov-Smirnov test, homoscedasticity by the Levene test, and block additivity by the Tukey's test, all at 5% probability. Treatment means were compared by Tukey's test at the 5% probability level. When significant differences were detected, regression models were adjusted for the means of the evaluation times. Statistical analyses were performed using R software (version 3.4.3).

From April 2020 to May 2021, images were captured with a remotely piloted aircraft (ARP) on April 23, 2020, June 23, 2020, March 02, 2021, and May 04, 2021. The flights were performed from 12:00 p.m. to 1:00 a.m. to avoid clouds that would later interfere with the image processing and to maintain a standard in data collection. The sampling points were the 240 plants in the experimental useful area. The position of the points was obtained from a static relative geodetic survey with a pair of Ashtech Promark 220 L1/L2 GNSS receivers. Those images were acquired using a low-cost Mapir 3 Survey3W camera coupled to an ARP drone - Phantom4, which collects images of the RGN bands, being respectively green (550 nm), red (660 nm), and near-infrared (850 nm), respectively. Flights were performed at 100 m height with the capture of images of good spatial resolution.

Once images were captured Using Mapir 3 sensor, the mosaics were built for each of the four flights, using the Pix4D software. After generating the mosaics, radiometric normalization was performed, according to equation 1:

$$T_i = m_i + x_i + b_i \quad (1)$$

Where: Ti = Digital number (RGB) and reflectance (RGN) of the normalized image; mi = (Bri − Dri)/(Bsi −Dsi); xi = spectral band to be normalized; bi = (Dri × Bsi − Dsi × Bri)/(Bsi − Dsi); Bri = mean of the clear Reference set; Dri = mean of the dark reference set; Bsi = mean of the clear set to be normalized; Dsi = mean of the dark set to be normalized; i = bands of the sensor under study.

For this approximation between the points, the mosaic of the first flight performed on April 23, 2020, was used, as it presented better radiometric clarity in relation to the georeferencing points. After the radiometric normalization, the accuracy of the coordinates was checked with the normalized images using the QGIS3 software, observing if the georeferencing of the points corresponding to the same locations in both images, to better monitor the development of the crop throughout the experiment, always evaluating the same reference points.

The mean reflectance values (RGN) collected from images of the eight coffee plants of each experimental plot were used to calculate the vegetation indices NDVI (Normalized Difference Vegetation) = (B850 − B660) / (B850 + B660); GNDVI (Green Normalized Difference Vegetation Index) = (B850 − B550) / (B850 + B550); NGRDI (Normalized Green Red Difference) = (B550 − B650) / (B550 + B650); SR (Simple Ratio) = B850 / B660; DVI (Difference Vegetation) = B850 − B660; MCARI1 (Modified Chlorophyll Absorption Reflectance) = 1.2 × [2.5 × (B850 − B660) − 1.3 × (B850 − B550)], where B: Band, Red (B660); Green (B550) and Near Infrared (B850) (Rouse *et al.*, 1973; Gitelson *et al.,* 2002).

Regarding coffee class discrimination, a supervised classification of the Random Forest type was performed, available in the Waikato Environment for Knowledge Analysis - Weka 3.9.4 software. The data were organized into three equally balanced classes, where 30 data for training files and 10 for validation. The three classes were organized according to the fertilizer source of each treatment, such as organomineral, mineral, and standard. The organomineral class was composed of three treatments, the mineral class was composed of two treatments and the standard class was represented by the conventional fertilizer treatment of the farm. After the organization of the classes for each of the four evaluations carried out during the experiment, the processing began, using the Randon Forest classifier, to differentiate the classes of treatments.

Treatments were classified using the input data sets used for each evaluation where the agronomic parameters, the reflectance of the RGN band, and the vegetation indices were calculated. The subsets selected for classification in each evaluation interval were: 1- all agronomic parameter; 2- plant height; 3- only canopy growth parameter; 4- chlorophyll; 5- RGN and vegetation indices; 6- RGN; 7 – Vegetation indices. Subdivisions were carried out to observe which data collected promoted greater differentiation and possibilities for better classifications among the classes of treatments used. To analyze the performance of each classification, the following data were used: the global accuracy (EG) and the Kappa coefficient (K), which were calculated using the Weka software.

RESULTS AND DISCUSSION

For the foliar contents of primary macronutrients in coffee plants, a significant effect of treatments at the 1% probability level was observed only for nitrogen ($p < 0.01$). In the nutritional analysis of the soil, there was a significant difference between the doses and sources of fertilizer for magnesium, calcium, pH H_2O, the sum of bases, potential cation exchange capacity ($p < 0.01$), and for base saturation ($p < 0.05$).

The highest foliar nitrogen contents were observed in treatments that received doses of 100% and 70% of organomineral fertilizer, with an average increase of 16.9 g kg^{-1} in relation to the other treatments (Table 1). All fertilization doses, except for the standard treatment of the farm (T5) and 70% of the mineral fertilization (T6), showed nitrogen levels above the critical ranges recommended for fertirrigated coffee trees in Minas Gerais for January and February, where the threshold is 32.40 g kg^{-1} (Assis *et al.*, 2015).

Nevertheless, the excess of nitrogen increases the amino acid and protein content in the leaves, as well as the vegetative growth, delayed tissue lignification, which is related to the greater intensity of halo leaf spot in coffee (*Pseudomonas syringae* pv. garcae) (Pérez *et al.*, 2017) resulting from the rise in the concentration of short-chain sugars, which provide energy for the establishment of parasitism (Marschner, 2012). Therefore, the balance between nutrients in the plant reflects not only on productivity and growth but also on tolerance to biotic stresses.

There was no significant difference between the doses and sources of fertilization for the nutritional levels of phosphorus and potassium (Table 1). All treatments showed levels close to or within the adequate range of nutritional contents, from 0.9 to 1.6 g kg^{-1} for phosphorus and from 21.3 to 29.4 g kg^{-1} for potassium (Martinez *et al.*, 2003). So, it was possible to infer that lower doses of organomineral fertilization, using 50% of the recommended dose, supplied the nutritional needs of the coffee plant concerning phosphorus and potassium.

Regarding soil attributes, despite the non-significant difference between the treatments for potassium and base saturation (Table 1), potassium fell into the appropriate category in all treatments, between 120 and 200 mg kg^{-1}. In addition, base saturation was higher than 60%, according to the recommendations for fertilization of coffee trees in production (Guimarães *et al.*, 1999).

For phosphorus, in treatments with 100% and 50% of organomineral fertilization (T1 and T3), 100% with mineral fertilization (T4) and producer standard (T5), the levels of this nutrient in the soil were classified in the fertility class “low”; between 2.0 and 4.0 mg kg^{-1}, considering a soil with a clay percentage greater than 60%. In treatment 6 (70% of the mineral fertilization), the phosphorus content was classified as medium (between 4.1 and 6.0 mg kg^{-1}) and with the use of 70% of the organomineral fertilization (T2), the level of this nutrient in the soil was adequate (between 6.1 and 9.0 mg kg^{-1}), according to the recommendation by Guimarães *et al.* (1999) (Table 1).

The standard treatment (T5) presented higher magnesium content in the soil in relation to the 50%-organomineral and 100%-mineral treatments. For calcium, the highest content in the soil was observed with the use of a dose of 70% of mineral fertilization (T6), which was higher than treatments with 50% of organomineral fertilization (T3) and 100% of mineral fertilization (T4) (Table 1).

The relationship between calcium, magnesium, and potassium in the soil is extremely important for the development of the coffee tree. The levels of each of these nutrients were classified as adequate in all treatments (0.9 to 1.5 cmolc dm^{-3} for Mg and between 2.4 to 4.0 cmolc dm^{-3} for Ca) (Guimarães *et al.*, 1999). The ideal Ca:Mg:K ratio in the soil varies from 9:3:1 to 25:5:1, as proposed by Malavolta (2001). The treatments with 100% and 70% of the organomineral fertilization revealed a ratio of 9:3:1, while the treatments with 50% of the organomineral fertilization and 100% of the mineral fertilization showed a relation of 8:3:1 (Table 1).

Table 1: Mean of the leaf nutritional contents of nitrogen (N) (g.kg^{-1}), phosphorus (P) (g.kg^{-1}), potassium (K) (g.kg^{-1}), and means of soil chemical parameters: remaining phosphorus (P meh^{-1} mg kg^{-1}), potassium (K) (mg kg^{-1}), magnesium (Mg) (cmol$_c$ dm^{-3}), calcium (Ca) (cmolc dm^{-3}), pH (pH H_2O) , potential acidity (H+Al) (cmol$_c$ dm^{-3}) organic matter (MO) (g kg^{-1}), base sum (SB) (cmol$_c$ dm^{-3}), potential cation exchange capacity (T) (cmol$_c$ dm^{-3}) and base saturation (V%) in coffee soils as a function of mineral and organomineral fertilization rates

Means of the Leaf and Soil Nutritional contents							
Treatment	**Foliar means**			**Soil means**			
	N (g.kg^{-1})	**P (g.kg^{-1})**	**K (g.kg^{-1})**	**P meh^{-1} mg kg^{-1}**	**K mg kg^{-1}**	**Mg cmol$_c$ dm^{-3}**	**Ca cmolc dm^{-3}**
T1	50.7 a	1.6	21.5	3.2	164.9	1.2 abc	3.7 ab
T2	49.2 a	1.8	23.7	7.8	157.3	1.4 ab	3.7 ab
T3	37.0 b	1.8	24.1	3.3	159.7	1.2 bc	3.2 b
T4	35.7 b	1.6	22.9	2.9	157.7	1.1 c	3.1 b
T5	31.1 bc	1.7	22.9	3.8	159.6	1.5 a	3.9 ab
T6	28.2 c	1.8	24.4	5.1	155.3	1.4 ab	4.0 a

Means of soil chemical parameters						
Treatment	**Soil means**					
	pH H_2O	**H+Al cmolc dm^{-3}**	**MO g kg^{-1}**	**SB cmol$_c$ dm^{-3}**	**T cmol$_c$ dm^{-3}**	**V%**
T1	6.66 b	1.44	25.1	5.46 abc	6.89 ab	78.9
T2	6.79 ab	1.35	24.8	5.66 ab	7.01 ab	80.6
T3	6.57 b	1.38	25.2	4.86 bc	6.24 bc	77.7
T4	6.77 ab	1.38	25.4	4.68 c	6.06 c	77.2
T5	6.94 a	1.34	26.1	5.87 a	7.22 a	81.3
T6	6.97 a	1.29	24.7	5.95 a	7.23 a	82.0

Means followed by different letters are significantly different from each other by the Test of Tukey at the 5% significance level.

The pH values, in all treatments, were greater than the reference range for coffee cultivation, between 5.5 and 6.5. The highest pH values were observed in the standard treatment (T5) and with the use of 70% of the mineral fertilizer (T6), being significantly higher in relation to those observed in the doses of 100% (T1) and 50% of the organomineral fertilization (T3). Despite the rapid availability of nutrients from mineral fertilizers, acidification of the soil can occur over time, which possibly explains the higher pH of the soil where exclusively mineral fertilization was carried out (Francioli *et al.*, 2016).

Organic matter (OM) achieved similar values in all treatments evaluated and was within the ideal levels recommended for coffee (21 - 45 g kg^{-1}) (Guimarães *et al.*, 1999) (Table 1). The potential acidity considered adequate for coffee cultivation is less than 2.0 cmol$_c$ dm^{-3}. It should be observed that treatments did not affect this attribute, which remained below 1.44 cmol$_c$ dm^{-3}.

The sum of bases fell within the appropriate category for coffee, from 3.6 to 6.0 cmol$_c$ dm^{-3} for all treatments (Guimarães *et al.*, 1999). The farmer's standard treatment (T5) and the dose of 70% of the mineral fertilization (T6) provided higher levels of base sum and potential cation exchange capacity in relation to the dose of 50% of the organomineral fertilization and 100% of the mineral fertilization.

Regarding the growth parameters, for the number of nodes in the primary plagiotropic branch ($p < 0.01$), a significant difference was found among treatments at the level of 5% probability by the F Test, with no differences for the other evaluated parameters. For the evaluation periods, there was a significant difference for all characteristics ($p < 0.01$), except crown diameter.

The use of 50% of the organomineral fertilization dose did not interfere in plant growth or the chlorophyll in relation to the other treatments. Likely, the adequate levels of nutrients in the soil, combined with base saturation above 77%, organic matter content between 2.47 and 2.61 dag kg$^{-1,}$ and low acidity had contributed to the satisfactory development of coffee plants, even at lower doses of fertilization. The plants were, on average, 1.99 m tall and showed 2.03 m of crown diameter; 0.19 m of branch length, and a total chlorophyll index of 63.44 (Table 2).

The results achieved in this experiment corroborate those of Sobreira *et al.* (2011), who found that a 30% reduction in nitrogen and potassium fertilization was the most recommended in a fertigated coffee crop in the formation phase. However, it is important to emphasize that in the productive phase, the fruits constitute the drain of the greatest activity in the plant and although there is no damage to growth, the reduction in fertilization can cause "hidden hunger" in the coffee tree, so monitoring the crop through foliar and soil analysis for fertilization adjustments is necessary.

Table 2: Means of agronomic parameters height (m), crown diameter (m), number of nodes, length of branches (m), total chlorophyll (Falker Chlorophyll Index), and productivity (bags of 60 kg ha^{-1} of coffee) of coffee plants as a function of doses of mineral and organomineral fertilization

Means of the growth parameter				
Treatment	**Height**	**Crown diameter**	**Number of nodes**	**Length of branches**
T1	2.00	1.89	8.28 ab	0.20
T2	1.98	1.91	8.00 ab	0.19
T3	1.98	1.87	8.19 ab	0.18
T4	2.02	2.70	8.21 ab	0.19
T5	1.96	1.87	8.84 a	0.21
T6	2.03	1.92	7.52 b	0.18
Means of the chlorophyll indices and productivity				
Treatment	**Chlorophyl**	**Productivity 2020**	**Productivity 2021**	**20/21 Mean productivity**
T1	64.15	21.92 a	78.92	50.40
T2	63.11	17.44 ab	71.80	44.62
T3	62.65	20.00 ab	72.38	46.20
T4	62.56	17.04 ab	82.22	49.62
T5	65.09	9.28 b	88.12	48.70
T6	63.08	19.84 ab	73.00	46.42

Means followed by different letters are significantly different from each other by the Test of Tukey at the 5% significance level.

The number of nodes in the primary plagiotropic branch is an important vegetative trait that is positively correlated with productivity. It is observed that in the standard treatment (T5), the coffee trees showed an increase of one node per primary plagiotropic branch in relation to the use of 70% of mineral fertilization (T6), which represents an increase of 4,386 nodes per productive branch in a hectare, considering the crop spacing of 3.8 m between rows and 0.6 m between plants. In this case, it is possible that a reduction in the application of nutrients by 30% with mineral sources harmed the emission of buds in the coffee tree.

As for the chlorophyll content, no significant difference was found among the treatments at the 5% probability level by the F Test. The coffee plants had an average Falker chlorophyll index of 63.44. However, an exponential model adjustment was observed for this response variable as a function of the evaluation times (R^2 = 69.74%) (Figure 1A).

By relating the Falker chlorophyll index in each phenological stage of coffee allowed to observe a gradual increase in chlorophyll from fruit maturation (April 2020, at 150 days after differentiation (DAD) of treatments) to the resting and maturation phase of floral buds (August 2020, at 288 DAD). From this stage, the chlorophyll index stabilized in the plants (Figure 1A). During the small-green stages (October 2020, at 350 DAD), fruit expansion (December 2020, at 400 DAD), and grain-filling (February 2021, at 460 DAD), the coffee plants showed, on average, a Falker chlorophyll index of 64.00 units. Although the reproductive period is characterized by a high nitrogen demand because of the fruit growth, it was found in this work that the highest rates were detected in the grain-filling phase. This may be explained as fertilization was carried out in November 2020 and January 2021, warm months in south America, which increased nitrogen availability in the plants. The outcomes of this experiment corroborate those of Godoy *et al.* (2008), who found that the strongest correlation between the relative chlorophyll index in plants and productivity was observed in the small-green and expansion stage.

The coffee tree has a seasonal growth pattern, mostly influenced by the monthly average temperature (Amaral *et al.*, 2006) and rainfall. The quadratic model was adjusted as a function of the evaluation periods for the characteristics of branch length and number of nodes per primary plagiotropic branch of coffee, with coefficients of determination of 98.37% and 99.29%, respectively (Figures 1B and 1C). For plant height, the mathematical model that presented the best fit (R^2 = 89.96%) was the linear one (Figure 1D).

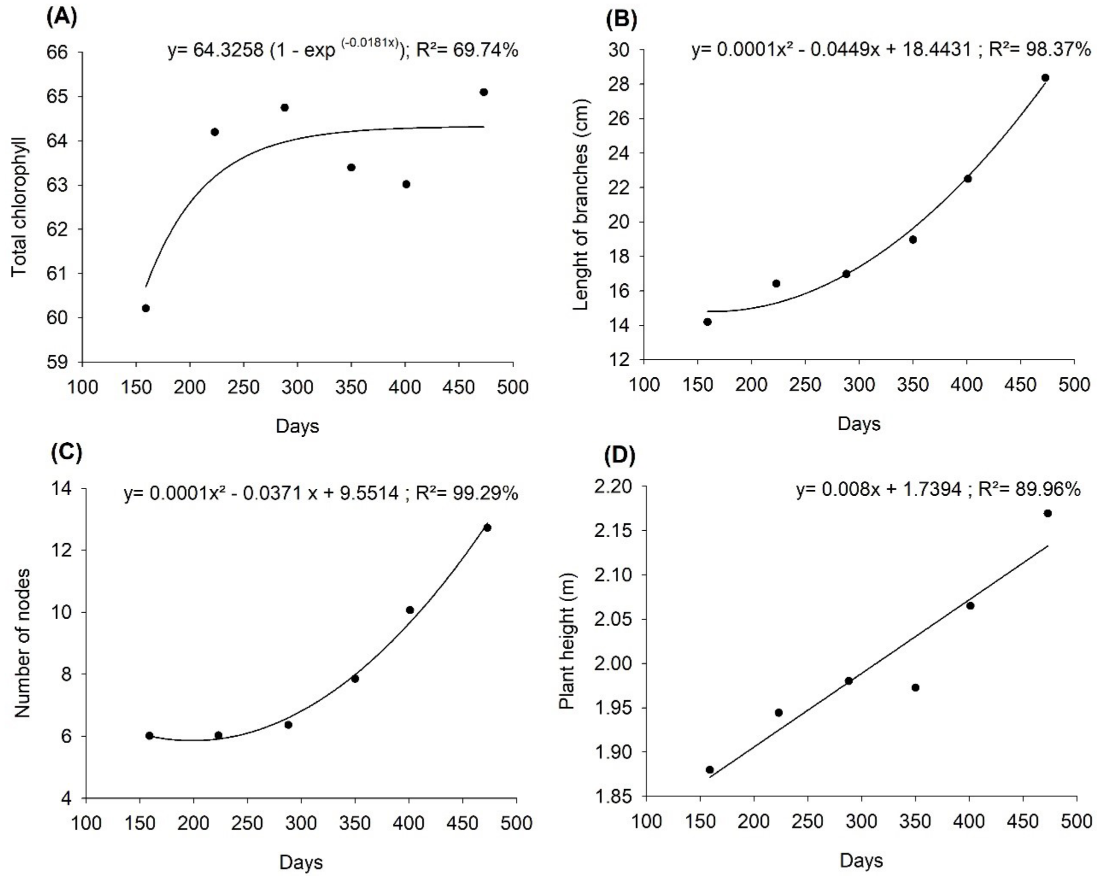

Figure 1: Falker chlorophyll index (A), branch length (B), number of nodes in the primary plagiotropic branch (C), and plant height (D) of coffee plants over the experiment (150 days to 470 days after the differentiation of the treatments).

The most expressive plant growth occurred between 400 and 460 DAD for branch length, number of nodes per primary plagiotropic branch, and height, coinciding with the expansion and grain-filling stages of the fruits. The factors related to the higher growth rate of coffee trees in this period are characterized by the occurrence of higher average monthly temperatures and rainfall, which stimulated plant Growth. Allied to this, the highest relative levels of Falker chlorophyll were also observed in these stages, contributing to the adequate growth of the plant.

For processed coffee productivity, significant differences were found between treatments for productivity in 2020 ($p < 0.05$) by the F Test. For productivity of 2021 and the average of the biennium, no differences were found among the doses of mineral and organomineral fertilization (Table 2).

In the 2020 crop, the highest productivity was obtained with the use of 100% of the dose of organomineral fertilization (T1) in relation to the standard treatment (T5), with an increase of 12.64 sacs ha^{-1} (Table 2). In the standard treatment, fertilization was carried out via fertigation using exclusively mineral sources, which may have caused nutrient losses, mainly by leaching. Cavalcante *et al.* (2020) found that the use of fertilizer containing 50% of the composition with organic sources and 50% with mineral sources provided greater productivity of coffee trees in relation to exclusively mineral fertilization, corroborating the results obtained in this work.

The alternation of productivity between one crop and another is a characteristic of the coffee tree. It is observed that in the 2021 crop, considered to be a positive biennial, the treatments did not show differences, with average productivity of 77.7 bags of 60 kg ha^{-1} of coffee (Table 2). Considering the average of the biennium, the doses of mineral and organomineral fertilization did not promote differences in the productivity of processed coffee, which may be related to the adequate levels of most nutrients in the soil, promoting satisfactory vegetative and reproductive development of the plant even with reduction in organomineral fertilization by 50% of the standard recommendation.

In conditions of low variability in the biometrics of coffee trees, our results showed that the classification of low-cost images, when used in the discrimination of treatments, is more accurate than the classification based on agronomic parameters (Table 3). Statistical analysis of agronomic parameters showed low variability between different fertilization rates. The Table 3 shows seven subsets classified in the four evaluations carried out throughout the experiment, in which four were for agronomic parameters and three for images.

Table 3: Supervised classification of coffee classes in each evaluation for different subsets and computed confusion matrix for agronomic parameters data, RGN, and vegetation indices

Classified subsets	1st Evaluation 150 DAD		2nd Evaluation 210 DAD		6th Evaluation 460 DAD		7th Evaluation 560 DAD	
	Random Forest							
	EG	K	EG	K	EG	K	EG	K
Agronomic parameter	73.33%	0.60	63.33%	0.45	70.00%	0.55	73.33%	0.60
Plant Height	50.00%	0.25	63.33%	0.45	36.66%	0.05	56.66%	0.35
CD, NN, CM	73.33%	0.60	66.66%	0.50	70.00%	0.55	76.66%	0.65
Chlorophyl	30.00%	-0.05	63.33%	0.45	66.66%	0.50	70.00%	0.55
RGN and indices	73.33%	0.60	70.00%	0.55	73.33%	0.60	86.66%	0.80
RGN	26.66%	-0.10	66.66%	0.50	73.33%	0.60	86.66%	0.80
Indices	40.00%	0.10	66.66%	0.50	66.66%	0.50	73.33%	0.60

Confusion matrix on the 1rst evaluation day (150 DAD)						
Class	Agronomic parameter			RGN and Vegetation indices		
	a	b	c	A	b	C
a	10	0	0	9	1	0
b	1	4	5	3	7	0
c	0	2	8	1	3	6
Confusion matrix on the 2nd evaluation day (210 DAD)						
a	9	1	0	9	0	1
b	5	2	3	3	6	1
c	1	1	3	1	3	6
Confusion matrix on the 6th evaluation day (460 DAD)						
a	9	1	0	9	1	0
b	3	5	2	1	6	3
c	3	0	7	0	3	7
Confusion matrix on the 7th evaluation day (560 DAD)						
a	9	1	0	10	0	0
b	2	7	1	0	8	2
c	2	2	6	2	0	8

CD: Crown diameter; NN: Number of nodes; BL: branch length, K: Kappa index, EG: Global accuracy.
The treatment classes were classified into farm's pattern (a), organomineral fertilization (b), mineral fertilization (c).

The parameters of the RGN band and vegetation indices resulted in the best Global Accuracy indices throughout the evaluations, being close to 100%, as well as the Kappa coefficient, which approached 1. In the first evaluation, the set of all agronomic parameters and the parameters of the RGN band and vegetation indices obtained the same global accuracy index. Although the first evaluation of the area was carried out 150 days after the beginning of fertilization, it was found that the supervised classification allowed the discrimination of coffee classes by up to 73.3%, due to the heterogeneity between plants that received different treatments. It should be stressed out that after the beginning of fertilization (November 2019), due to the occurrence of rainfall and higher temperatures, the plants were metabolically active and with more intense growth, with greater distinction between treatments.

The RGN bands and the vegetation indices, together, provided a more accurate classification of the plants in relation only to the agronomic parameters evaluated separately, due to their sensitivity to the typical spectral bands of the plants, which were not measured. This occurs because the green band is sensitive to vegetation pigmentation, the red band is sensitive to chlorophyll *a* and *b* and the senescence stage, and the near-infrared band to the leaf area. This can also be applied to vegetation indices, in particular the NDVI, which is sensitive to biomass and water stress (Carmo *et al.*, 2021).

In the second evaluation, carried out at 210 days after the differentiation of treatments, it was observed that only plant height and chlorophyll provided the same global accuracy (63.33%) as all agronomic parameters together. This evaluation, carried out in June 2020, coincided with water restriction and milder temperatures, with a reduction in the plant growth rate concerning the rainiest periods, which may explain the reduction in the classification accuracy.

The classification with all image parameters stood out in relation to agronomic parameters, as the bands, together with the indices, highlighted vegetation characteristics that change with treatments, such as greater plant growth, becoming more responsive to the image, in addition to evaluations such as senescence, leaf area index and biomass that influence the spectral response and were not evaluated in the field.

In the sixth evaluation, carried out in February 2021 when the fruits were in the grain-filling stage, the results are similar to those of the second evaluation. The classification through images in the seventh evaluation, at 560 days after the differentiation of treatments, showed very high accuracy, with an overall accuracy of 86.66% when using the index data together with the bands. Also, when these data are observed separately, it can be seen that the vegetation indices achieved only 73.33% of global accuracy and the RGN bands of 76.66%. In this case, the bands by themselves already highlight plant characteristics, enabling discrimination in treatment classes. The reflectance of the plants becomes very responsive at this point, showing that the evaluations carried out in the field were not enough to differentiate the treatments with as much accuracy as the spectral response that the images offer. Achieving higher Kappa index values means that the image data obtained better classification results than the agronomic parameters, according to the results and the interpretation of the Kappa interval agreement table of Landis & Koch (1977).

In all confusion matrices, the standard treatment (T5) designated as a class (a) showed greater differentiation, in which the largest number of plants were correctly classified for agronomic and imaging parameters in all evaluations performed (Table 3). To justify this fact, it is important to highlight that this class was composed of only one treatment, that is, belonging to plants that followed a similar pattern. In addition, it significantly differed from other treatments in relation to leaf nitrogen content (Table 1), number of nodes and productivity in 2020 (Table 2).

The software presented greater difficulties in classifying the organomineral class, composed of treatments T1, T2, and T3, always making confusion with other classes, in both analyses. This may be explained by the grouping of the classes of these treatments, and the analysis of the growth parameter revealed that both did not differ significantly from each other, and also did not differ from the mineral treatments (T4 and T6) grouped in the mineral class, in any phytotechnical aspect, creating more difficulties in the discrimination. The RGN parameters and vegetation indexes differentiate the plants of the organomineral class (b) from the treatments T1, T2, and T3 as the reflectance data were more sensitive in the detection of alterations in relation to the agronomic parameters measured in the field.

CONCLUSIONS

The reduction in the organomineral fertilizer doses did not have a negative influence on foliar and soil nutritional levels, growth parameters, and coffee productivity.

With a higher accuracy to analyze the agronomic parameters, the use of multispectral images for classification and monitoring of the crop constitutes a low-cost option for large-scale, reliable, and constant monitoring of the crop, reaching up to 86.66% of global accuracy in the RGN data classification and vegetation indices using the Randon Forest algorithm.

ACKNOWLEDGEMENTS, FINANCIAL SUPPORT AND FULL DISCLOSURE

The authors thank the rural producer Laércio Crippa for providing the experimental area and inputs used in the research.

Authors declare there is no conflict of interests in carrying the research and publishing this manuscript.

REFERENCES

Almeida FF, Almeida AA & Begnini ML (2020) Produção de fertilizante organomineral a partir de resíduos orgânicos. Brazilian Journal of Development, 6:12424-12432.

Amaral JATD, Rena AB & Amaral JFTD (2006) Crescimento vegetativo sazonal do cafeeiro e sua relação com fotoperíodo, frutificação, resistência estomática e fotossíntese. Pesquisa Agropecuária Brasileira, 41:377-384.

Assis GA, Guimarães RJ, Colombo A, Scalco MS & Dominghetti AW (2015) Faixas críticas de teores foliares de nitrogênio e potássio para o cafeeiro fertirrigado em fase de produção. Revista Ciência Agronômica, 46:126-134.

Barbedo JGA (2019) A review on the use of unmanned aerial vehicles and imaging sensors for monitoring and assessing plant stresses. Drones, 3:40-66.

Carmo GJDS, Castoldi RMGD, Jacinto ACP, Tebaldi ND, Charlo HCDO & Zampiroli R (2021) Detection of Lesions in Lettuce Caused by Pectobacterium carotovorum Subsp. carotovorum by Supervised Classification Using Multispectral Images. Canadian Journal of Remote Sensing, 48:144-157.

Cavalcante VS, Borges LS, Melo Moura W, Jacob LL & Freitas MAS (2020) Adubação organomineral na nutrição e produtividade de café arábica. Available at: <https://cadernos.aba-agroecologia.org.br/cadernos/article/view/6285>. Accessed on: March 8th, 2021.

Falker (2008) Manual CloroiLOG: medidor eletrônico do teor de clorofila. Porto Alegre, Falker automação agrícola. 33p.

Francioli D, Schulz E, Lentendu G, Wubet T, Buscot F & Reitz T (2016) Mineral vs. organic amendments: microbial community structure, activity and abundance of agriculturally relevant microbes are driven by long-term fertilization strategies. Frontiers in microbiology, 7:1446.

Gitelson AA, Kaufman YJ, Stark R & Rundquist D (2002) Novel algorithms for remote estimation of vegetation fraction. Remote Sensing of Environment, 80:76-87.

Godoy LJGD, Santos TDS, Villas Bôas RL & Leite Júnior JB (2008) Índice relativo de clorofila e o estado nutricional em nitrogênio durante o ciclo do cafeeiro fertirrigado. Revista brasileira de ciência do solo, 32:217-226.

Guimarães PTG, Ribeiro CR, Alvarez VV & Vitor H (1999) Recomendações para o uso de corretivos e fertilizantes em Minas Gerais. 5ª ed. Viçosa, Comissão de Fertilidade do Solo do Estado de Minas Gerais. 359p.

Landis JR & Koch GG (1977) The measurement of observer agreement for categorical data. Biometrics, 33:159-174.

Liakos KG, Busato P, Moshou D, Pearson S & Bochtis D (2018) Machine learning in agriculture: A review. Sensors, 18:2674.

Malavolta E (2001) Manual de química agrícola: adubos e adubação. 3ª ed. São Paulo, Agronômica Ceres. 594p.

Marschner H (2012) Mineral nutrition of higher plants. 3ª ed. New York, Academic. 889p.

Martinez HEP, Menezes JFS, Souza RBD, Alvarez Venegas VH & Guimarães PTG (2003) Faixas críticas de concentrações de nutrientes e avaliação do estado nutricional de cafeeiros em quatro regiões de Minas Gerais. Pesquisa agropecuária brasileira, 38:703-713.

Pereira FV, Martins GD, Vieira BS, Assis GA & Orlando VSW (2022) Multispectral images for monitoring the physiological parameters of coffee plants under different treatments against nematodes. Precision Agriculture, 23:01-33.

Pérez CDP, Pozza EA, Pozza AAA, Freitas AS & Silva MG (2017) Nitrogênio e potássio na intensidade da mancha aureolada do cafeeiro em solução nutritiva. Coffee Science, 12:60-68.

Pinheiro RM, Gadotti GI, Monteiro RDCM & Bernardy R (2021) Inteligência artificial na agricultura com aplicabilidade no setor sementeiro. Diversitas Journal, 6:2996-3012.

Rouse JW, Hass RH, Schell JA & Deering DW (1973) Monitoring vegetation systems in the Great Plains with ERTS. Nasa, 3:309-329.

Santos OL, Padolfi AS & Ramaldes GP (2018) Análise de índice de vegetação através de imagens obtidas por VANT. Revista Científica FAESA, 14:145-165.

Scheunders P, Tuia D & Moser G (2018) Contributions of machine learning to remote sensing data analysis. Comprehensive remote sensing, 2:199-243.

Sobreira FM, Guimarães RJ, Colombo A, Scalco MS & Carvalho JG (2011) Adubação nitrogenada e potássica de cafeeiro fertirrigado na fase de formação, em plantio adensado. Pesquisa Agropecuária Brasileira, 46:09-16.

Souza LA, Silva EA, Oliveira GC, Barbosa SM & Silva BM (2018) Análise qualitativa e quantitativa de agregados de solo sob filme plástico associado à fertilização organomineral em área cafeeira. Scientia Agraria, 19:142-153.