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Monitoring the spectral and agronomic behaviour of maize in response to nitrogen fertilisation[1]

Mauricio Lourenzoni Augusti[2]*, Valdinar Ferreira Melo[3], Sandra Cátia Pereira Uchoa[3], Marcio Rocha Francelino[4], Aston Vestris Adandonon[5], Aurele Hosanna Gbenagnon Sounou[5]

ABSTRACT - Maize is a demanding crop that is responsive to nitrogen fertilisation, and meeting its needs is essential to avoid a loss of productivity or environmental contamination. Monitoring nutrient status during crop development is fundamental for optimising nitrogen fertilisation, and using spectral sensors can help detect spatial variability in the field. Based on this premise, the aim of this study was to evaluate the effectiveness of three low-cost sensors in detecting variability in the spectral and agronomic characteristics of the maize cultivar, BM 3066 PRO2®, induced by different N doses (0, 100, 200 and 300 kg ha^{-1}) under two cropping systems, no-tillage and conventional. The study employed a camera with a sensor in the visible region of the spectrum (RGB), a camera in the visible-infrared region (OCN), both mounted on a drone, and a portable chlorophyll meter. Spatial variability was assessed during the crop cycle using the normalised difference vegetation index (NDVI) and chlorophyll index. The results showed that the NDVI(ON) vegetation index from the OCN sensor was more effective at differentiating the treatments than was the NGR vegetation index from the RGB sensor. Furthermore, the chlorophyll b index was better at detecting variations induced by different nitrogen doses, outperforming the vegetation indices obtained by means of aerial images. The airborne sensors under test are more suitable for detecting early spatial macro-variability, while the chlorophyll meter is more effective at assessing the degree of nitrogen deficiency.

Keywords: Chlorophyll meter. Drone. Conventional tillage. Direct planting. Vegetation indices.

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*Author for correspondence
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[2]Post-graduate programme in agronomy of the Federal University de Roraima (UFRR), Boa Vista-RR, Brazil, mauricioaugusti86@gmail.com (ORCID ID 0000-0001-8441-7361)
[3]Department of Soils and Agricultural Engineering, Federal University de Roraima (UFRR), Boa Vista-RR, Brazil, valdinar@yahoo.com.br (ORCID ID 0000-0002-7943-9969), sandra.uchoa@ufrr.br (ORCID ID 0000-0003-4224-070X)
[4]Department of Soil Science, Federal University of Viçosa (UFV), Virçosa-MG, Brazil, marcio.francelino@ufv.br (ORCID ID 0000-0001-8837-1372)
[5]Graduate programme in Agronomy, Federal University de Roraima (UFRR), Boa Vista-RR, Brazil, vestast30@gmail.com (ORCID ID 0009-0006-5416-6884), sounouaurele2@gmail.com (ORCID ID 0009-0009-6609-5288)

INTRODUCTION

The economic viability and environmental impact of maize production are directly linked to the application of nitrogen fertiliser. In view of this relationship, improved methods of diagnosis and recommendation are necessary to optimise the use of nitrogen (N). By understanding spatial variation in the growth and development of maize, it becomes possible to implement localised management practices, with the aim of increasing production potential (Vian *et al*., 2016).

The spatial variability of maize crops is expressed by the long-term interaction of such factors as soil and plant attributes. In the case of N, the amount available to plants results from the residual content of the fertiliser and mineralised N from soil organic matter, minus the content lost in the rhizosphere during the crop cycle; however, it is only possible to determine the N applied through mineral fertilisation (Morris *et al*., 2018). In addition to traditional recommendations based on the levels of soil organic matter, desired productivity, residue of previous crops, management history and recovery efficiency (Cantarella, 2007), new approaches include the use of optical sensors to prescribe the N dose, improving the accuracy of the recommendations (Muñoz-Huerta *et al.*, 2013; Vian *et al*., 2018). The main advantages of using sensors to measure the N content of plants indirectly include identifying the actual deficiency of the nutrient and the possibility of managing spatial variation based on the applied rates, especially in the case of proximal or airborne sensors (Morris *et al*., 2018).

The sensors of airborne cameras capture the different levels of solar electromagnetic radiation reflected by each of the elements that make up the cultivated landscape (cultivated plants, dead plant remains, bare soil, shadows, etc.) and their interactions, recording these differences spatially in the form of images (Florenzano, 2011). In the visible spectrum, leaf pigments, especially chlorophyll, absorb significant radiation in the red and blue bands, while in the near infrared region, the radiation is mainly reflected due to the cellular structure of the leaves (Formaggio; Sanches, 2017). Images obtained by cameras mounted on drones can be used at different times during crop development to reveal production inefficiencies (Ahirwar *et al*., 2019) by detecting the health or stress of the plants (Barbedo, 2019; Dutta; Goswami, 2020).

Active sensors, such as portable chlorophyll meters, use their own source of radiation and can provide an estimate of the relative levels of chlorophyll, and therefore of N, in leaf tissue by measuring the light absorbed by the chlorophyll and the leaf tissue. These devices are able to detect variations in the nutritional status of maize by directly assessing the plant response to different levels of supplied N, as shown in studies by Chapman and Barreto (1997) and Hurtado *et al*. (2010).

Spectral sensors detect the spatial variability of N in the crop resulting from variability in the N content of the plants and soil. Based on this premise, the aim of this study was to evaluate the effectiveness of three low-cost sensors: two digital cameras carried by drones, one with a sensor in the visible spectrum (RGB) and the other in the visible-infrared region (OCN) and a portable chlorophyll meter, in detecting variability in the spectral and agronomic characteristics of the maize cultivar BM 3066 PRO2® induced by different N doses (0, 100, 200 and 300 kg ha^{-1}) under two cropping systems, no-tillage and conventional.

MATERIAL AND METHODS

Setting up the experiment

The research was conducted at the experimental unit of the Cauamé campus of the Federal University of Roraima, in Boa Vista, Roraima, Brazil, located at 2°52’17.64” N and 60°42’41.70” W at an altitude of 85 m (Figure 1). According to the Köppen classification, the climate in the region is type Aw, tropical wet, characterised by a dry period from December to March. The soil in the area is classified as a Dystrophic Yellow Latosol with flat terrain and the predominance of savanna.

Two experiments were set up in an area of 1800 m^2 that had previously been cultivated with soya beans (*Glycine max* L.) and subjected to two cropping systems, conventional (CS) and no-tillage (NT). To maintain these systems, the area under CS was prepared by incorporating crop residue with the use of a plough, while the area under NT underwent chemical desiccation 35 days before sowing.

The experimental design was of randomised blocks with four replications. Each block of 180 m^2 (15 x 12 m) was split into four plots of 42 m^2 (3.5 x 12 m). The N doses, applied as topdressing, were randomised in the plots as follows: 0 (T0); 100 (T1); 200 (T2) and 300 (T3) kg ha^{-1} N. Each plot consisted of seven rows spaced 0.5 m apart, with 0.25 m between the plants, to obtain a population of 80,000 plants per hectare. The three central rows (1.5 m) made up the working area of each plot leaving two rows of border on either side (1 m).

The soil was corrected with 300 kg ha^{-1} dolomitic limestone (PRNT 99%) when sowing. This was broadcast but not incorporated, with the aim of increasing the base saturation of the soil to 60%. Agricultural gypsum and triple superphosphate were used, at doses of 200 and 110 kg ha^{-1}, respectively, to increase the available S and P. Potassium chloride (110 kg ha^{-1}) and ammonium sulphate (50 kg ha^{-1})

were applied before plant emergence, with potassium chloride (60 kg ha^{-1}) being applied 28 days after emergence (DAE). In both systems, the treatments, comprising N doses as topdressing, were applied throughout the cycle as follows: ammonium sulphate at 9 DAE (corresponding to 20% of the total N dose), urea at 19 DAE (40% of the N dose) and 34 DAE (40% of the N dose) at stages V3, V6 and V11, respectively. Due to the slower growth and initial development of the maize in treatment T0 (designed not to receive a topdressing of N) under NT, it was decided to apply 20 kg ha^{-1} N in the form of urea at 29 DAE to maintain a minimum of productive potential in the crop.

Two complementary foliar applications of nutrients were made at 17 and 27 DAE, at a dose of 0.4 kg ha^{-1}, containing 1.1% Mg, 0.85% B; 0.5% Cu (Cu-EDTA), 3.4% Fe (Fe-EDTA), 3.2% Mn (Mn-EDTA), 0.05% Mo and 4.2% Zn.

The maize (*Zea mays* L.) was sown manually, using the hybrid cultivar BM 3066 PRO2®, recommended for green maize and silage. Sowing took place on 25 January 2021, with plant emergence beginning four days later.

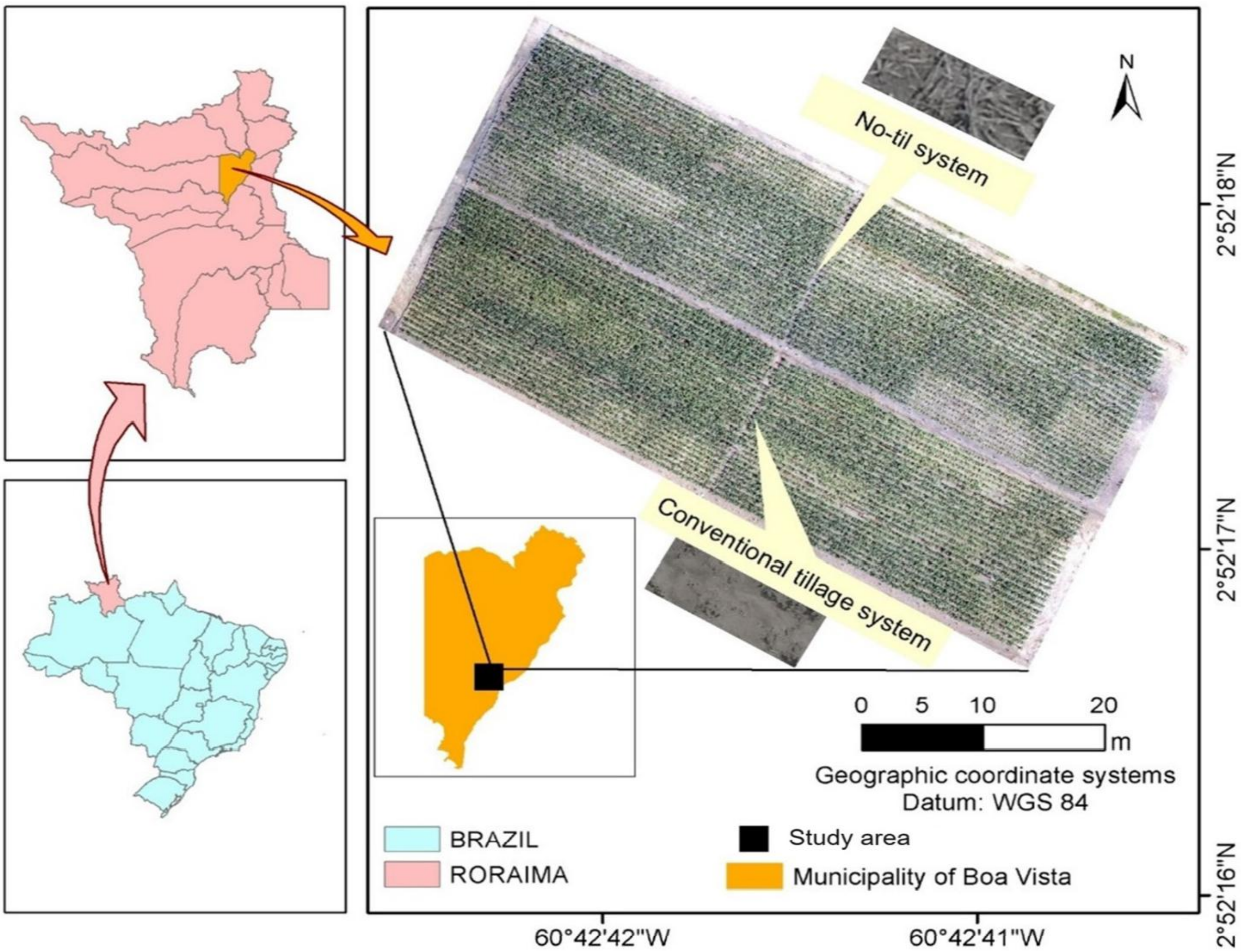
Chemical weed management was carried out using 0.4 kg ha^{-1} diquat, applied 23 days before emergence to avoid the presence of green weeds during the initial phase. Any weeds that emerged after sowing were controlled using glyphosate (1.068 kg ha^{-1}) at 19 DAE.

The soil moisture was maintained by means of a sprinkler system whenever necessary. The sprinklers were positioned at a height of 2.8 m at the division between each plot.

Acquiring the aerial images

The aerial images were obtained using the MAPIR Survey 3W – OCN/NDVI on-board camera (Mapir, San Diego, USA) mounted on the Phantom 4 Pro quadcopter drone (DJI, Nanshan District, China), as shown in Figure 2.

Figure 1 - Location and layout of the study area with details for the no-tillage and conventional systems



The images were acquired at a height of 60 m on different days throughout the crop cycle, and were used to generate the vegetation indices. Shorter intervals between the images were adopted at the start of the cycle and longer intervals towards the end, based on the importance of these periods for carrying out N management. The stages chosen for image capture corresponded to the periods close to, before and following the applications of N, with the aim of recording the changes in pigmentation caused by the treatments (Table 1).

The images were captured in the afternoon (Table 1), when the lighting was uniform and the weather conditions suitable for flight. Situations where water accumulated on the surface of the ground or on the leaves, as well as gusts of wind, were also avoided.

To standardise the flight path during image capture on different dates, a flight plan was established with the help of the Droneploy application (DroneDeploy, San Francisco, USA). Image overlap at the front and sides was set to 80%, based on the technical characteristics of the camera built into the drone. These settings increase the side overlap of the images from the onboard camera, due to the larger viewing angle.

To standardise the height of the drone, a location at the same level as the test area was chosen as the single launch point. The same location was used to acquire images of the calibration target used for the VIR sensor.

The integrated camera has a 1” CMOS sensor with filters for the following wavelengths: blue (B) - 450 nm ± 16 nm, green (G) - 560 nm ± 16 nm and red (R) - 650 nm ± 16 nm. Most of the settings were left in automatic mode or controlled by the flight plan manager. Other variables were set manually: 4:3 aspect ratio, true colour system and JPEG image format.

Figure 2 - Principal components of the drone/camera set showing the MAPIR Survey 3W (C) camera

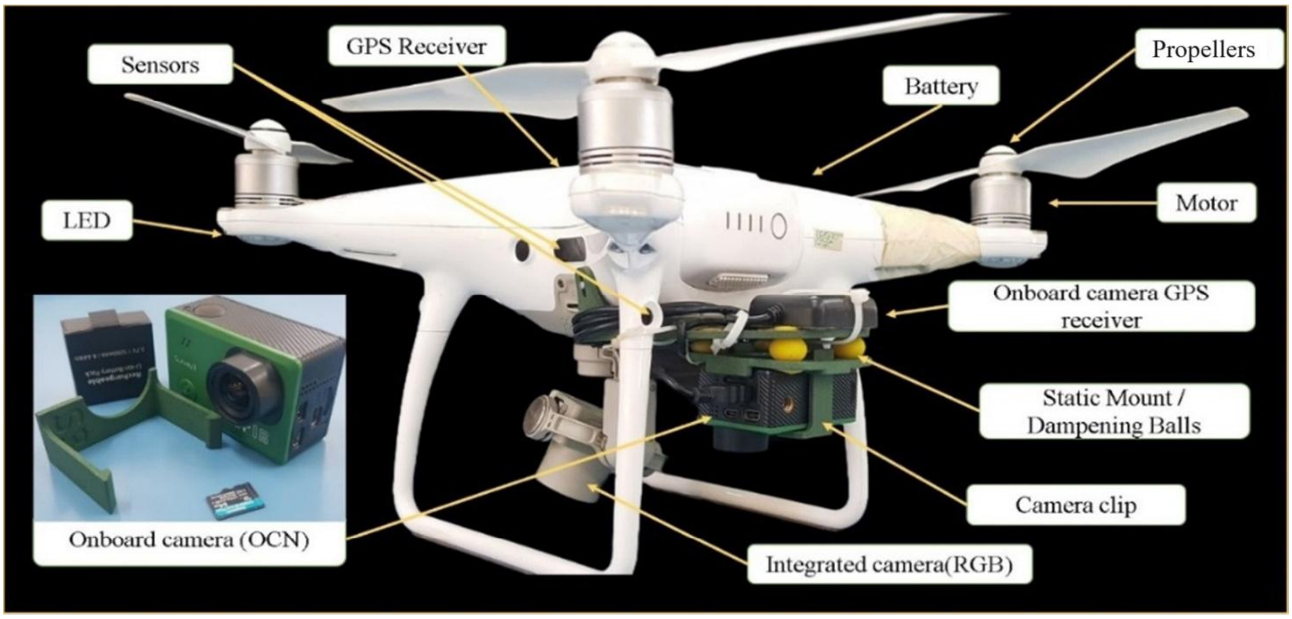


Table 1 - Dates and situation of the maize crop at the time of image acquisition

Date	Interval (days)	DAE	Time	Situation	Degree days
13/02/2021	-	15	15:08	6 days after the first treatment (V4)	290.4
18/02/2021	5	20	10:03	1 day after the second treatment (V6)	382.7
26/02/2021	8	28	15:10	9 days after the second treatment (V9)	532.5
09/03/2021	11	39	14:46	5 days after the third treatment (V12)	743.7
20/03/2021	11	50	13:11	Pre-silking	945.4
31/03/2021	11	61	14:46	Green maize pre-harvest (milky grain)	1149.7

The MAPIR Survey 3W camera (Mapir, San Diego, USA) is equipped with the Sony Exmor R IMX117 12MP CMOS sensor (Bayer RGB), which records reflected light in the Orange (O) 615 nm, Cyan (C) 490 nm and near infrared (N) 808 nm wavelengths, corresponding to the Red, Green and Blue bands of the RGB system.

The Mapir Survey 3W camera was configured as follows: image format, 4:3; shutter speed, automatic; capture interval, 2 seconds; sharpness, medium; white balance, auto; exposure, +0.0; metering, local; ISO, auto; colours, normal; contrast, medium; format, RAW.

Image processing

The images from the MAPIR Survey 3W camera were automatically converted from RAW to TIFF format using the Mapir Camera Control software (Mapir, San Diego, USA). The images were then corrected radiometrically in the same software using images from the V2 Reflectance Calibration Ground Target Package (Mapir, San Diego, USA). The images from the RGB camera were not corrected, and processed directly as digital radiance numbers in 8-bit resolution.

The next step involved building orthomosaics for the images from each of the cameras using the PhotoScan Agisoft® software (Agisoft LLC, St Petersburg, Russia), followed by exporting an orthorectified image in GeoTIF format.

With the orthomosaics in hand, the ArcMap 10.6.1 software (ESRI, USA) was used to carry out the relative georeferencing of each image, considering as a reference for the other images at least six control points from an RGB image of 18 February 2021 from a survey carried out at a height of 30 m. The transformations were adjusted using a second-order polynomial. In addition, a new clipping process of the study area was carried out to include the cultivated area and a small border. The same reference image was also used to define the sample areas of the plots (three digital sub-plots per plot).

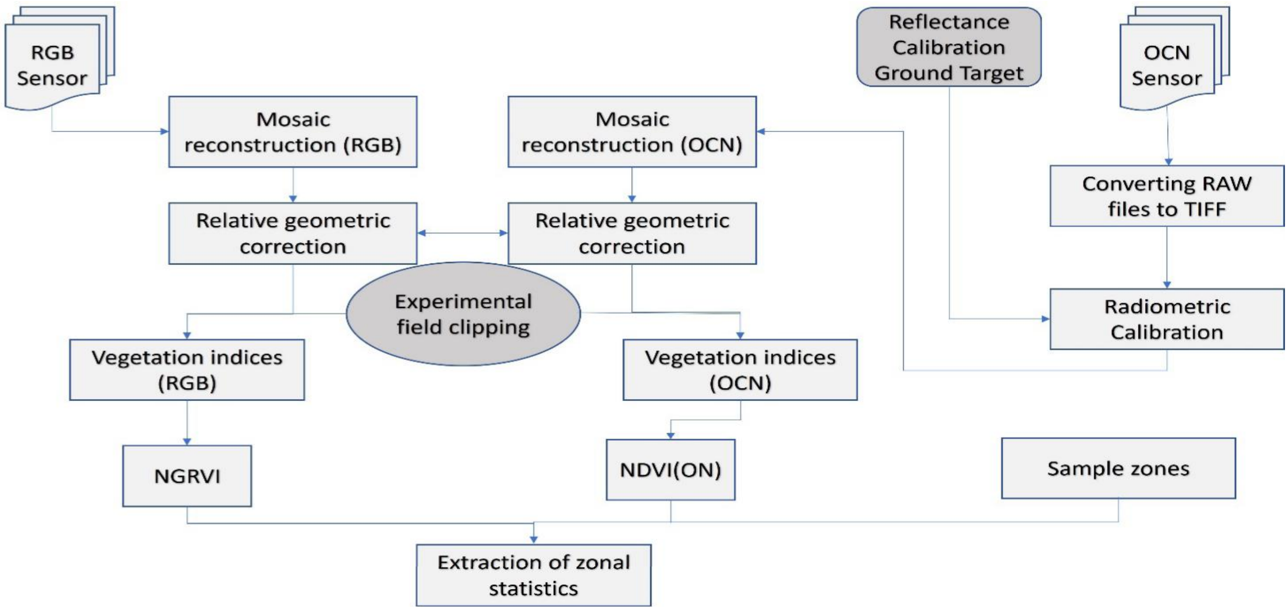
Using the ModelBuilder tool, two models were built to calculate the vegetation indices. For the RGB camera, the normalised green red vegetation index (NGRVI) was used: NGRVI=(G-R)/(G+R), as proposed by Motohka *et al.* (2010); and for the OCN camera, the normalised difference vegetation index (NDVI-ON) between the near infrared (NIR) and orange (O) bands, NDVI(ON)=(NIR-O)/(NIR+O), as described by Batista *et al.* (2021).

To extract the mean values of the vegetation indices, the zonal statistics tool was used to calculate and export the data as a data table. The operation was carried out on the area delimited in the vector file of zonal samples and separated according to the plot identifier entered in the attribute table. The data were then exported in text format, tabulated and prepared for statistical analysis (Figure 3).

Chlorophyll indices

The indices for chlorophyll a, chlorophyll b and total chlorophyll were obtained 15, 20, 29, 39 and 52 DAE using the Clorofilog CFL1030 chlorophyll meter (Falker Automação Agrícola, Brazil), taking 20 readings between the midrib and the edge of the leaf in the central third of random leaves with horizontal exposure in the upper layer of the canopy, from 15:00 to 17:00.

Figure 3 - Flowchart of the image processing steps



Agronomic variables

The following agronomic variables were evaluated: initial population count at 10 DAE, calculated as the average of three samples of three 1-m rows, equal to an area of 1.5 m²; plant height at 16, 20, 29, 41 and 51 DAE, initially using a graduated rule and, later, a tape measure, measuring from the ground to the tip of the largest leaf extended perpendicularly relative to the soil, sampling 10 plants per plot; and number of green leaves below the ear at 65 DAE, obtained by counting the leaves that were completely green in 10 plants per plot.

Maize productivity at 64 DAE was evaluated by randomly harvesting a sample of 10 plants from the working area of each experimental unit; these were cut at ground level and separated into the different parts of the plant. The fresh weight of the grains and the dry weight of the grains, cobs, leaves, ear husks and stalks were quantified using a forced-air oven at 65 ºC to constant weight, with the total dry weight determined as the sum of the individual dry weights. Finally the green-grain harvest index was determined as the ratio of the dry weight of the green grains to the total dry weight.

The last variable to be estimated was mature grain production, which was obtained from the average grain production of 10 randomly selected ears, adjusted to 14% moisture. Each of the variables expressed in units per hectare were obtained by converting the number of sampled plants by the plant population per hectare corresponding to each plot.

Statistical analysis

The data were subjected to analysis of variance and, when significant, the mean values were compared by Tukey's test ($p \leq 0.05$). An exploratory analysis of the data was also carried out using regression analysis to verify the effect of the doses on the quantitative variables measured in the field, and Pearson's correlation to establish a relationship between the variables, considering each of the observations. The SAS (Statistical Analysis System), RStudio, R and Microsoft Excel software were used for the analyses and to demonstrate the results.

RESULTS AND DISCUSSION

Agronomic variables

In order to better understand the effects of the treatments on the crop and, consequently, on the data and information obtained from the vegetation and chlorophyll indices, the behaviour of the agronomic variables is briefly described.

Total shoot dry matter production (TSDM) was higher in treatments T3 and T2 for both cropping systems, with all of the treatments differing significantly from T0. However, under NT, treatment T1 did not differ from T2, whereas under CS the difference was significant (Table 2).

Green grain production (PRODGG), assessed 61 DAE, showed differences for treatment T0 under NT only, with similar behaviour for mature grain production at the end of the cycle (PRODMG). While T0 and T1 differed from each other and from the other treatments for green grain production under NT, only T0 and T3 differed in terms of mature grain production (Table 2).

The average plant population (NP) under NT was 82,612 plants per hectare, while under CS it was 78,575 plants per hectare (Table 2). The number of green leaves remaining before physiological grain maturation showed no statistically significant differences under NT, but was different between treatments T0 and T3 under CS.

Under NT, the average height of the maize plants was 2.54 m at 51 DAE, while under SPC it was 2.63 m. Under CS, at 16, 20 and 51 DAE, only treatment T0 differed significantly from the other treatments. At 29 and 41 DAE, T3 differed from T0 and T1, while T2 did not differ from T1 or T3. There was no significant difference between treatments under CS at 16 DAE. At 20 DAE, T0 differed from all the other treatments, while T2 differed from T1, but not from T3. At 29 and 41 DAE, only T3 and T2 did not differ. Finally, at 51 DAE, there was a significant difference between T0 and the other treatments only.

Assessing spatial variability using the chlorophyll indices

The treatments with higher N doses promoted an increase in the chlorophyll indices. Under both cropping systems and on all sampling dates, the chlorophyll b index was more sensitive at differentiating between treatments (data on chlorophyll a and total indices not shown). Under NT, at 20 DAE the results stand out, the chlorophyll b index differentiating between the four treatments, and at 29 DAE, when the index was only unable to differentiate T2 from T3 and T1. Likewise under CS, when at 20, 29 and 39 DAE, the chlorophyll b index was only unable to differentiate between T2 and T3 (Table 3).

The chlorophyll b index showed the best result and was considered the most appropriate for differentiating between treatments and indirectly diagnosing the nutrient status of N, since it shows greater differences to environmental stimuli compared to the chlorophyll a index (Jinwen *et al*., 2009; Wang *et al*., 2008). The ability of the chlorophyll b index to differentiate between treatments was seen at 20 DAE under NT, when all of the treatments presented statistically distinct values, demonstrating the usefulness of the chlorophyll b index in evaluating the nutrient status of the maize crop.

Table 2 - Measurements of the agronomic variables of the maize crop under the no-tillage and conventional systems

Treatment	PRODGG (kg ha^{-1})	TSDM (kg ha^{-1})	PRODMG (kg ha^{-1})	NP	NL
			NT		
T0	3632 b	9234 c	8273 b	82750	433565
T1	6209 a	12275 b	10632 a	83300	485855
T2	7010 a	13181 ab	10711 a	81100	484380
T3	7461 a	15337 a	11984 a	83300	491415
Overall mean	6078	12507	10400	82612	473804
P-value treat.	0.0002*	0.0006*	0.0036*	0.3548^{ns}	0.3183^{ns}
CV (%)	12.78	10.3	9.59	2.27	9.8
			CS		
T0	2.661 c	8.643 c	7.223 b	78875	224762 b
T1	4.749 b	11.079 b	8.862 ab	78275	331617 ab
T2	6.700 a	13.239 a	10.294 ab	78300	431712 ab
T3	7.293 a	14.343 a	11.037 a	78850	484467 a
Overall mean	5.350	11.826	9.354	78575	368.140
P-value treat.	0.00007*	0.000016*	0.03340	0.94674^{ns}	0.03523
CV (%)	14.8	11.85	16.88	2.45	29.53

PRODGG (Green grain production). PRODMG (Mature grain production). NL (Number of green leaves below the ear per hectare). NP (Average plant population per hectare). TSDM (total shoot dry matter production). DAE (days after emergence); T0 (0 kg ha^{-1} N); T1 (100 kg ha^{-1} N); T2 (200 kg ha^{-1} N); T3 (300 kg ha^{-1} N). NT (no-tillage system). CS (conventional system). Mean values followed by the same letter in the columns do not differ by Tukey's test at 5% probability; *significant at 1% probability; ^{ns} = not significant at 5% probability by F-Test

Table 3 - Values of the chlorophyll b index in maize, evaluated on different days after emergence, for the no-tillage and conventional systems under different N treatments

Treatment	Days after emergence				
	15	20	29	39	52
			NT		
T0	49.600 b	36.925 d	57.800 c	66.125 b	90.000 c
T1	97.625 a	75.075 c	94.450 b	110.300 a	123.300 bc
T2	110.050 a	112.425 b	127.975 ab	113.475 a	151.250 ab
T3	108.800 a	138.375 a	153.500 a	125.950 a	174.050 a
Overall mean	91.519	90.700	108.431	103.963	134.650
P-value treat.	0.00015*	0.00000*	0.00009*	0.00217*	0.00018*
CV (%)	13.01	12.48	14.92	15.03	11.54
			CS		
T0	52.275 b	49.750 c	71.525 c	60.750 c	77.675 c
T1	76.825 a	82.625 b	104.375 b	100.200 b	122.350 bc
T2	87.125 a	127.350 a	151.625 a	132.325 a	154.075 ab
T3	82.375 a	141.050 a	168.675 a	143.350 a	205.450 a
Overall mean	74.650	100.194	124.050	109.156	139.888
P-value treat.	0.000961*	0.00000*	0.000001*	0.00000*	0.000379*
CV (%)	11.08	11.17	1.83	6.44	18.1

DAE (days after emergence); T0 (0 kg ha^{-1} N); T1 (100 kg ha^{-1} N); T2 (200 kg ha^{-1} N); T3 (300 kg ha^{-1} N). NT (no-tillage system). CS (conventional system). Mean values followed by the same letter in the columns do not differ by Tukey's test at 5% probability; *significant at 1% probability; ^{ns} = not significant at 5% probability by F-test

The average values of the chlorophyll b index during the period under evaluation show a high correlation with the amount of applied N for rates lower than 162.77 kg ha^{-1} under NT, and 251.10 kg ha^{-1} under CS (Figure 4). A positive relationship between the chlorophyll indices and nitrogen doses in maize was also found by Kappes *et al.* (2013), Kappes *et al.* (2014) and Segatto *et al.* (2017). Based on the productive response of both green and mature grains, values close to or greater than 110 for the chlorophyll b index could be considered ideal under similar conditions to those of this study.

Spectral behaviour of the treatments

The spectral responses up to 20 DAE show similar pixel values in the NIR and orange bands of the OCN camera and, green and red bands of the RGB camera, demonstrating the mixed effect of the soil and vegetation on the spectral response of the plots (Figure 5).

Figure 4 - Chlorophyll b indices throughout the crop cycle as a function of the treatments under the NT (A) and CS (B) systems. Each point observed corresponds to a period of evaluation in days after plant emergence (DAE) within the respective N doses (kg ha^{-1})

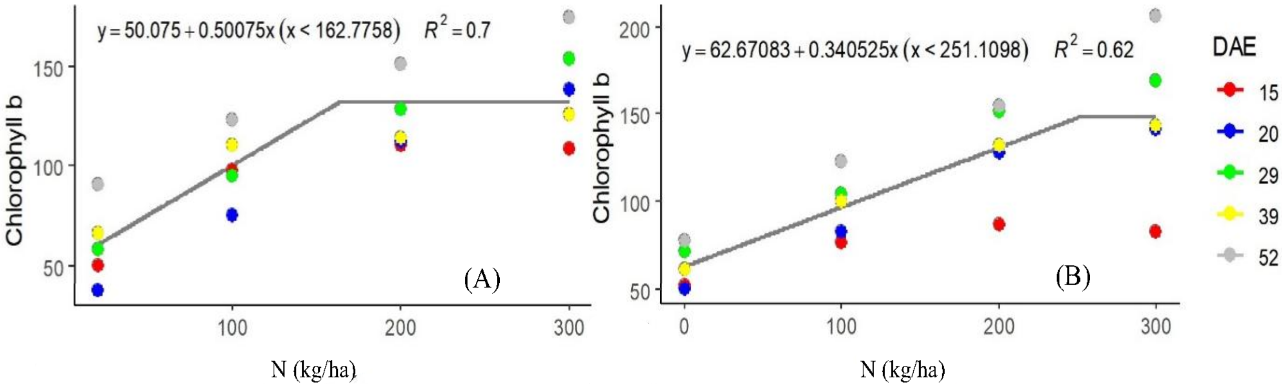
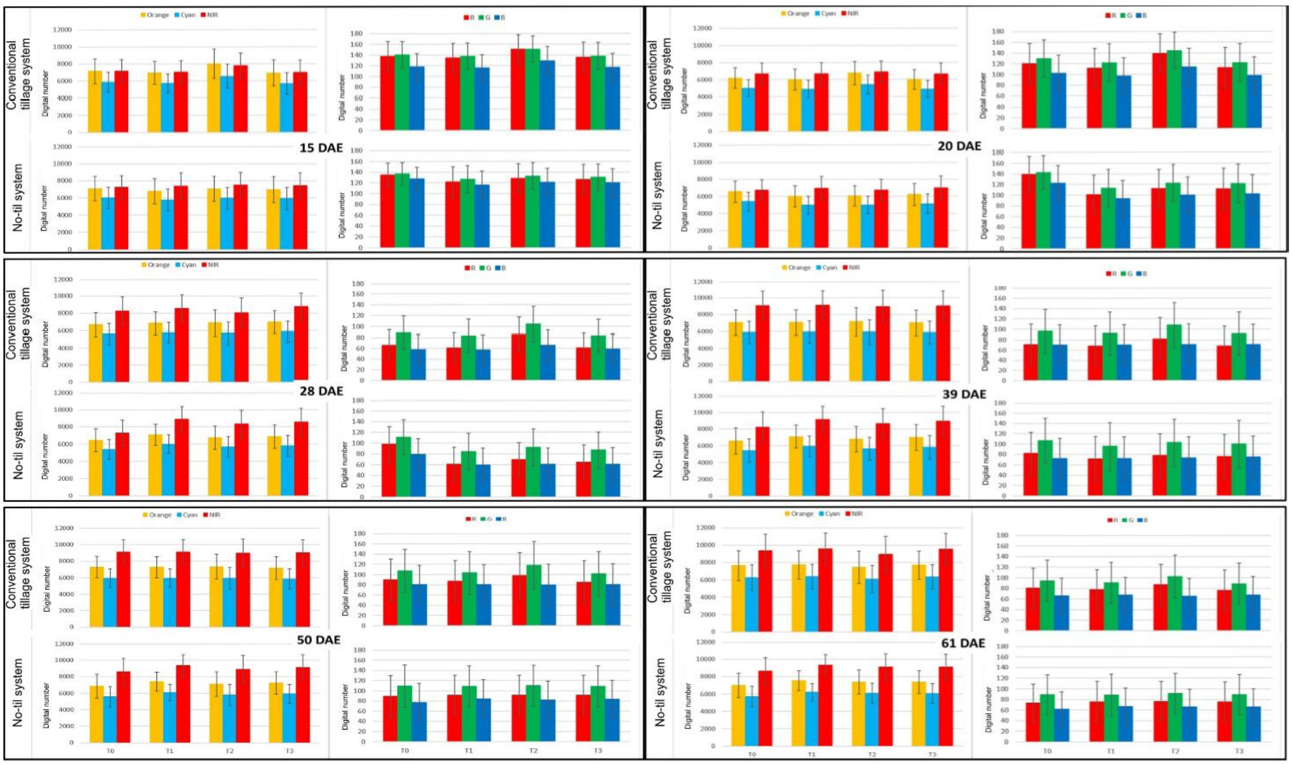


Figure 5 - Average spectral response of treatments T0, T1, T2 and T3 per spectral band of the OCN and RGB cameras, from 15 to 51 DAE, under the conventional and no-tillage systems



During the following period, between 28 and 61 DAE, higher pixel values can be seen in the NIR and green bands compared to the orange and red bands, characterising the predominance of plant cover in relation to bare soil. Another fact that demonstrates the increase in plant cover over time is the reduction in pixel values for bands in the visible region of the electromagnetic spectrum, and an increase in values in the NIR region. The greater contrast seen in the NIR and orange bands, and between the green and red bands for the OCN and RGB sensors, respectively, support the use of only those vegetation indices that make use of the normalised difference between these bands to evaluate the differences between the treatments.

The cropping systems appear to have little effect on the average spectral response of the treatments; however, at 20 and 28 DAE, the digital values from the RGB sensor increased, especially in treatment T1 under NT compared to under CS.

Assessing spatial variability by means of the NGRVI and NDVI(ON) vegetation indices

The NGRVI vegetation index (Figure 6) showed lower values for all treatments from 15 to 20 DAE, a period during which bare soil and mulch could still be seen between the plants and rows. Later, at 61 DAE, the average values decreased again under both cropping systems.

Under NT (Table 4) at 15 DAE (6 days after the first N application), the NGRVI index differed statistically for treatments T0 and T3 only. Then, at 20 DAE (11 days after the first N application), differences were detected between all the treatments for T0, and between T1 and T3. At 28 DAE (9 days after the second N application), it was possible to differentiate treatment T0 from the other treatments. There was no significant difference between the treatments on the other dates.

Under CS (Table 4), at 15, 20, 39, 50 and 61 DAE, the NRGVI index was unable to detect any difference between the treatments. At 28 DAE (11 days after the first application), differences were detected between all the treatments in relation to T0.

Figure 6 - NGRVI vegetation indices obtained from RGB camera images during the maize crop cycle. Blocks under the conventional planting system: I-CS, II-CS, III-CS, IV-CS. Blocks under the no-tillage system: I-NT, II-NT, III-NT, IV-NT

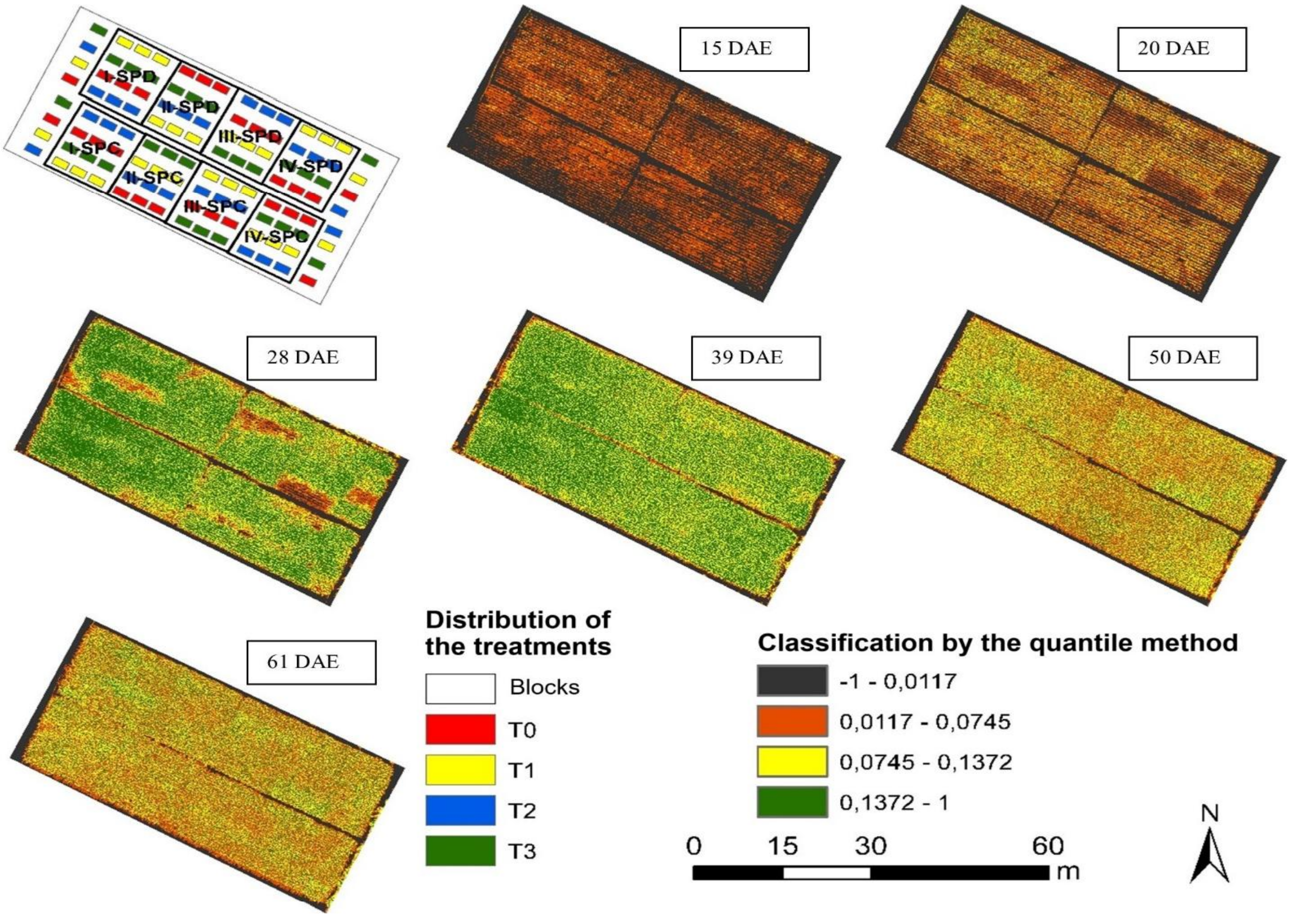


Table 4 - NGRVI indices of the effect of N doses on maize after emergence during six growing seasons, under the NT and CS systems

Treatment	Days after emergence					
	15	20	28	39	50	61
NT						
T0	0.0086 b	0.0169 c	0.0743 b	0.1616	0.1361	0.1222
T1	0.0215 ab	0.0517 b	0.1639 a	0.1841	0.1212	0.1137
T2	0.0206 ab	0.0594 ab	0.1720 a	0.1850	0.1151	0.1078
T3	0.0241 a	0.0716 a	0.1939 a	0.1869	0.1184	0.1104
Overall mean	0.0187	0.0499	0.1510	0.17945	0.1227	0.1135
P-value treat.	0.03532*	0.00007*	0.00001*	0.04679^{ns}	0.05787^{ns}	0.05889^{ns}
CV (%)	34.71	17.84	10.96	6.66	7.95	5.83
CS						
T0	0.0030	0.0245	0.1114 b	0.1657	0.1206	0.0987
T1	0.0133	0.0453	0.1647 a	0.1847	0.1159	0.1002
T2	0.0130	0.0528	0.1784 a	0.1822	0.1186	0.0980
T3	0.0117	0.0531	0.1755 a	0.1820	0.1221	0.0963
Overall mean	0.0102	0.0439	0.1575	0.1787	0.1193	0.0983
P-value treat.	0.4949^{ns}	0.07166^{ns}	0.00256*	0.18169^{ns}	0.74881^{ns}	0.94832^{ns}
CV (%)	102.33	33.59	12.16	6.86	7.05	9.61

DAE (days after emergence); T0 (0 kg ha^{-1} N up to 28 DAE and then 20 kg ha^{-1} under NT); T1 (100 kg ha^{-1} N); T2 (200 kg ha^{-1} N); T3 (300 kg ha^{-1} N). NT (no-tillage system). CS (conventional system). Mean values followed by the same letter in the columns do not differ by Tukey’s test at 5% probability; *significant at 1% probability; ^{ns} = not significant at 5% probability by F-test

For the NDVI(ON) vegetation index (Figure 7), which comprises the orange and near-infrared bands, values close to zero were seen initially, increasing with plant development up to stage V12 (39 DAE) and then decreasing under both cropping systems.

Under NT (Table 5), at 15, 20, 28 and 39 DAE, the NDVI(ON) index for T0 was significantly lower than for the other treatments. Under CS (Table 5), at 15 DAE, there was no visible difference between the treatments for the NDVI(ON) index, while at 20, 28, 39 and 50 DAE, a difference was seen for all treatments in relation to T0. At 61 DAE (green maize pre-harvest), treatment T3 differed from treatment T0.

During the period following the first nitrogen application (20 DAE), an important time for adjusting the N dose based on the crop response to the first application, it was found that the NDVI(ON) index showed a high correlation with the variability induced by the treatments of different N doses under both cropping systems (Pearson’s correlation: 0.94 under NT and 0.89 under CS). This demonstrates the viability of using this vegetation index as a possible reference in the creation of variable N-management zones at this stage of crop development. The view perpendicular to the ground provided by the airborne sensors also gives a better appreciation of the proportion of bare soil under the canopy than the oblique view obtained by an observer on the ground, improving the ability to detect sowing or fertilisation errors.

The vegetation indices under test were partially able to identify the four treatments that were applied to induce variability during the crop cycle at a confidence level of 95% using Tukey’s test. Although the statistical demands were high, better results were expected, given that the sensors are able to detect differences in the evolution of plant cover in relation to bare soil or mulch, as well as variations in the greenness of the crop caused by the different doses of applied nitrogen.

Indices such as the NDVI show good spectral separability between vegetation and bare soil (Torres-Sánchez et al., 2013), the infrared reflectance in the vegetation indices responding more to the structures and spaces of the mesophyll cells and less to the chlorophyll content of the palisade layer of the leaves (Rasmussen *et al*., 2016). On the other hand, the so-called green indices, such as the NGRDI, respond to the quantity and overall quality of the photosynthetic material in the vegetation, and are indicators of the joint effects of chlorophyll concentration, canopy leaf area and canopy architecture (Rasmussen *et al.*, 2016). However, following an increase in the leaf area index of a crop, the vegetation indices may suffer a saturation effect due to overlapping of the leaf blades (Formaggio; Sanches, 2017), reducing the ability to differentiate between different conditions of crop development.

Figure 7 - NDVI(ON) vegetation index obtained from images from the OCN camera during the maize crop cycle. Blocks under the conventional system: I-CS, II-CS, III-CS, IV-CS. Blocks under the no-tillage system: I-SPD, II-SPD, III-SPD, IV-SPD. T0 (0 kg ha^{-1} N); T1 (100 kg ha^{-1} N); T2 (200 kg ha^{-1} N); T3 (300 kg ha^{-1} N)

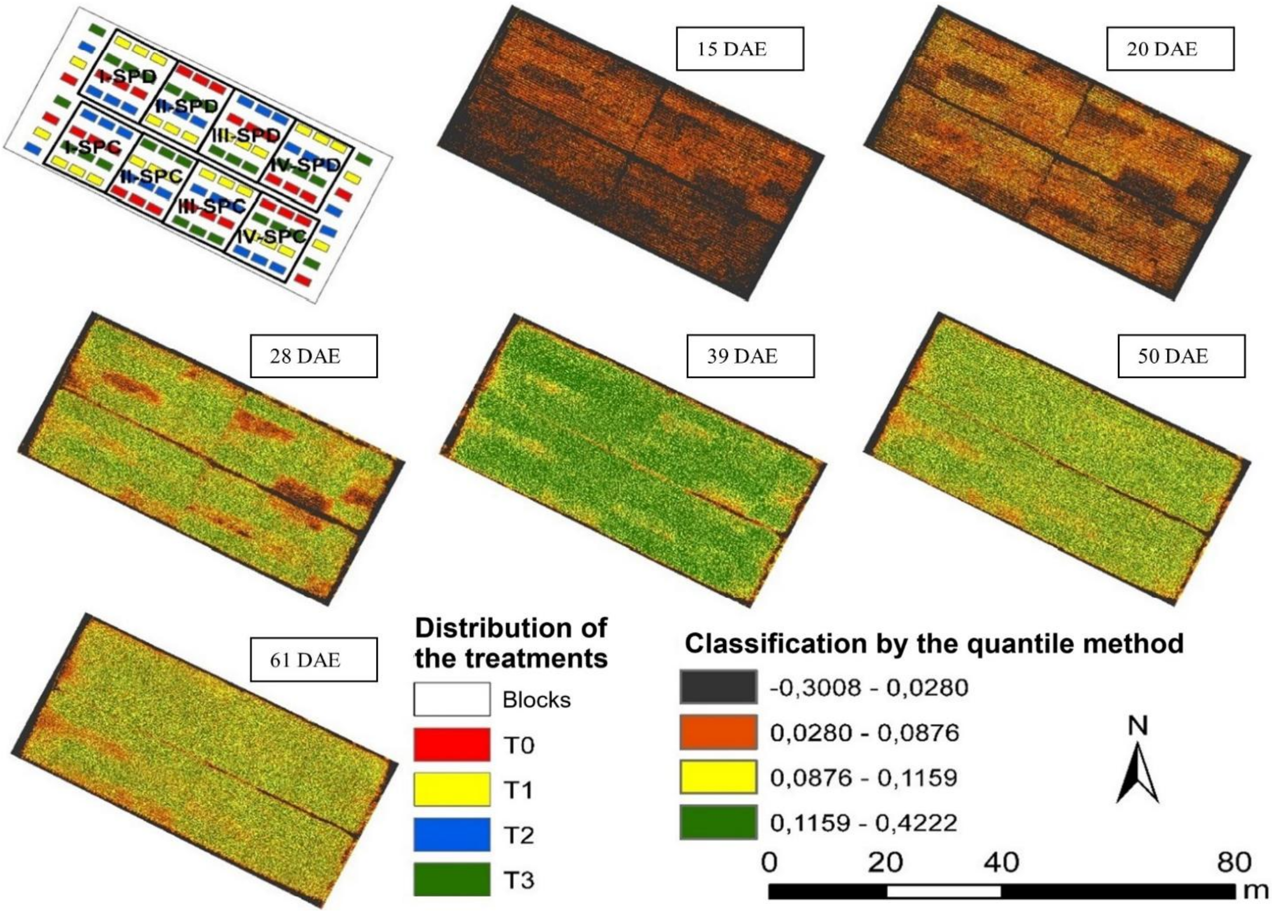


Table 5 - Average NDVI(ON) values throughout the crop cycle as a function of the different nitrogen treatments, under the NT and CS systems

Treatment	Days after emergence					
	15	20	28	39	50	61
			NT			
T0	0.0103 c	0.0165 c	0.0597 b	0.1160 b	0.1135	0.1067
T1	0.0308 b	0.0534 b	0.1053 a	0.1242 a	0.1138	0.1054
T2	0.0325ab	0.0619 ab	0.1112 a	0.1261 a	0.1153	0.1079
T3	0.0408 a	0.0725 a	0.1145 a	0.1293 a	0.1164	0.1077
Overall mean	0.0286	0.0510	0.0977	0.1239	0.1148	0.1069
P-value treat.	0.00003*	0.000005*	0.00012*	0.00155*	0.09299^{ns}	0.6701^{ns}
CV (%)	15.52	13.15	10.71	2.61	1.36	2.95

Continuation Table 5

CS						
T0	-0.0123	0.0132 b	0.0787 b	0.1141 b	0.1028 b	0.0924 b
T1	0.0036	0.0404 a	0.1044 a	0.1246 a	0.1128 a	0.1032 ab
T2	0.0066	0.0524 a	0.1128 a	0.1271 a	0.1151 a	0.1082 ab
T3	0.0050	0.0526 a	0.1141 a	0.1283 a	0.1168 a	0.1097 a
Overall mean	0.0007	0.0397	0.1025	0.1235	0.1119	0.10343
P-value treat.	0.15061^{ns}	0.00157*	0.00005*	0.00001*	0.00349*	0.03996*
CV (%)	1534.07	26.65	5.96	1.52	3.58	7.33

DAE (days after emergence); T0 (0 kg ha^{-1} N up to 28 DAE and then 20 kg ha^{-1} under NT); T1 (100 kg ha^{-1} N); T2 (200 kg ha^{-1} N); T3 (300 kg ha^{-1} N). NT (no-tillage system). CS (conventional system). Mean values followed by the same letter in the columns do not differ by Tukey's test at 5% probability; *significant at 1% probability; ^{ns} = not significant at 5% probability by F-test

Under NT, the NDVI(ON) index from the OCN sensor showed a more satisfactory response than the NGRVI index since it separated treatments T0 and T1 from treatment T3 at 15 and 20 DAE. Under such initial conditions, the spectral behaviour of the crop before the canopy closes is the result of a mixture of the spectral behaviour of the soil and of the green vegetation (Formaggio; Sanches, 2017), meaning that greater contrast between the soil and the plant cover benefits the index comprising the NIR band. The fact that there was no difference between treatments T2 and T3 during this period was the same for total dry matter production when harvesting the green grains, and for other variables collected in the field, except for the chlorophyll b index. The lack of biomass data when acquiring the image makes it difficult to better assess whether there is any difference between these treatments and the actual ability of the sensors to detect any variability. Under CS, the NDVI(ON) index was again better than the NGRVI index, differentiating treatment T0 from the other treatments at 20 DAE. Under CS, there was less difference between the spectral variables compared to NT; however, even under these conditions, the chlorophyll b index identified one more treatment than the NDVI(ON) index.

The difference between cropping systems in relation to spectral response can be explained by the dynamics of nitrogen availability in the soil, which is controlled by the processes of immobilisation and mineralisation of plant residue, and which results in a phase of low nitrate availability that then increases over time due to microbial activity (Jadeja *et al*., 2021). Under CS, mineralisation is speeded up by the pre-sowing, ploughing and harrowing operations, increasing the rate of decomposition due to greater contact between the soil and the residue (Carvalho *et al*., 2008), and meeting the initial demand for N (Loecke *et al*., 2012). On the other hand, under NT, the plant residue and microbial biomass immobilise part of the mineral N, making up a labile reserve of N that is not readily available during the initial stages of development (Aulakh *et al*., 1991; Gao *et al*., 2021; Jat *et al*., 2018), resulting in greater differences between the treatments. The lower initial availability of N is reversed when the C/N ratio of the soil organic matter decreases (Jadeja *et al*., 2021), which explains why, according to the NDVI(ON) index, there was less differentiation between the treatments in the last few evaluations (e.g. the number of green leaves below the ear) under NT and more under CS for the same period.

The low value of the NDVI(ON) vegetation index is probably linked to problems inherent in the use of filters for forming images in single-sensor cameras (Santos *et al*., 2021). Lower NDVI values were also found by Gomes *et al*. (2021) when monitoring coffee using a similar camera, albeit with Red-Green-NIR filters, compared to the values obtained by a multisensor camera. It should also be considered that the orange band shows greater reflectance for green vegetation compared to the red band, affording less contrast with the near infrared.

The data extracted from the spectral response, recorded by images and analysed by means of vegetation indices, gave inferior results to those obtained directly in the field using the portable chlorophyll meter in terms of the ability to differentiate between the conditions induced by the different nitrogen treatments. Therefore, considering the results and the time required to collect the data, it would be advantageous in larger areas to use images to identify the more obvious variability in the field and, based on this analysis, use the chlorophyll meter for calibrating any adjustments in the nitrogen rates.

CONCLUSIONS

1. The sensors under evaluation can be used as tools to assist in field diagnosis of the nutrient status of maize crops, with the airborne sensors aimed at detecting initial macro-variability in the field, and the chlorophyll meter used for assessing the degree of nitrogen deficiency;

2. The NDVI(ON) vegetation index from the OCN sensor showed a greater capacity for distinguishing between treatments than the NGRVI index from the RGB sensor;

3. The chlorophyll b index, obtained using the portable chlorophyll meter, was better able to detect the variability induced by different doses of nitrogen under the no-tillage and conventional systems.

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