Estimation of nitrogen and phosphorus content in cotton leaves from medium-resolution satellite images

Estimativa do teor de nitrogênio e fósforo em folhas de algodão por imagens de satélite de média resolução

Estimación del contenido del nitrógeno y fósforo en las hojas de algodón a partir de imágenes satelitales de resolución media

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ABSTRACT
Satellite images are valuable tools to assess the nutritional status of plants and, thus, understand the variability of cotton yield in farmers' fields. By identifying soil variability and nutritional crop reflectance, Precision Agriculture (PA) techniques enable more precise variable rate application of inputs such as fertilizers and pesticides. One important PA technique is geostatistics, resulting in interpolated

maps that assist in evaluation during the crop cycle. These kriged maps provide a unique opportunity to overcome both spatial and temporal scaling challenges and understand the factors leading to crop yield. This study combines conventional statistical analysis, spatial regression modeling of georeferenced data, and vegetation indices assessment from medium-resolution satellite images to support decisions on improving cotton yield. The experiments were conducted in a 44.8 ha commercial field in Goiás state, Brazil. Multispectral satellite images at 56 m spatial resolution were collected in a rainfed cotton field on 04/01/2011 and 04/10/2012 from the AWiF sensor during the peak flowering cotton stage. Measures of leaf nitrogen (N) and phosphorus (P) contents were determined over previously georeferenced central points of 70 plots of a regular grid, each one measuring 80X80 m. Using descriptive statistics and geostatistical analyses, data were analyzed by building and setting semivariograms and kriging interpolation. The best correlation was found between IVs and nitrogen contents of cotton leaves. Results indicated that NDVI, MSAVI, and SAVI were the best indices for estimating P contents at cotton peak flowering. Identifications of spatial differences were possible using geostatistical methods with remote sensing data obtained from medium-resolution satellite images, allowing the identification of distinct nutritional needs and growth status of canopy to cotton plants.

Keywords: Vegetation Indices. Spatial Variability. Kriging. Remote Sensing. Precision Agriculture.

RESUMO

Imagens de satélite são ferramentas valiosas para avaliar o estado nutricional das plantas, e assim compreender a variabilidade da produtividade do algodão no campo. Através da identificação da variabilidade do solo e da refletância das culturas, as técnicas de Agricultura de Precisão (AP) permitem uma aplicação mais precisa de insumos em taxas variáveis, como fertilizantes e pesticidas. Uma das importantes técnicas em AP é a geoestatística, que resulta em mapas interpolados que auxiliam na avaliação durante o ciclo da cultura. Esses mapas *krigados* oferecem uma oportunidade única para superar desafios de escala espacial e temporal e compreender os fatores que levam ao rendimento das culturas. Este estudo combina análise estatística convencional, modelagem de regressão espacial de dados georreferenciados e avaliação de índices de vegetação obtidos a partir de imagens de satélite de média resolução para apoiar decisões sobre a melhoria da produtividade do algodoeiro. Os experimentos foram conduzidos em um campo comercial de 44,8 ha no estado de Goiás, Brasil. Imagens multiespectrais de satélite com resolução espacial de 56 m foram coletadas em um campo de algodão de sequeiro em 01/04/2011 e 10/04/2012 a partir do sensor AWiF durante a fase de pleno florescimento do algodão. As medições dos teores foliares de nitrogênio (N) e fósforo (P) foram determinadas em pontos centrais previamente georreferenciados nas 70 parcelas da grade regular, cada uma medindo 80X80 m. Utilizando estatística descritiva e análises geoestatísticas, os dados foram analisados por meio da construção e configuração de semivariogramas e interpolação de krigagem. A melhor correlação foi encontrada entre IVs e teores de nitrogênio nas folhas de algodoeiro. Os resultados indicaram que NDVI, MSAVI e SAVI foram os melhores índices para estimar os teores de P no pico de florescimento do algodoeiro. A identificação de diferenças espaciais foi possível utilizando métodos geoestatísticos com dados de sensoriamento remoto obtidos a partir de imagens de satélite de média resolução, permitindo a identificação de necessidades nutricionais distintas. e status de crescimento da copa do algodoeiro.

Palavras-chave: Índices de Vegetação. Variabilidade Espacial. Krigagem. Sensoriamento Remoto. Agricultura de Precisão.

RESUMEN

Las imágenes satelitales son herramientas valiosas para evaluar el estado nutricional de las plantas y así comprender la variabilidad de la productividad del algodón en el campo. Al identificar la variabilidad del suelo y la reflectancia de los cultivos, las técnicas de agricultura de precisión (AP) permiten una aplicación más precisa de insumos en dosis variables, como fertilizantes y pesticidas. Una de las técnicas importantes en AP es la geoestadística, que resulta en mapas interpolados que ayudan en la evaluación durante todo el ciclo del cultivo. Estos mapas kriged ofrecen una oportunidad única para superar desafíos de escala espacial y temporal y comprender los factores que impulsan el rendimiento de los cultivos. Este estudio combina análisis estadístico convencional, modelo de regresión espacial de datos georreferenciados y evaluación de índices de vegetación obtenidos a partir de imágenes satelitales de resolución media para respaldar decisiones sobre la mejora del rendimiento del algodón. Los experimentos se realizaron en un campo comercial de 44,8 ha en el estado de Goiás, Brasil. Se recolectaron imágenes satelitales multiespectrales con una resolución espacial de 56 m en un campo de algodón comercial en las fechas del 1/04/2011 y 10/04/2012 desde el sensor AWiF durante la fase de plena floración del algodón. Las mediciones de los contenidos foliares de nitrógeno (N) y fósforo (P) se determinaron en puntos centrales previamente georreferenciados en las 70 parcelas de 80X80 m cada una. Utilizando estadística descriptiva y análisis geoestadísticos, los datos fueron analizados mediante la construcción y configuración de semivariogramas e interpolación kriging. La mejor correlación se encontró entre los IV y el contenido de nitrógeno en las hojas de algodón. Los resultados indicaron que NDVI, MSAVI y SAVI fueron los mejores índices para estimar el contenido de P en el pico de floración del algodón. La identificación de diferencias espaciales fue posible mediante métodos geoestadísticos con datos de teledetección obtenidos a partir de imágenes satelitales de resolución media, permitiendo identificar diferentes necesidades nutricionales, y el estado de crecimiento del dosel algodonero.

Palabras clave: Índices de Vegetación. Variabilidad Espacial. Kriging. Teledetección. Agricultura de Precisión.

1 INTRODUCTION

Optimization of crop nutrition is essential for maximizing cotton yield. Reduced nutrition will diminish the crops' yield potential, while too much fertilizer can impact your profitability, increasing costs and risks of groundwater contamination. Macronutrient elements such as N and P account for plant growth and health, affecting cotton yield and fiber quality (Rochester et al., 2012). Therefore, careful monitoring and management of nutrient levels is essential in agriculture to ensure that yield potential will be reached without inefficient fertilizer application.

However, anything that causes plant stress will affect nutrient uptake. Thus, conventional chemical analyses are usually made to determine the nutrient element status of plants using laboratory techniques to achieve the proper cotton fertilization. But, laboratory analyses are expensive, laborious, and time-consuming.

Spectral reflectance is being used to solve these problems. Orbital or sub-orbital images help detect nutritional failures by providing fast and nondestructive field information, especially in large areas. Remotely sensed data have been widely used to develop vegetation indices as indicators of crop growth, nutrient status assessment, and yield prediction (Eitel *et al*., 2008).

Vegetation indices from spectral reflectance have been the subject of many studies as a method of crop evaluation and management for large areas since the sensitivity of spectral indices can explain up to 92% of the variability in crop biophysical and biochemical variables (Zhao *et al*. 2005; Shiratsuchi *et al*., 2014; Zhang *et al*., 2023).

Excessive nitrogen delays maturity can intensify insect infestations and increase the risk of boll rot, reducing lint quality (Robertson and Roberts, 2010). N deficiency will cause pale green leaves, small bolls, fruit drops, and reduced yields.

Unlike N, phosphorus has low mobility in the soil, and leaching is not a problem. Instead, mobility to the roots is the prime limitation to uptake (Rochester et al., 2012). Plants with shallow P content exhibit red or purplish color (anthocyanin pigment) in leaves, especially undersides, and death of tissue or necrosis may follow (Salisbury and Ross, 1978). Root growth could be better, and lower stems may be purplish. Thus, insufficient phosphorus results in dwarfed plants, delays fruiting and maturity, and reduces yield. Fortunately, even though cotton is in the flowering stage, there is still time to supplement it with extra nitrogen and phosphorus by using plant monitoring. Therefore, N and P visual deficiencies in cotton leaves combined with plant structure and many other physiological changes can be measured through crop reflectance using multi and hyperspectral instruments and have proven to be a robust estimator of cotton leaf N and P status (Osborne *et al*., 2002; Zhao *et al*., 2005; Mahajan *et al*., 2014; Zhang *et al*., 2023).

Additionally, geostatistical estimation makes it possible to estimate values at unsampled locations by considering the spatial correlation between estimated and sampled points. Geostatistics also provides an interpolation technique (kriging) to predict response variables at unsampled locations (Oliver and Webster, 2014).This interpolation method allows the data visualization into maps and became a valuable tool to evaluate the variability of many crop properties (Brandão *et al*. 2014). Measures readings and spectral data can be converted into maps showing the variability for direct application in precision farming.

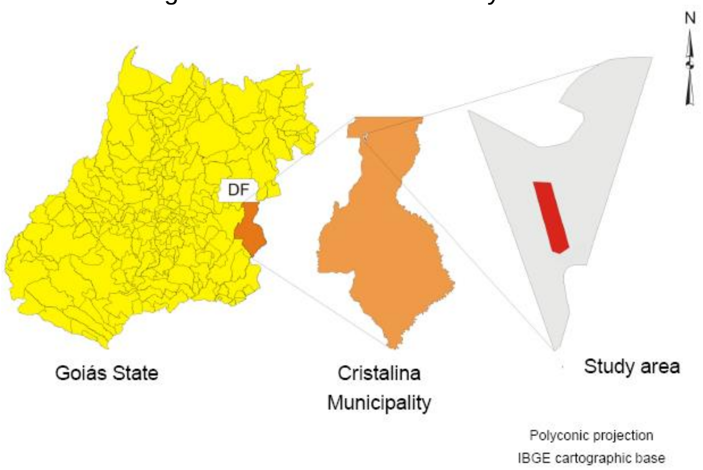
In this context, the objective of this study was to analyze, through geostatistical methods, the influence of N and P contents on the spatial identification of vegetation indices (VIs) from AWFIS images on a cotton commercial field in Goiás state, Brazil.

2 MATERIAL AND METHODS

2.1 LOCATION AND FIELD DATA

This study was conducted for two years in an experimental area of 44.8 ha, located at Pamplona Farm (16º10’16’’ S, 47º37’47’’ W), Cristalina, GO state, Brazil (Figure 1). The soil is Type Hapludox. In the initial soil analysis, the following average values were obtained: clay, 59.5%; sand, 16.1%; silt, 24.3%; pH in water, 5.67; Ca, 3.11 cmolc dm³; organic matter, 2.93%; available phosphorus, 3.52 mg dm³; and potassium, 0.25 $cmol_c$ dm^{-3}.The work was carried out in the 2010/11 and 2011/12 harvests, with the cotton crop and the cultivars: FMT 701, from Fundação Mato Grosso and Fiber Max 993 from Bayer CropScience, respectively, and row spacing of 0.76 m in both seasons.

Figure 1. Location of the study area.



Source: own authorship

Fertilization was carried out based on soil analysis. In the first year, nitrogen was applied in four crop stages (before planting, sowing, emergence and at 45 DAE), adding up to 160 N kg ha^{-1} in the urea and ammonium sulfate forms. A total of 204 kg ha^{-1} of phosphorus was applied on three dates: eight days before sowing, at sowing, and 45 DAE at rates of 151, 47, and 6 kg $P_2O_5ha^{-1}$, respectively, with formulated fertilizer (05-32-00). K, Ca, Mn and B fertilizations were made before planting and at 45 DAE, adding up to 129 kg K_2O ha^{-1}; 61,8 kg Ca ha^{-1}; 3 kg Mn ha^{-1}; and 3 kg B ha^{-1}. Sulfur (S) was applied on sowing at a single rate of 37 kg S ha^{-1}. For the second season, fertilization was delayed due to the intense rainfall at two first months after sowing. The nitrogen fertilizer used was the same amount, but started at 41 DAE. Therefore,160 kg ha^{-1} of nitrogen top dressing was applied, in the form of ammonium sulfate (149 kg ha^{-1}) at 41 DAE, and two applications of urea, 141 and 145 kg ha^{-1}, at 63 and 100 DAE, respectively, as 120 kg ha^{-1} of P_2O_5, in the form of formulated fertilizer (05-32-00 + micronutrients) and 120 kg ha^{-1} of K_2O with potassium chloride application. The remaining fertilizers were applied according to the first year.

Row spacing was 0.76 m and plant density was ~195,000 plants ha^{-1} (13–18 plants m^{-1}). According to the farm's technical recommendations, diseases and weeds were controlled based on their occurrence.

A sampling grid was made with 70 plots of 80X80 m, and measures were made around a central point in the middle of each plot. All plants and boll samples were collected into a 10m radius of each central point, previously georeferenced with a 76CSx GPS by GARMIN®. Field data were acquired at 110 and 100 DAE (days after emergence) in 2011 and 2012, corresponding to peak flowering, around F3-F6 phenological cotton stages (Marur; Ruano, 2001), and were collected into a 10m radius of each central point, previously georeferenced.

The dates were chosen considering that after 100-120 DAE, the nitrogen and phosphorus levels usually decline in leaf tissue, significantly decreasing as the crop ages (Rochester et al., 2012). Therefore, the same phenological period was considered for taking satellite images in both years.

Determining leaf nutrient content in the peak flowering stage followed the methodology suggested by Marur and Ruano (2001). For each experimental plot, thirty plants were chosen. The fifth most expanded leaf (always from the top of the main stem), was collected from them, according to the methodology proposed (Malavolta et al. 1997; Marur; Ruano, 2001), during the 2011 and 2012 seasons. Afterward, the leaves were dried, and the total leaf concentrations of nitrogen and phosphorus were obtained according to the procedures described in Miyazawa (1992).

2.2 SATELLITE DATA

Two images generated by the sensor AWiFS (Advanced Wide Field Sensor) were acquired to identify the correlation with cotton yield. The first one was on 01/04/2011 (110 DAE), with orbit 327 and point 087, and the second image was on 10/04/2012 (100 DAE), (330/089).

The spectral bands of the AWiFS sensor used in this work correspond to channels 2(green), 3(red), and 4(near infrared). After corrections and radiometric calibration of the images, reflectance and vegetation index for two sampling dates were determined. All image rectification and calibration procedures were performed using the software ERDAS IMAGINE® 9.3.

From the reflectance images, Leaf area index (LAI) and spectral indices as Normalized difference vegetation index (NDVI), Soil Adjusted Difference Vegetation Index (SAVI), Modified SAVI (MSAVI), MTVI2 (Second Modified Triangular Vegetation Index), and MCARI2 (Second Modified Chlorophyll Absorption Ratio Index) were calculated based on the equations provided by many authors and summarized by Shiratsuchi et al. (2014):

LAI (*Leaf Area Index*)*	$LAI = \frac{[(0.69 - SAVI)/0.59]}{0.91}$	Allen et al. (2007)	(1)
NDVI (*Normalized Difference Vegetation Index*)	$NDVI = (\rho_{NIR} - \rho_R)/(\rho_{NIR} + \rho_R)$	Rouse et al. (1973)	(2)
SAVI (*Soil Adjusted Difference Vegetation Index*)	$SAVI = (1+L))(\rho_{NIR} - \rho_R)/(\rho_{NIR} + \rho_R + L)$	Huete (1988)	(3)
MSAVI (*Modified SAVI*)	$MSAVI = \frac{1}{2}\left[2\rho_{NIR} + 1 - \sqrt{(2\rho_{NIR}+1)^2 - 8(\rho_{NIR} - \rho_R)}\right]$	Qi et al., 1994	(4)
MTVI2 (*Second Modified Triangular Vegetation Index*)	$MTVI2 = \frac{1.5[1.2(\rho_{NIR} - \rho_G) - 2.5(\rho_R - \rho_G)]}{\sqrt{(2\rho_{NIR}+1)^2 - 0.5 - 6(\rho_{NIR} - 5\sqrt{\rho_R})}}$	Haboudane et al., 2004	(5)
MCARI2 (*Second Modified Chlorophyll Absorption Ratio Index*)	$MCARI2 = \frac{1.5[2.5(\rho_{NIR} - \rho_R) - 1.3(\rho_{NIR} - \rho_G)]}{\sqrt{(2\rho_{NIR}+1)^2 - 0{,}5 - (6\rho_{NIR} - 5\sqrt{\rho_R})}}$	Haboudane et al., 2004	(6)

Where:

ρ_x , represents the reflectance, and *x*= AWiFs Green (*G*), Red(*R*) and (*NIR*) Near Infrared spectral bands. LAI from satellite images was estimated using METRIC method (*Mapping Evapotranspiration with high Resolution and Internalized Calibration*) used by FAO (Allen et al., 2007).

2.3 GEOSTATISTIC ANALYSIS

Data were submitted to statistical analysis to determine mean, maximum, minimum, skewness, kurtosis coefficient to check frequency distribution, and the coefficient of variation (CV). The Kolmogorov-Smirnov test, on which skewness and kurtosis values should be near zero for normal distributions, was used to verify the normality of the data frequency. The coefficients of variation were evaluated based on Warrick and Nielsen criteria (Oliver and Webster, 2014), which classify as low a CV <12%, regular CV from 12% to 60%, and high a CV > 60%.

Semivariogram analysis (Figures 2, 3) studied the spatial dependence of nutrients, LAI, and IVs obtained from cotton plants. Geostatistical analysis was performed by constructing and adjusting semivariogram and ordinary kriging interpolation using the geostatistical software GEOEST (Vieira *et al*., 2002).

Semivariograms were estimated by equation (6):

$$\gamma^{*}(h)=\frac{1}{2\,N(h)}\sum_{i=1}^{N(h)}[Z(x_i)-Z(x_i+h)]^2 \qquad (6)$$

Where:

N(*h*) is the number of pairs of measured values $Z(x_i)$, $Z(x_i + h)$ separated by distance (vector *h*).

After that, based on the spatial correlation models selected, interpolations were performed with ordinary kriging, to estimate unsampled data, and cross-validation was applied to select models. For each model, the degree of spatial dependence was measured through the ratio between the nugget and sill parameters Co/(Co+C), and the range value was determined. The Co/(Co+C) ratio indicates the degree of uncertainty when the interpolation takes place (0-25% strong spatial dependence, 26-75% moderate spatial dependence, and >75% weak spatial dependence).

Finally, contour maps were made with the estimated data as a function of geographic coordinates, using QGIS 3.3 open source software (QGIS, 2024). All the results were presented as two-dimensional maps representing the spatial distribution of the values of VIs and leaf contents of N and P.

3 RESULTS AND DISCUSSION

Descriptive statistics of cotton nutrients, plant height, LAI, and IVs values are presented in Table 1 for the two sampling dates, corresponding to peak flowering, i. e., around F3-F6 phenological cotton stages (110 DAE in 2011 and 100 DAE in 2012). All variables showed low CV variation for the two years, with values lower than 12%. This indicated that the data analysis was homogeneous with significant averages and, therefore, can be used to represent the study area.

Plant attributes showed skewness and kurtosis coefficients as a normal distribution, agreeing with Motomiya et al. (2011). The nugget effect (C0) represents non-explained variance, frequently caused by measurement errors or property variations not detected in the sampling scale (Oliver and Webster, 2014). The semivariance model (Sph or Exp) and the parameters C0, C, and range are within each graph of Figures 2 and 3.

Table 1. Descriptive statistical analysis for leaf cotton nitrogen (N) and phosphorus (P) contents, plant height (Hgt) and the vegetation indices (NDVI, SAVI, MSAVI, MTVI2, MCAI2, and LAI) obtained from satellite image data at flowering stage(110 and 100DAE in 2011 and 2012, respectively).

Year	Variable	Mean	Variance	Std. Dev	CV (%)	Minimum	Maximum	Skewness	Kurtosis
2011	LAI_{11}	1.108	3.42E-03	0.0059	5.275	0.99	1.2	-0.2468	-0.9347
	Hgt_{11}	116.4	155.9	12.48	10.72	98.8	158.2	1.28	1.649
	N_{11}(g kg^{-1})	45.53	5.065	2.251	4.943	41	51.7	0.3934	0.6009
	P_{11}(g kg^{-1})	3.26	4.51E-02	0.2124	6.524	2.8	3.8	0.3529	-0.4055
	$SAVI_{11}$	0.46	4.05E-04	0.002	4.234	0.42	0.53	0.336	0.2783
	$NDVI_{11}$	0.85	7.66E-04	0.0028	3.254	0.8	0.93	1.021	0.6988
	$MSAVI_{11}$	0.49	3.30E-04	0.0012	3.741	0.44	0.55	0.4687	1.409
	$MTVI2_{11}$	0.36	3.94E-04	0.0019	5.566	0.31	0.4	0.4129	-0.2855
	$MCARI2_{11}$	0.36	3.72E-04	0.0019	5.415	0.31	0.4	0.445	-0.0054
	LAI_{12}	2.034	3.17E-02	0.1779	8.747	1.42	2.38	-1.143	1.971
	Hgt_{12}	104.3	62.6	7.91	7.58	88.0	130.1	0.798	1.158
	N_{12}(g kg^{-1})	35.53	5.64	2.375	6.684	26.39	41.09	-0.3298	2.445

	P_{12}(g kg^{-1})	2.042	3.96E-02	0.199	9.745	1.68	2.51	0.1731	-0.6035
2012	$NDV1_{12}$	0.7781	7.72E-04	0.0028	3.57	0.72	0.88	0.8572	2.717
	$SAV1_{12}$	0.6007	1.25E-03	0.0035	5.879	0.51	0.73	1.034	3.269
	$MSAVI_{12}$	0.624	1.14E-03	0.0034	5.405	0.5	0.72	-9.42E-03	3.408
	$MTVI2_{12}$	0.3501	5.12E-04	0.0024	6.46	0.29	0.41	0.268	1.225
	$MCARI2_{12}$	0.343	4.71E-04	0.0022	6.324	0.28	0.4	6.56E-02	1.606

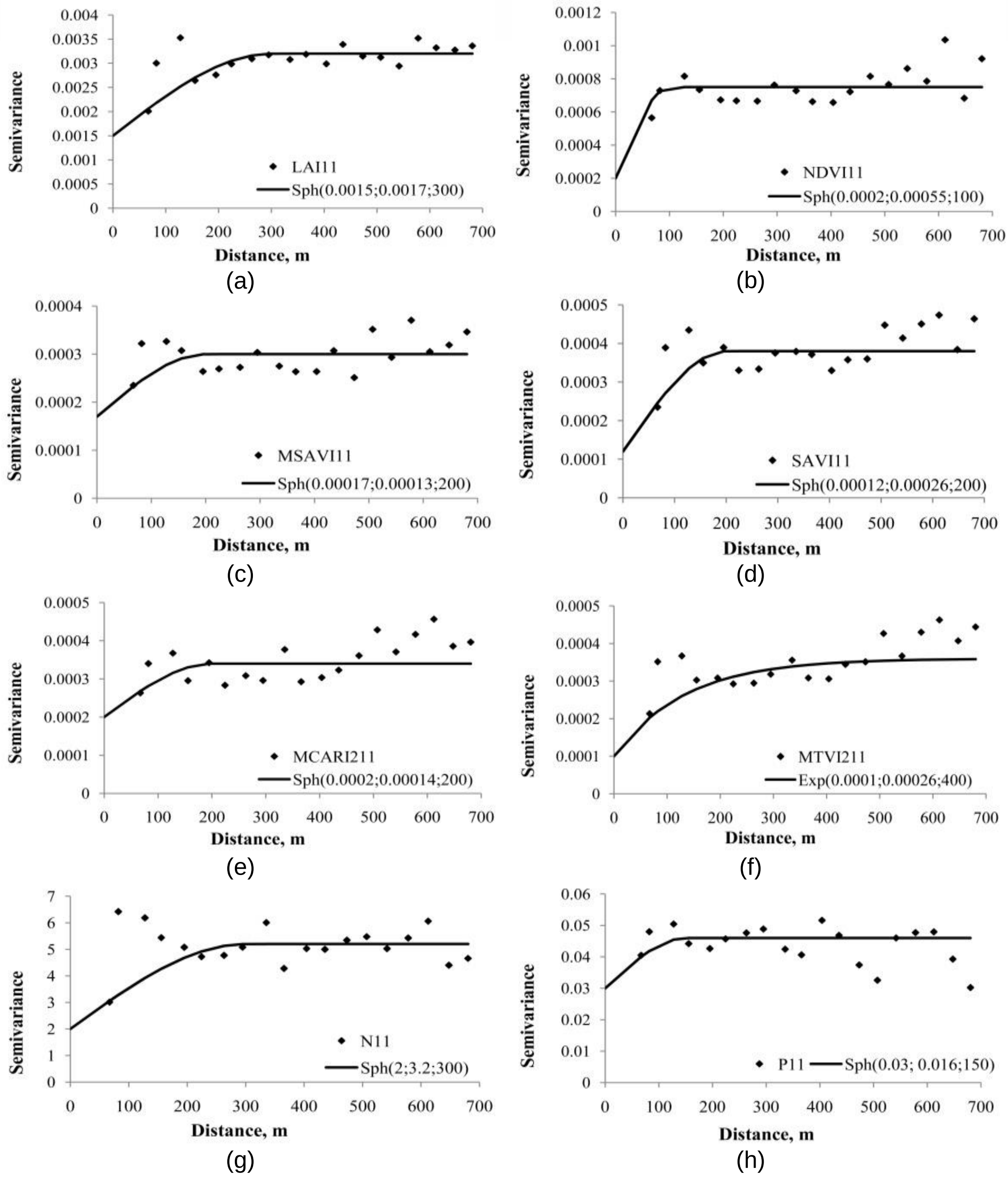
LAI: Leaf Area Index; NDVI: Normalized difference vegetation index; SAVI: Soil Adjusted Difference Vegetation Index; MSAVI: Modified SAVI; MTVI2: Second Modified Triangular Vegetation Index; MCARI2: Second Modified Chlorophyll Absorption Ratio Index.
Source: Own authorship.

Results from the geostatistical analysis are presented in Figures 2 and 3 for the 2011 and 2012 seasons, respectively.

Experimental semivariograms, fitted using the best-adjusted model with a smaller root mean square (RMS) and validated by the jack-knifing method (Vieira et al., 2002), observed the spatial dependence of nutrients, LAI, and IVs. Measurements within some neighborhoods are expected to be more similar than those separated by large distances (Vieira et al., 2002). If the semivariogram shows spatial dependence, unsampled data can be estimated by kriging, with minimum variance and without trend (Oliver and Webster, 2014).

Except for the vegetation index $MTVI2_{11}$, adjusted to the exponential model, all data and crop characteristics were fitted to the spherical model.

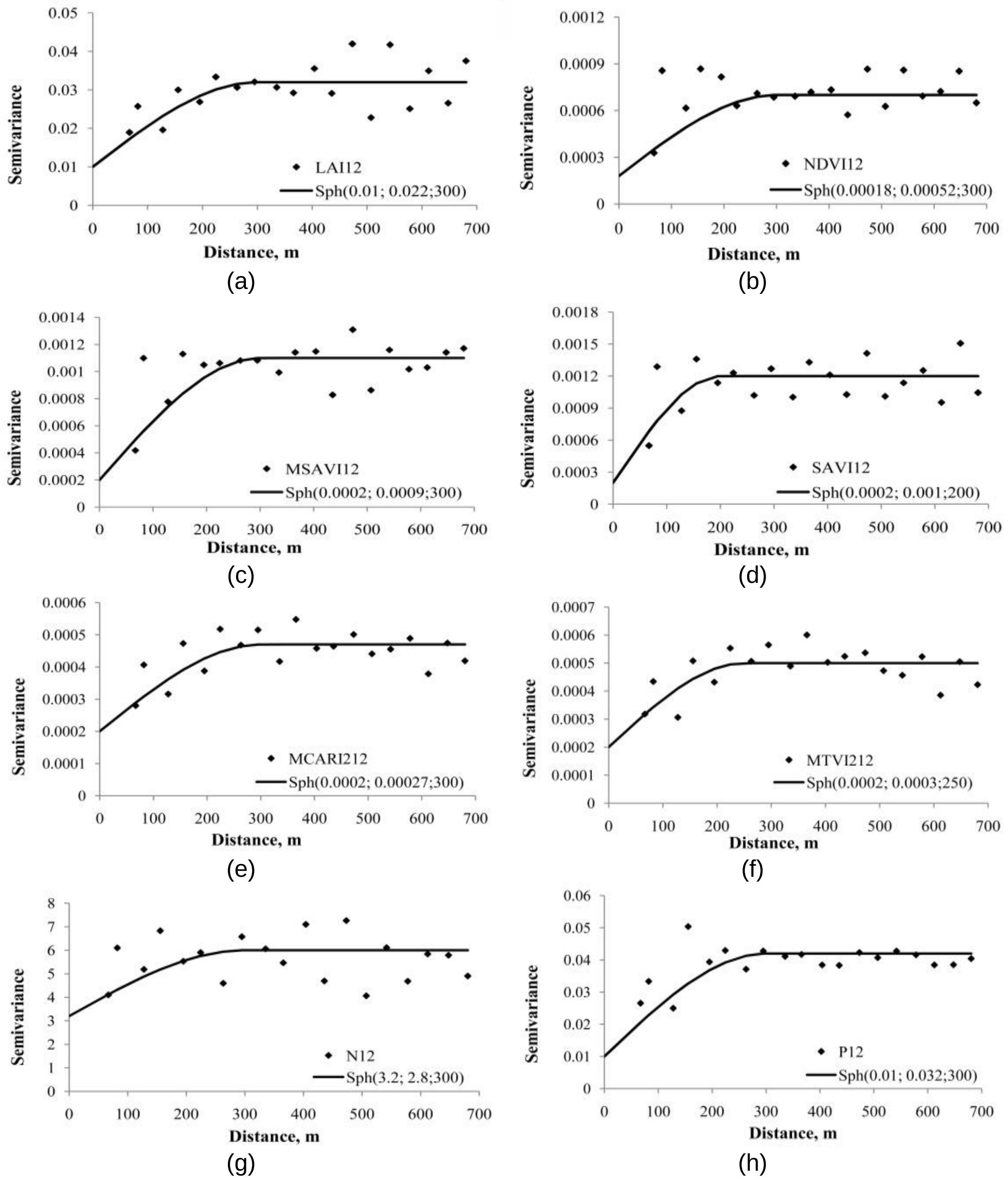
Figure 2. Semivariograms fitted with parameters such as nugget effect range and partial sill of the variable to 2011 data at flowering stage on 110 DAE.(a) LAI_{11}; (b) $NDVI_{11}$; (c) $MSAVI_{11}$; (d) $SAVI_{11}$; (e) $MCARI2_{11}$; (f) $MTVI2_{11}$; (g) Leaf N_{11} content; (h) Leaf P_{11} content.



Source: Own authorship, based on experimental data

Satellite images provided good results for predicting N status in the first year and N and P status during the cotton peak bloom stage to the 2012 season. Nitrogen uptake by cotton peaks at about 2.2 to 3.3 kg per hectare per day during the fruiting stage (Rochester et al., 2012; Brandão et al., 2014).

Figure 3. Semivariograms fitted with parameters such as nugget effect range and partial sill of the variable to 2012 data at the flowering stage on 100 DAE: (a) LAI_{12}; (b) $NDVI_{12}$; (c) $MSAVI_{12}$; (d) $SAVI_{12}$; (e) $MCARI2_{12}$; (f) $MTVI2_{12}$; (g) Leaf N_{12} content; (h) Leaf P_{12} content.

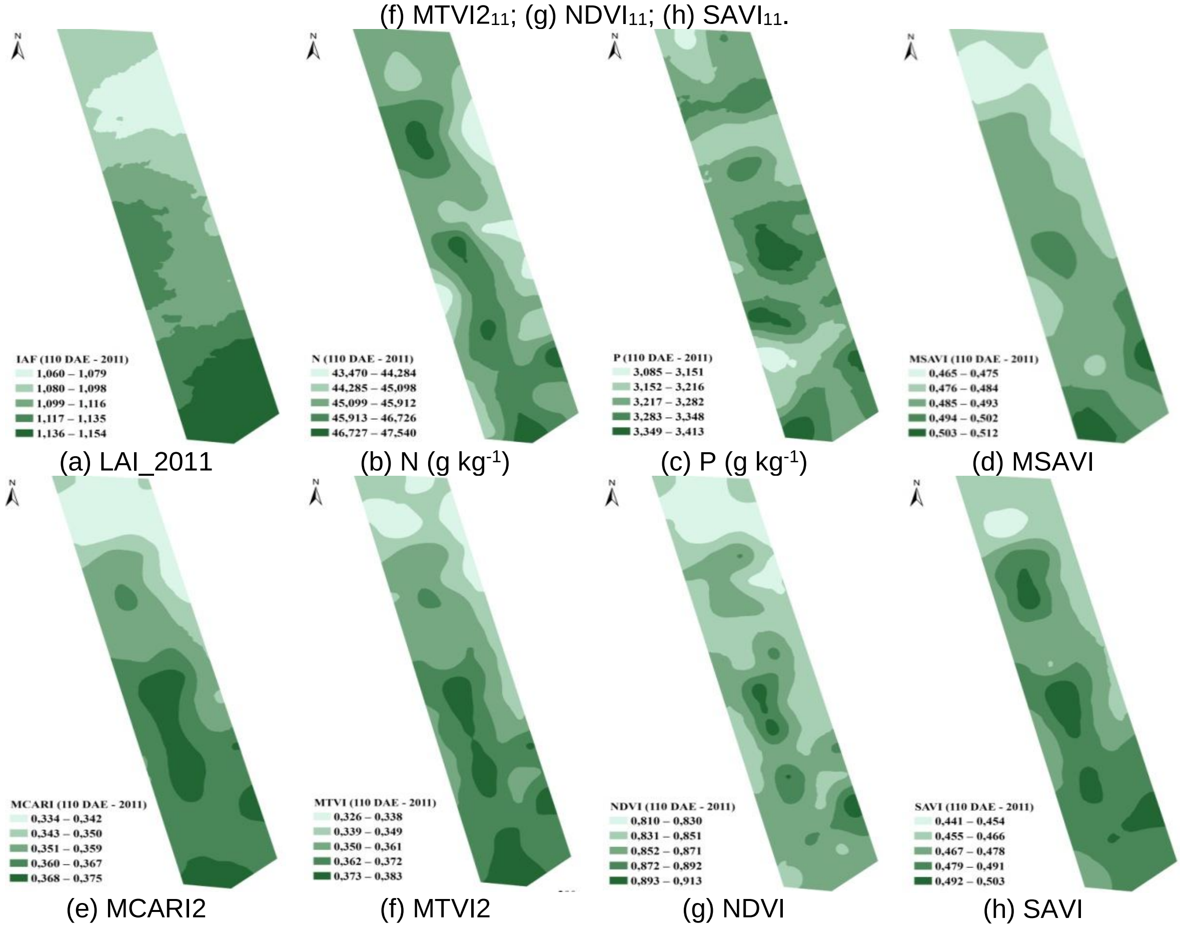


Source: Own authorship, based on experimental data

To examine if IVs could be used as an alternative for cotton leaf nitrogen content, Pearson's correlations (*r*) were evaluated. Statistically significant ($p<0.0001$) correlations (***r***) between VIs and N contents were obtained for the first season, with an ***r*** range of 0.67–0.75, while in 2012, correlations were between 0.62 and 0.72. However, by accounting for spatial dependence, regression coefficients may change (Calderón, 2009), and the best way to evaluate the spatial distribution is using kriging maps of estimated data, as shown in Figures 4 and 5, for 2011 and 2012, respectively.

Leaf nitrogen content is a good indicator of healthy plants. Plant vigor was represented as a dark gray color in Figure 4b for high N values, which varied from 41 to 45.5 g kg^{-1} in 2011. The great N content stimulated crop growth and produced a more significant amount of biomass, further influencing the crop canopy's optical properties. In 2011, these values were above the sufficiency range for nitrogen in this cotton peak flowering stage (35-43 g kg^{-1}).

Figure 4. Maps for satellite imageand field data during the 2011 season, showing the spatial distribution of: (a) LAI_{11}; (b) Leaf N_{11} (g kg^{-1}); (c) Leaf P_{11} (g kg^{-1}); (d) $MSAVI_{11}$; (e) $MCARI2_{11}$; (f) $MTVI2_{11}$; (g) $NDVI_{11}$; (h) $SAVI_{11}$.

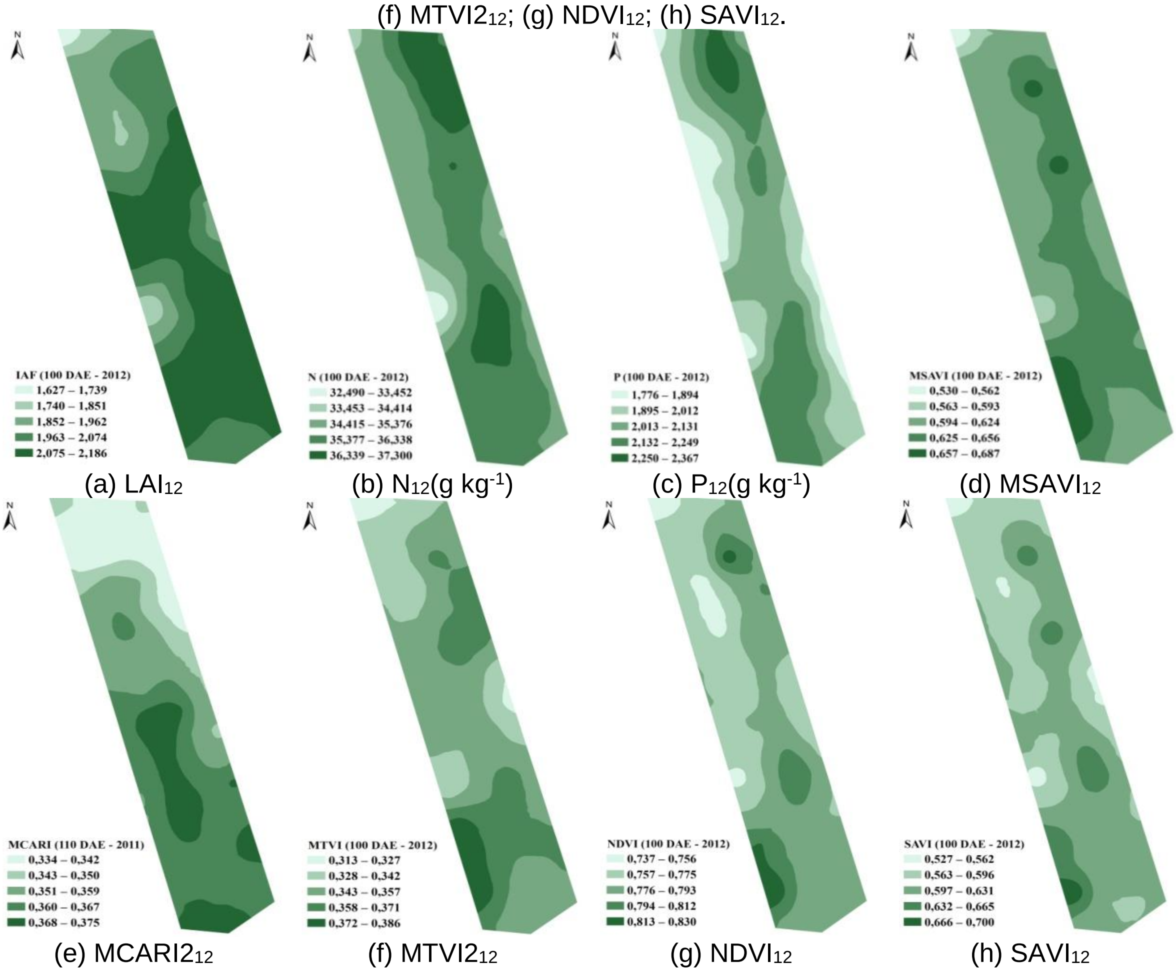


Source: Own authorship.

For the second year (Figure 5b), N leaf contents did not reach the expected values and ranged from 26 to 41 g kg^{-1}. Thus, in 2012, nitrogen content in many experimental plots was below the expected, indicating that cotton plants were still in high nutrient consumption. This fact may be explained by the high rainfall during the first three months of 2012, which caused leaching and soil surface displacement along the crop area, causing delays in plant development (Rochester et al., 2012).

Satellite images at the flowering stage on 110 and 100 DAE (Figures 4b and 5b) presented good correlations with the intense leaf greenness. All indices showed remarkable similarity in spatial distribution maps for the two seasons, confirming the good correlation. This indicates that the IVs obtained by AWIFS images can help estimate the leaf nitrogen content for this culture.

Figure 5. Maps for satellite imageand field data during the 2012 season, showing the spatial distribution of: (a) LAI_{12}; (b) Leaf N_{12} (g kg^{-1}); (c) Leaf P_{12} (g kg^{-1}); (d) $MSAVI_{12}$; (e) $MCARI2_{12}$; (f) $MTVI2_{12}$; (g) $NDVI_{12}$; (h) $SAVI_{12}$.



Source: Own authorship

LAI presented a CV lower than 12%, indicating a homogeneous data set during the 2011 and 2012 seasons (Figures 4 and 5). The results suggest that plants cover almost all the space between the sowing lines, with mean values of 1.11 and 2.03 for 2011 and 2012. This difference between LAI values was probably because phosphorus foliar contents were higher in the first year than in the second season, allowing plants to grow taller. Under P deficiency, different metabolic responses are expected (Rochester et al., 2012; Sun et al., 2022), mainly because it affects carbohydrate accumulation and distribution in cotton leaves and bolls. On the contrary, elevated P supply before the peak flowering phenological phase, increases the number of reproductive branches. Consequently, it results in great N fixation capacity and higher N foliar content (Brandão et al., 2012; IQBAL et al., 2020). According to Mullins and Burmester (2010), P uptake by cotton varies in a range of 0.2-0.74 kg ha^{-1} per day during the flowering stage.

Despite the height of the plants, the results showed a lower reflectance in 2012 compared to 2011. This is probably due to the P deficit, which left some leaves purplish at the points with a lower P_{12} content. Osborne et al. (2002) found similar results for corn, who observed purpling at the leave margins in the P-stressed plots. Salisbury and Ross (1978) stated that anthocyanin is strongly absorbed in the green region while reflecting in the blue or red region of the spectrum.

In 2012, the foliar concentrations for P_{12} were below the sufficiency range established by different authors (Table 2) for 93% of plots, ranging from 1.68 to 3.12 g kg^{-1}, what can suggest that there is still a high demand for P during the cotton flowering stage. Similar results were obtained by Motomiya et al. (2011), which found average values below the sufficiency level for cotton in the same stage. According to Rochester et al. (2012), nutrients are taken up throughout the growing season, agreeing with the demand for nutrients by developing crop biomass and boll load, and phosphorus uptake is completed when the crop reaches the 50% open boll stage.

Best similarities with phosphorus spatial distribution were observed in 2012 for $NDVI_{12}$, $SAVI_{12}$, and $MSAVI_{12}$ (Figure 5), which presented statistically significant correlations of 0.52, 0.42, and 0.41 with P_{12} contents. The light purple color likely influenced the reflectance data in some experimental spots with shallow P content. Özyiğit and Bilgen (2013), studying reflectance bands to represent cotton P contents, found the best agreement of the spatial distribution in the experimental area to red bands (675 and 680 nm).

Table 2. Nutrient content sufficiency established by different authors for cotton crops during full flowering and four classes of interpretation of leaf analysis results estimated by the DRIS Index proposed by Kurihara et al. (2013).

Nutrient	**Established sufficiency*1**			**Classification estimated*2 (by DIRS indexes)**			
	Author a	**Author b**	**Author c**	**Low**	**Sufficient**	**High**	**Surplus**
				$g\ kg^{-1}$			
N	35 to 43	45 to 50	33 to 45	< 39.1	39.1 to 43.2	43.3 to 47.3	> 47.3
P	2.5 to 4.0	2.5 to 4.0	3.8to5.3	< 2.3	2.3 to 2.8	2.9 to 3.4	> 3.4

*1) Author a: Silva et al. (2009); Author b: Malavolta (2006); Author c: Camacho et al. (2012).
*2) Source of classification: Kurihara et al. (2013)
Sources: adapted from: Malavolta (2006); Silva et al. (2009); Camacho et al. (2012); Kurihara et al. (2013)

On the other hand, even with very green plants and sufficient P_{11} contents (2.8-3.8 g kg^{-1}), as presented in 2011, $MSAVI_{11}$ and $NDVI_{11}$ kept significant ($p<0.001$) correlations with P_{11} contents (***r*** = 0.39 and 0.36). Both IVs kriging maps showed similarities in distribution, where the highest and lowest values practically occur in the same position of the study area.

4 CONCLUSIONS

Spatial dependence was found for all data analyzed. Similarities between the two years in the spatial distribution of vegetation indices (IVs) obtained by AWiFs data and foliar content of nitrogen and phosphorus indicated that satellite data could estimate N and P for nutritional requirements at the cotton's peak flowering stage.

Normalized difference vegetation index (NDVI), Soil Adjusted Difference Vegetation Index (SAVI), and Modified SAVI (MSAVI) were well correlated with nitrogen and phosphorus contents of cotton leaves, even with cotton in low rate nutrition.

Identifications of spatial differences were possible using geostatistical methods with remote sensing data obtained from medium-resolution satellite images, allowing the identification of distinct nutritional needs and growth status of canopy to cotton plants.

The possibility of nutritional deficit detection in large areas, especially up to the flowering stage of the cotton plants, is precious because the yield can be improved even during the crop cycle with nutritional supplementation, thus favoring increased profits.

It is important to note that the soil in the region has been corrected over the years. Future studies on large areas, considering other satellite spatial resolutions should be carried out to validate the technology for producers to apply.

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