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Performance of UAV-derived vegetation indices (NDVI, NDRE, and SAVI) in response to nitrogen rates and correlation with agronomic traits in corn-forage intercropping systems

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Abstract: The intercropping of corn with forage species has been widely used, aiming at high grain production and greater straw accumulation on the soil surface. The objective of this study was to evaluate the performance of vegetation Indices (VIs) obtained by Unmanned Aerial Vehicle (UAV) in response to nitrogen (N) topdressing rates and their correlations with agronomic traits in corn intercropped with forages. Two experiments were carried out in the 2021/2022 growing season, in a randomized block design with four replications, in a factorial scheme. The experiment was conducted in two adjacent and independent experimental areas. The first factor consisted of six intercrops: single corn; corn + *Urochloa ruziziensis*; corn + *Urochloa brizantha* cv. Piatã; corn + *Stylosanthes* cv. Campo Grande; corn + *U. brizantha* + *Stylosanthes*; and corn + *U. ruziziensis* + *Stylosanthes*. The second factor consisted of four Nitrogen (N) rates (0, 60, 120, and 240 kg ha^{-1}). At the V6 stage, the vegetation indices Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge Index (NDRE), and Soil-Adjusted Vegetation Index (SAVI), were evaluated. The Vegetation Indices (VIs) responded positively to increasing N rates. NDVI showed saturation in intercrops with greater vegetative mass, while NDRE demonstrated higher sensitivity and lower saturation. NDRE and SAVI proved to be the most responsive indices to N fertilization and showed the highest correlations with grain yield. However, as no direct measurements of plant N status (e.g., leaf N concentration, SPAD, or N uptake) were performed, these results should be interpreted as spectral responses to N rates rather than validated estimates of plant N status. Further studies with direct N-status measurements are recommended to confirm the potential of these indices for nutritional monitoring in intercropped systems.

Keywords: NDRE; NDVI; remote sensing; SAVI; *Stylosanthes*; *Urochloa*.

Introduction

Corn (*Zea mays* L.) is estimated to have a production of 122 million tons in the 2024/2025 crop year, an increase of 5.5% or 6.3 million tons above the production of the previous crop year (CONAB, 2025).

The intercropping of corn with forage species has been widely used, aiming at high grain production of the crop and accumulation of straw on the soil surface, generating benefits for the soil and cultivated plants, optimizing the production area. The adoption of cover crops is widely recognized as an effective strategy to increase the sustainability of agricultural production (Pedrão et al., 2025). Among the various nutrients necessary for the proper development of this crop, nitrogen (N) stands out as a fundamental and indispensable element in crop fertilization, strongly contributing to the maintenance and increase of productivity (Ribeiro et al., 2024).

Excessive application of fertilizers can compromise the success of agricultural production, in addition to negatively impacting groundwater and surface water (Dhakal and Lange, 2021). In this sense, remote sensing information, through the use of vegetation indices (VIs), are fundamental tools for environmental monitoring and applications in agriculture. Estimates of development and productivity for corn crops are important predictions for decision-making regarding fertilizer use and forecasting economic responses for producers (Venancio et al., 2020).

Identifying and correcting areas with restrictions on crop yield increases crop efficiency, and through vegetation indices (VIs) it is possible to estimate N levels through leaf reflectance, making them important in diagnosing nutritional deficiencies (Farrell et al., 2018). The most widely used vegetation index to measure the "greenness" of aboveground vegetation is the normalized difference vegetation index (NDVI), which has a strong relationship with the health and productivity of vegetation, and can demonstrate various changes in the characteristics of land surface properties (Liu et al., 2024). The use of vegetation sensors can be an important tool to assist in quantifying productive potential, N use efficiency, and estimating nitrogen fertilizer doses, according to the actual needs of the crop (Vian et al., 2018).

In the presence of intense vegetation mass, NDVI becomes limiting in the crop reflectance content, due to the rapid saturation that occurs as a function of the spectral response in the near-infrared range, used in the NDVI calculation.

Saturation occurs when vegetation cover or plant population reaches a high level, affecting monitoring (Li et al., 2015; Gitelson et al., 2002).

NDRE is more appropriate for determining N demand in cotton crops, due to its greater sensitivity (Raper and Varco, 2015), and for detecting foliar N content in C4 plants (Portz et al., 2012). Its application helps predict the nutritional conditions of the crop, identifying the need for fertilizer use in certain locations, improving crop productivity. Thus, it shows a greater association with the foliar and total N content of corn plants (Flores et al., 2020), and together with NDVI, provides accurate information on the grain yield of the corn crop (Santana et al., 2021).

SAVI stands out for minimizing the effects of soil and generating more reliable results, better representing vegetative vigor. It does not saturate like NDVI. It can also be used to estimate the nutrition index in corn crops (Zhao et al., 2018). In addition to estimating foliar N content, it is also an important tool in identifying grain productivity (Santana et al., 2022; Zhao et al., 2018).

Given the above, the objective was to evaluate the performance of the vegetation indices NDVI, NDRE, and SAVI obtained by UAV, in response to increasing nitrogen topdressing rates and their correlation with agronomic traits (grain yield, plant height, and number of grains per ear) in corn intercropped with forage grasses. Additionally, we aimed to identify the interference of brachiaria in spectral readings and the occurrence of saturation of the indices in systems with high biomass density. It is important to note that this study does not include direct measurements of plant N status (e.g., leaf N concentration, SPAD, or N uptake); therefore, the results are presented as spectral responses to N fertilization rather than validated estimates of plant nitrogen status.

Results

This study evaluated two distinct areas in which corn was intercropped with forage crops under N topdressing doses, both differentiated by the presence and absence of rock phosphate (P) application. The results are described below, separated by area.

Without rock phosphate

Table 1 presents the mean squares and the significance of the F-test for the vegetation indices analyzed, as well as their interactions.

Nitrogen (N) showed a positive response for all VIs (NDVI, NDRE, and SAVI). The interaction effect between C × N showed significance for all VIs, demonstrating that these indices respond differently depending on the doses and intercrops.

Table 1. Summary of the analysis of variance for the vegetation indices NDVI, NDRE, and SAVI evaluated in all intercropping systems (C) and nitrogen (N) topdressing doses, in the area without rock phosphate in the 2021/2022 growing season.

SV	DF	NDVI	NDRE	SAVI
Block	3	0.02*	0.00^{ns}	0.01*
C	5	0.00^{ns}	0.00^{ns}	0.00^{ns}
Error a	15	0.00	0.00	0.00
N	3	0.01***	0.01***	0.01***
C × N	15	0.00**	0.00*	0.00*
Error b	54	0.00	0.00	0.00
CV1 (%)		16.15	11.58	15.75
CV2 (%)		5.34	4.26	5.91

*, **, ***: significant at 5%, 1%, and 0.1% probability, respectively; ^{ns}: not significant; SV: source of variation; CV: coefficient of variation; DF: degrees of freedom. Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge Index (NDRE), and Soil-Adjusted Vegetation Index (SAVI) all intercropping systems (C) and nitrogen (N)

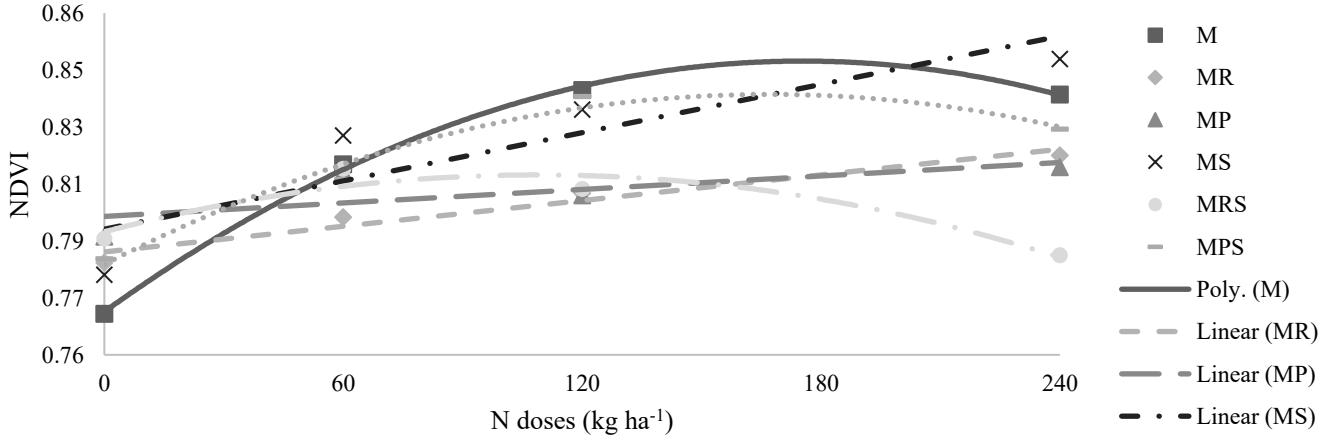
In the breakdown of the intercrops within the N doses (Table 2), there was no difference between the intercrops for NDVI, NDRE, and SAVI indicating that all means are statistically equal. This result indicates that, at the V6 stage, the spectral reflectance of the intercropped systems did not differ significantly from that of single corn at any N dose. Therefore, the data do not support the conclusion that the presence of brachiaria specifically altered the spectral response of the canopy in a way that masked the response of corn to nitrogen fertilization.

Table 2. Breakdown of the significant interaction of the analysis of variance regarding the vegetation indices NDVI, NDRE, and SAVI as a function of N doses for corn intercropped with forage crops in the 2021/2022 growing season, area without rock phosphate.

Doses N (kg ha^{-1})	C	CR	CP	CS	CRS	CPS
NDVI						
0	0.77 a	0.78 a	0.79 a	0.78 a	0.79 a	0.79 a
60	0.82 a	0.80 a	0.81 a	0.82 a	0.81 a	0.81 a
120	0.84 a	0.81 a	0.81 a	0.83 a	0.81 a	0.84 a
240	0.84 a	0.82 a	0.81 a	0.85 a	0.79 a	0.83 a
NDRE						
0	0.17 a	0.17 a	0.17 a	0.17 a	0.18 a	0.16 a
60	0.19 a	0.19 a	0.18 a	0.19 a	0.19 a	0.18 a
120	0.20 a	0.20 a	0.19 a	0.20 a	0.19 a	0.20 a
240	0.21 a	0.20 a	0.20 a	0.21 a	0.18 a	0.20 a
SAVI						
0	0.52 a	0.54 a	0.54 a	0.53 a	0.54 a	0.54 a
60	0.57 a	0.56 a	0.57 a	0.59 a	0.57 a	0.57 a
120	0.60 a	0.57 a	0.56 a	0.60 a	0.57 a	0.60 a
240	0.60 a	0.58 a	0.57 a	0.63 a	0.54 a	0.59 a

Means followed by the same letters in the rows do not differ from each other by Tukey's test at 5% probability. C: single maize; CR: maize + U. ruziziensis; CP: maize + U. brizantha cv. Piatã; CS: maize + *Stylosanthes*; CRS: maize + U. ruziziensis + *Stylosanthes*; CPS: maize + U. brizantha + *Stylosanthes*. Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge Index (NDRE), and Soil-Adjusted Vegetation Index (SAVI).

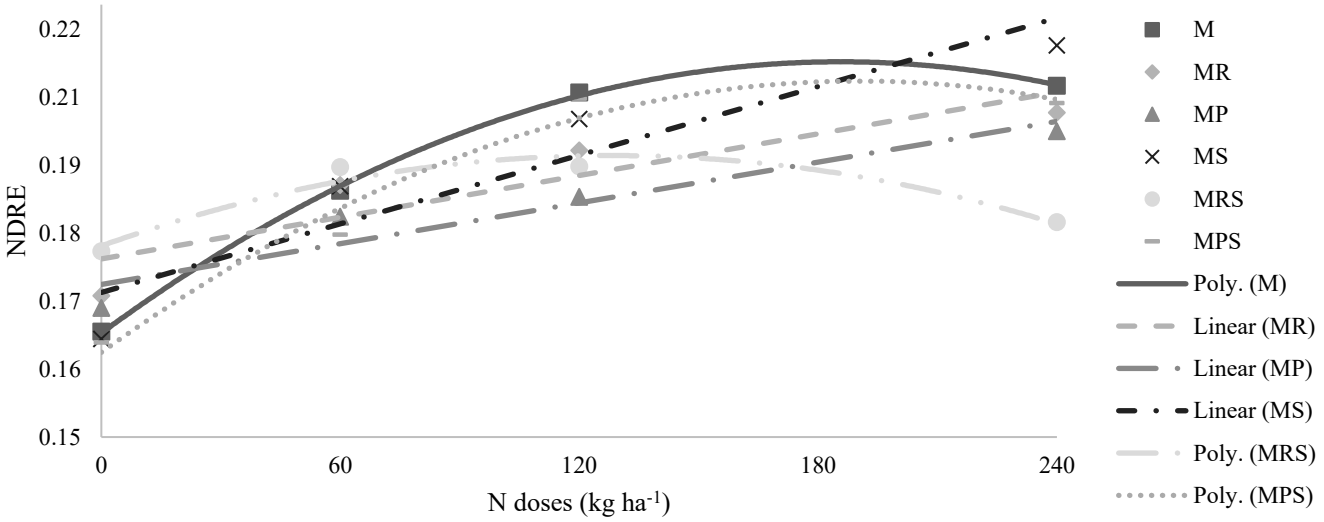
In the interaction between the intercropping systems and N doses applied as topdressing for NDVI (Fig. 1), the CR, CP, and CS intercropping systems fit the linear model, while C stood out, obtaining the highest value, reaching the maximum reflectance of the vegetative canopy with an increase up to the dose of 150 kg ha^{-1} of N, with adjustment to the quadratic model.



(C) $\hat{Y} = -3E-06x^2 + 0.0009x + 0.7696$; $R^2 = 0.9986$
(CR) $\hat{Y} = 0.000135286x + 0.78852$; $R^2 = 0.953229$
(CP) $\hat{Y} = 7.10476e-05x + 0.79974$; $R^2 = 0.531895$
(CS) $\hat{Y} = 0.000254286x + 0.7957$; $R^2 = 0.797118$
(CRS) $\hat{Y} = -2E-06x^2 + 0.0003x + 0.7949$; $R^2 = 0.8928$
(CPS) $\hat{Y} = -2E-06x^2 + 0.0006x + 0.7846$; $R^2 = 0.9729$

Fig. 1. Normalized Difference Vegetation Index (NDVI) as a function of the following intercropping systems: single maize (C); maize + U. ruziziensis (CR); maize + U. brizantha cv. Piatã (CP); maize + *Stylosanthes* (CS); maize + U. ruziziensis + *Stylosanthes* (CRS); maize + U. brizantha + *Stylosanthes* (CPS) and nitrogen topdressing doses, area without rock phosphate. Plot keys: M = C, MR = CR, MP = CP, MS = CS, MRS = CRS and MPS = CPS.

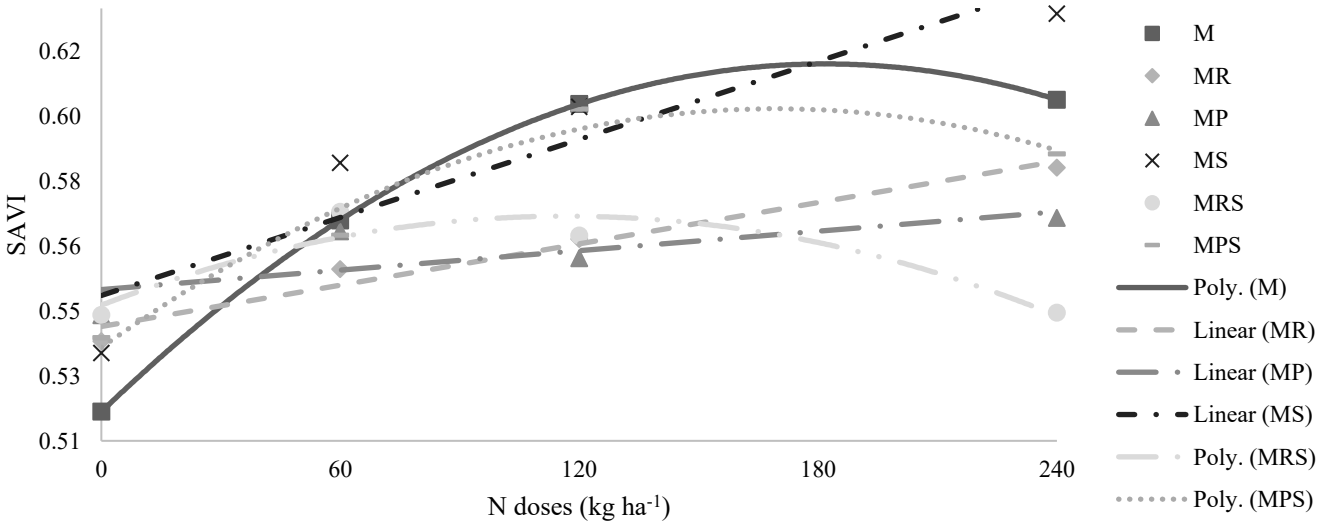
The results observed for NDRE (Fig. 2) indicated that CR, CP, and CS fit the linear model, and C stood out, with a fit to the quadratic model.



(C) $\hat{Y} = -1E-06x^2 + 0.0005x + 0.1668;\ R^2 = 0.9991$
(CR) $\hat{Y} = 0.000112476x + 0.17884;\ R^2 = 0.815652$
(CP) $\hat{Y} = 0.00011x + 0.1747;\ R^2 = 0.910731$
(CS) $\hat{Y} = 0.000185238x + 0.1734;\ R^2 = 0.879832$
(CRS) $\hat{Y} = -9E-07x^2 + 0.0002x + 0.181;\ R^2 = 0.9358$
(CPS) $\hat{Y} = -1E-06x^2 + 0.0005x + 0.1637;\ R^2 = 0.9715$

Fig. 2. Vegetation index by normalized difference for red transition (NDRE) as a function of intercrops and nitrogen doses in topdressing, area without rock phosphate. Plot keys: M = C, MR = CR, MP = CP, MS = CS, MRS = CRS and MPS = CPS.

In Fig. 3 for SAVI, the CR, CP and CS intercrops were similar to the NDRE, with a linear model fit for these intercrops, and C also stood out with maximum N efficiency up to the dose of 183 kg ha^{-1} with less drop in leaf canopy reflectance, fitting the quadratic model.



(C) $\hat{Y} = -3E-06x^2 + 0.0011x + 0.5181;\ R^2 = 1$
(CR) $\hat{Y} = 0.000191048x + 0.54174;\ R^2 = 0.965133$
(CP) $\hat{Y} = 8.99524e-05x + 0.55198;\ R^2 = 0.593811$
(CS) $\hat{Y} = 0.00036081x + 0.55034;\ R^2 = 0.865537$
(CRS) $\hat{Y} = -2E-06x^2 + 0.0004x + 0.5477;\ R^2 = 0.8667$
(CPS) $\hat{Y} = -2E-06x^2 + 0.0008x + 0.5359;\ R^2 = 0.9594$

Fig. 3. Soil-adjusted vegetation index (SAVI) as a function of intercropping and nitrogen doses in topdressing, area without rock phosphate. Plot keys: M = C, MR = CR, MP = CP, MS = CS, MRS = CRS and MPS = CPS.

With rock phosphate

Table 3 presents the mean squares and the significance of the F-test for the vegetation indices analyzed in the area with rock phosphate.

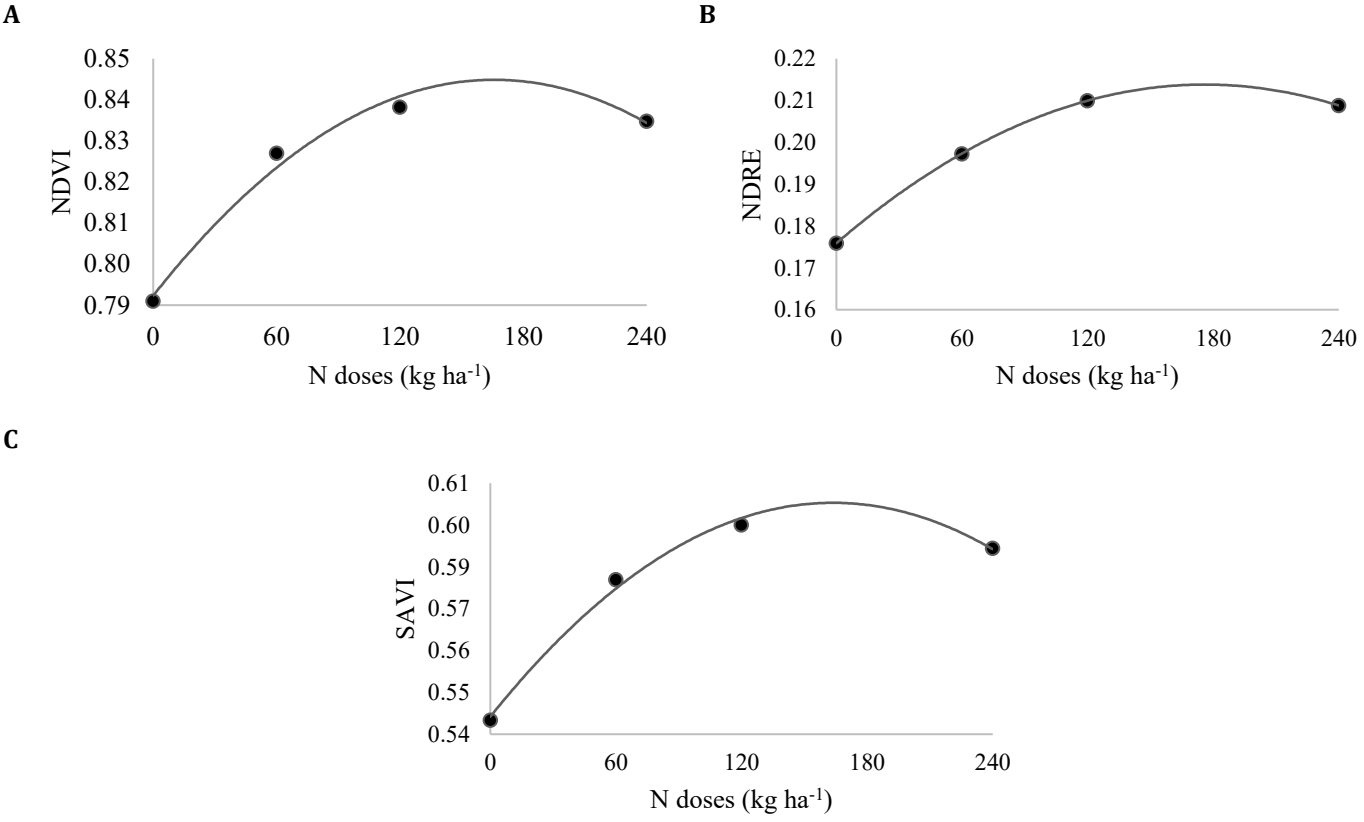
Table 3. Summary of the analysis of variance for the vegetation indices NDVI, NDRE, and SAVI in the area with rock phosphate in the 2021/2022 crop season.

SV	DF	NDVI	NDRE	SAVI
Block	3	0.00^{ns}	0.00^{ns}	0.01^{ns}
C	5	0.01^{ns}	0.00^{ns}	0.01^{ns}
Error a	15	0.00	0.00	0.01
N	3	0.01***	0.01***	0.02***
C × N	15	0.00^{ns}	0.00^{ns}	0.00^{ns}
Error b	54	0.00	0.00	0.00
CV1 (%)		14.95	14.35	19.65
CV2 (%)		4.58	4.57	6.22

*, **, ***: significant at 5%, 1%, and 0.1% probability, respectively; ^{ns}: not significant; SV: source of variation; CV: coefficient of variation; DF: degrees of freedom. Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge Index (NDRE), and Soil-Adjusted Vegetation Index (SAVI), all intercropping systems (C) and nitrogen (N).

The VIs were significant for the different N topdressing doses in the area with rock phosphate (Fig. 4), with positive responses fitted to quadratic models for all indices. When comparing the two experimental areas (with and without rock phosphate), the response patterns of the VIs to N doses were broadly similar, with both areas showing positive quadratic or linear responses depending on the intercropping system (Figs. 1–4).

The NDVI indicated maximum canopy reflectance at the dose of 175 kg ha^{-1} (Fig. 4A). The equation for the NDRE graph presented in Fig. 4B indicates that this model efficiently explained the NDRE between doses, and can be used to determine ideal N doses for plants. The VIs (NDRE, and SAVI) provided responses with increasing N up to the dose of 200 kg ha^{-1}.



(A) $\hat{Y} = -2E-06x^2 + 0.0007x + 0.7921$; $R^2 = 0.9899$
(B) $\hat{Y} = -1E-06x^2 + 0.0004x + 0.1759$
(C) $\hat{Y} = -2E-06x^2 + 0.0008x + 0.5404$; $R^2 = 0.9939$

Fig. 4. Vegetation indices NDVI (A), NDRE (B), and SAVI (C) managed with N doses in the area with rock phosphate.

Correlations between vegetation indices and agronomic variables

Correlation analyses between the vegetation indices (VIs) and agronomic variables (Table 4) showed positive and significant correlations between all VIs and grain yield (PROD), both in the area without rock phosphate and in the area

with rock phosphate. NDRE showed the highest correlations with PROD (r = 0.78 and 0.81, respectively), followed by SAVI (r = 0.75 and 0.77). NDVI showed the lowest correlations, especially in the area with rock phosphate (r = 0.68).

Table 4. Pearson correlation coefficients between vegetation indices and agronomic variables in areas without and with rock phosphate.

Variable	Area	NDVI	NDRE	SAVI
PROD	without P	0.72**	0.78**	0.75**
PROD	with P	0.68**	0.81**	0.77**
AP	without P	0.65*	0.70**	0.68**
AP	with P	0.62*	0.73**	0.71**
NGE	Without P	0.58*	0.69**	0.65*
NGE	with P	0.55*	0.72**	0.68**

*, **: significant at 5% and 1% probability, respectively. PROD: productivity; AP: plant height; NGE: number of grains per ear. Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge Index (NDRE), and Soil-Adjusted Vegetation Index (SAVI).

Discussion

Corn, when intercropped with brachiaria grasses, is greatly influenced by the speed of establishment of the forage grass and the increased competition for environmental resources, which can harm the development and productivity of the crop (Pariz et al., 2011). This fact corroborates Silva et al. (2015), who state that the emergence of brachiaria grass together with corn may have contributed to greater competitive capacity and an 8% reduction in productivity.

Considered the constituent of chlorophyll responsible for capturing sunlight for photosynthesis, N is highly required by corn. Therefore, the N content in plants indicates high photosynthetic activity of chlorophyll in the leaves, a factor that highlights the reflectance at the green wavelength (Resende and Shiratsuchi, 2016), indicating an influence on reflectance under the corn crop (Santana et al., 2021). Aiming to reduce the environmental impacts of excessive fertilization, remote monitoring techniques have been used, such as vegetation indices (VIs), which assist in decision-making regarding the appropriate amount of N that should be supplied to a crop according to the nutritional needs of the crop (Santana et al., 2021). This is due to the sensitivity that VIs have in detecting the "green" of the vegetation (Xue and Su, 2017).

The most widely used vegetation index to measure the "green" of aboveground vegetation is the normalized difference vegetation index (NDVI), which has a strong relationship with the health and productivity of the vegetation, and can demonstrate various changes in the characteristics of the land surface properties (Liu et al., 2024). The use of vegetation sensors can be an important tool to assist in quantifying the productive potential, efficiency of N use and estimating nitrogen fertilizer doses, according to the real needs of the crop (Vian et al., 2018).

In the areas studied, NDVI highlights the positive influence of nitrogen fertilization on the reflectance of the vegetative canopy; however, when intercropped, the reflectance level is influenced by the other crops present. The NDVI response observed in this research indicated greater prominence for the C and CS intercropping modalities; possibly the other intercropping systems presented greater vegetation mass that influences the reflectance of the vegetative canopy.

NDRE is more appropriate for determining nitrogen demand in cotton crops due to its greater sensitivity (Raper and Varco, 2015). Its application helps predict the nutritional conditions of the crop, identifying the need for fertilizer use in specific locations, improving crop productivity. Therefore, it shows a greater association with the foliar and total nitrogen content of corn plants (Flores et al., 2020), and together with NDVI, provides accurate information on corn grain yield (Santana et al., 2021). For this index, the responses to nitrogen were similar to NDVI, being more prominent in the C4 intercropping modality, also indicating saturation when intercropped with other crops. There are several spectral metrics related to the red edge, among which the normalized difference red edge index (NDRE) is a promising spectral metric that can be used to analyze the characteristics of the hyperspectral reflectance curve (Liu and Zhu, 2024). The NDRE uses the reflectance difference between the near-infrared (NIR) and red edge bands to indicate the physiological conditions of the vegetation (Thompson et al., 2019).

The SAVI stands out for minimizing the effects of soil and generating more reliable results, better representing vegetative vigor. It does not saturate like the NDVI. It can also be used to estimate the nutrition index in corn crops (Zhao et al., 2018). In addition to estimating foliar N content, it is also an important tool in identifying grain productivity (Santana et al., 2022; Zhao et al., 2018). In the area without P, the regression analysis for SAVI highlighted the C and CS intercropping modalities, indicating that they are more vigorous and well-nourished plants that responded better in grain production. The Soil Adjusted Vegetation Index (SAVI) is derived from the near-infrared (NIR) spectrum and red bands, taking into account additional factors such as soil brightness or canopy background, to increase sensitivity to biophysical variables of vegetation and are useful for increasing the accuracy of vegetation analysis (Fadl et al., 2024).

In this study, canopy spectral reflectance data were used to identify the three vegetation indices in the two areas studied, as a function of the intercrops and N doses provided in topdressing. Specifically, the indices used were NDVI, NDRE, and SAVI. The results observed for the VIs suggest that they can be used to estimate nitrogen fertilization for the crop to express

its productive potential. However, due to the sensitivity they showed in detecting intense plant mass, their use is limited when intercropped with forage species and corn, not generating reliable results. As for the intercropping modalities, all responded similarly for the same C and CS intercropping systems in relation to N doses. Therefore, the identification of limiting factors for each IV, in addition to its suitability for use, must be carried out carefully, considering the advantages and limitations that each one offers, in order to apply them in a given location.

Although the vegetation indices showed significant responses to N rates across all intercropping systems, no statistically significant differences were detected between single corn and intercropped treatments for any index at any N dose (Table 2). This suggests that, under the conditions of this study, the spectral reflectance of the canopy was not significantly altered by the presence of brachiaria at the V6 stage. However, the regression analyses (Figs. 1-4) revealed that the response patterns to N rates differed among intercropping systems, with single corn showing quadratic responses while some intercropped systems exhibited linear responses. This difference in response curves may indicate that the intercropped systems have distinct spectral behavior, even though pairwise comparisons at individual doses did not reach statistical significance. Further studies with larger sample sizes or more sensitive indices may be needed to detect potential interference effects.

The response patterns of the vegetation indices to N doses were broadly similar between the two experimental areas (with and without rock phosphate), as observed by the similarity in the regression models (Figs. 1–4) and correlation coefficients (Table 4). However, it is important to note that the areas with and without rock phosphate were not established as randomized treatments within a single experimental design, but rather as independent adjacent areas. Therefore, while the observed similarity suggests that rock phosphate application did not markedly alter the spectral response of the canopy to N fertilization, a formal statistical comparison of the effect of rock phosphate cannot be made from this experimental setup. The similarity in responses may also reflect other uncontrolled factors between the two areas. Future studies should incorporate rock phosphate as a randomized factor within a combined experimental design to enable formal inference on its effects on canopy reflectance and nitrogen status estimation.

A limitation of this study is the absence of direct measurements of plant nitrogen status, such as leaf N concentration, SPAD index, or plant N uptake. While the vegetation indices responded positively to increasing N rates and showed significant correlations with grain yield, these relationships are indirect evidence of N responsiveness rather than validated estimates of plant N status. As highlighted by previous studies (e.g., Flores et al., 2020; Santana et al., 2021), the correlation between VIs and agronomic traits can be influenced by multiple factors, including canopy structure, biomass accumulation, and species composition in intercropping systems. Therefore, the results presented here should be interpreted as spectral responses to N fertilization, and direct N-status measurements are recommended in future studies to confirm the potential of these indices for nutritional monitoring in corn-forage intercropping systems.

Materials and methods

Location and characterization of the experimental area

The experiment was conducted in the experimental field of the Federal University of Mato Grosso do Sul, Chapadão do Sul campus - MS (18°46'13.4" S and 52°37'19.8" W, average altitude of 819 m) (Fig. 5), during the 2021/2022 growing season. The region's climate is humid tropical (Aw), with an average annual rainfall of 1,850 mm and an average temperature of 24.1 °C. During the experiment, the accumulated rainfall was 1,385.5 mm, adequate for the crop's needs. The soil is classified as a Dystrophic Red Latosol with a clayey texture (Santos et al., 2018).

Experimental design and treatments

The experiment was conducted in two adjacent and independent experimental areas, differentiated by the application or not of rock phosphate (P). One area received rock phosphate application, while the other area did not (control). In each of these areas, the same experimental design was adopted: a randomized complete block design with four replications, in a 6 × 4 factorial scheme.

The first factor consisted of six cropping systems: maize alone (C); maize + *Urochloa* ruziziensis (CR); maize + *Urochloa* brizantha cv. Piatã (CP); maize + *Stylosanthes* cv. Campo Grande (CS); maize + U. brizantha + *Stylosanthes* (CPS); and maize + U. ruziziensis + *Stylosanthes* (CRS). The second factor corresponded to four nitrogen topdressing doses: 0, 60, 120, and 240 kg ha^{-1} of N.

Thus, each area (with and without rock phosphate) constituted an independent experiment, totaling 6 cropping systems × 4 N rates × 4 replications = 96 plots per area. The results are presented separately for each area.

Each plot consisted of 12 sowing rows spaced 0.50 m apart and 14 m long, totaling an area of 84 m^2. Topdressing fertilization occurred at the V4 stage, with N doses applied in split plots and 40 kg ha^{-1} of K_2O, using KCl as the source, with application performed manually in both experiments.



Fig. 5. Experiment location.

Spectral data acquisition

Multispectral images were obtained 33 days after planting (DAP), when the plants were at the V6 phenological stage. A Sensefly eBee RTK fixed-wing remotely piloted aircraft (UAV) equipped with a Parrot Sequoia multispectral sensor was used, which captures images at the following wavelengths: green (550 nm), red (660 nm), red edge (735 nm), and near-infrared (790 nm). The flight was conducted at an altitude of 100 m, resulting in a spatial resolution of 0.10 m, between 9 and 10 am, under clear sky conditions. The sensor has an attached solar light sensor for automatic irradiance correction (Silva et al., 2020). The images were mosaicked and orthorectified in Pix4Dmapper software, with accuracy verification by ground control points (RTK).

From the images, the following vegetation indices were calculated (Table 5):

Table 5. Vegetation indices evaluated.

Index	Equation	Reference
NDVI	$\frac{nir - red}{nir + red}$	Rouse et al., 1974
NDRE	$\frac{nir - rededge}{nir + rededge}$	(Barnes et al., 2000)
SAVI	$(1 + L) \times \frac{nir - red}{nir + red + L}, L = 0.5$	Huete, 1988

Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge Index (NDRE), and Soil-Adjusted Vegetation Index (SAVI).

Agronomic evaluations

At 130 DAP, at the wet grain stage (R5), grain yield (PROD, kg ha^{-1}), plant height (AP, m), and number of grains per ear (NGE) were evaluated for correlation with vegetation indices.

Phytosanitary management

The phytosanitary management of the crop was carried out according to the technical recommendations for the crop. For weed control, 2 L ha^{-1} of Atrazine (500 g L^{-1}) was used only in the single corn plots in post-emergence. Pest and disease control was carried out with the application of 400 ml ha^{-1} of Zeta-Cypermethrin (200 g L^{-1}); 0.4 L ha^{-1} of Picoxystrobin (200 g L^{-1}); and 1 L ha^{-1} of the mixture of beta-cyfluthrin (12.5 g L^{-1}) + imidacloprid (100 g L^{-1}), during the vegetative period of the crop.

Statistical analysis

The vegetation index data were subjected to analysis of variance (F-test). The means of the intercropping systems were compared using Tukey's test ($p < 0.05$). Polynomial regression equations were fitted for the N doses. Pearson correlation analyses were performed between the vegetation indices and the agronomic variables. The Rbio software (Bhering, 2017) was used.

The agronomic data (grain yield, plant height, and number of grains per ear) presented in this study were collected from the same experiment as a complementary article (https://doi.org/10.21475/ajcs.26.20.11.pne258) (Roque et al., 2026). While the companion paper focuses on agronomic performance and morphological components, the present manuscript evaluates the spectral response of vegetation indices to nitrogen fertilization and their correlations with those agronomic

traits. The two manuscripts address complementary aspects of the same experiment and are based on independent analyses of distinct datasets (spectral vs. agronomic).

Limitations of the study

It is important to acknowledge that this study did not include direct measurements of plant nitrogen status, such as leaf nitrogen concentration, SPAD index, plant N uptake, or nitrogen nutrition index (NNI). Therefore, the vegetation indices evaluated in this study are analyzed as spectral responses to N fertilizer rates and their correlations with agronomic variables, rather than as validated proxies for plant N status. Future studies should incorporate direct N-status measurements to confirm the predictive capacity of these indices for estimating nitrogen nutrition in intercropped systems.

It should be noted that the areas with and without rock phosphate were established as independent adjacent experiments, not as randomized treatments within a single combined design. Therefore, comparisons between the two areas are descriptive and do not allow formal statistical inference on the effect of rock phosphate.

Conclusion

The vegetation indices NDVI, NDRE, and SAVI respond positively to increased nitrogen topdressing doses in corn intercropped with forage crops.

NDVI showed saturation in systems with greater plant mass, limiting its sensitivity at higher N rates.

NDRE demonstrates greater sensitivity and lower saturation showing the highest correlations with grain yield, suggesting it is the most promising index for future studies on N monitoring in intercropped systems.

However, as direct measurements of plant N status were not performed, these results represent spectral responses to N fertilization rather than validated estimates of plant nitrogen status. Future research should include direct N-status indicators (e.g., leaf N concentration, SPAD, or N uptake) to confirm the predictive capacity of these indices for nutritional monitoring in intercropped systems.

The response patterns of the VIs were similar between the areas with and without rock phosphate, suggesting that rock phosphate did not appear to markedly alter the spectral response to N fertilization. However, as the areas were not established as randomized treatments, this observation is descriptive rather than inferential.

Statement of AI use

During the preparation of this manuscript, the authors used generative artificial intelligence tools (DeepSeek) solely for language review, grammatical correction, and text clarity enhancement. No AI tools were used for data generation, statistical analysis, result interpretation, or formulation of scientific conclusions. The authors assume full responsibility for the final content of this work and declare that all information presented is their own authorship and responsibility.

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