ADVANCED METHOD TO ASSESS THE IMPACT OF SOIL FERTILITY VARIABILITY ON MAIZE (*ZEA MAYS* L.) PRODUCTIVITY.

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Maize production in Brazil for the 2024/2025 season is estimated at 119.6 million tons, representing a 3.4% increase compared to the previous cycle, despite a 5.9% reduction in cultivated area. This scenario highlights the need for more efficient agricultural systems capable of sustaining high productivity levels under land-use restrictions. Traditionally, high-yield agriculture has relied on intensive input use, a practice that can lead to waste. In contrast, precision agriculture emerges as a strategic alternative, employing technologies to monitor spatial and temporal variability, optimize management, and reduce costs. Despite advances, uncertainties remain regarding the actual productivity gains achieved with nitrogen doses above technical recommendations, as well as the effectiveness of vegetation indices such as NDVI in providing reliable yield estimates. In this study, the average NDVI values were monitored throughout the crop cycle, showing an initial increase associated with biomass accumulation, followed by a decline from stage R5 (milk line formation), reaching lower values at stage R6 (physiological maturity). This pattern enabled dynamic crop analyses and correlation with yield. The objective of this work was to evaluate the effects of different nitrogen topdressing doses on maize productivity, considering spatial variability, and to investigate the potential of NDVI, obtained through drone-based remote sensing, as a yield indicator and a tool for nutritional management of the maize plants. The experiment was conducted in a 0.4 ha field, subdivided into four 0.1 ha plots, across three crop cycles (2019/2020, 2020/2021, and the 2021 off-season). Four nitrogen doses were applied (0%, 50%, 100%, and 200% of the recommended rate), while maintaining uniform base fertilization. Productivity was assessed using a regular sampling grid, along with soil fertility analyses at different depths. For field validation, up to eight drone flights with a multispectral camera were performed, enabling NDVI calculation, temporal analyses, and correlation with yield. Results indicated significant yield increases with higher nitrogen fertilization across all seasons. In regular crops, applying around 200% of the recommended dose resulted in limited gains of about 11%, whereas in the off-season, productivity increased substantially, reaching approximately 45%. Both phosphorus and potassium macronutrients showed no significant influence on results. NDVI exhibited strong correlation with yield at advanced stages (≥92 days after sowing) and moderate correlation at early stages (9 days after sowing). It is

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concluded that nitrogen fertilization above recommended levels may be economically relevant under specific off-season conditions. Furthermore, NDVI proved to be a promising tool for monitoring crop development dynamics and supporting decision-making in precision agriculture systems applied to maize production.

Precision Agriculture, Maize, Nitrogen Fertilization, NDVI, Remote Sensing.

Introduction

Maize holds a strategic position in Brazilian agriculture, being essential for animal feed, industrial applications, and export. Despite recent fluctuations in cultivated area, the crop maintains high economic and social relevance, which poses challenges for sustaining productivity under land-use restrictions and climatic variability (Conab, 2024). In this context, it is crucial to investigate management practices that reconcile efficiency and sustainability, encompassing both high-yield approaches based on intensive input use and precision agriculture strategies. The latter is characterized as an integrated management system that links physical and chemical field information to digital data, analyzed through geostatistical techniques to understand spatial and temporal variability (Bassoi, 2019; Grego, 2014; Molin, 2015), thereby employing technologies to optimize resources and minimize losses (Inamasu, 2011; Kumar et al., 2022; Barbosa Júnior et al., 2024).

Several studies emphasize the importance of proper nutritional management, particularly nitrogen fertilization, for increasing maize productivity. Coelho (2007) highlighted that practices such as crop rotation, no-tillage, and fertility management are fundamental, with nitrogen being the most critical nutrient for achieving high yields. Araújo et al. (2004) reported significant increases in grain production (28%) and dry matter (37%) when applying nitrogen topdressing doses above Werner's (1996) recommendation. Albuquerque et al. (2013) also demonstrated productivity gains by combining green manure with Crotalaria and mineral nitrogen fertilization under no-tillage systems. More recent studies in precision agriculture show that spectral indices, such as NDVI, exhibit strong correlations with maize yield, enabling early estimates and reinforcing the potential of remote sensing as a management support tool (Gonçalves, 2023; Valério, 2023). On the other hand, evidence suggests that nitrogen doses above technical recommendations may not result in additional yield gains, being characterized as "luxury consumption" (Schüller, 2023). This indicates that indiscriminate increases in input availability can lead to waste without agronomic benefits. Furthermore, studies such as Lima (2023) demonstrated limitations in using NDVI to predict yield in crops like sorghum, showing that the relationship between spectral indices and productivity may vary depending on species, phenological stage, and climatic conditions. Tavares (2023) also emphasized that, although NDVI can support nitrogen topdressing management, its practical application still requires validation under different scenarios due to environmental variability affecting correlation consistency. These findings highlight the need for caution in extrapolating results and reinforce the importance of further research to balance productivity and sustainability.

Given this background, the present study aims to evaluate whether increasing nitrogen availability beyond technical recommendations can enhance maize productivity without causing input loss. In addition, it seeks to correlate and classify yield models based on spatial and temporal data obtained through remote sensing, using NDVI analysis as a central tool.

Materials and Methods

The experiment was carried out at the National Reference Laboratory for Precision Agriculture of Embrapa Instrumentation, located in São Carlos, São Paulo (Brazil). The study area comprised a 0.4 ha field subdivided into four plots of 0.1 ha each. The region is characterized by a Humid subtropical (Cwa) climate, a dystrophic Red-Yellow Latosol, and predominance of the Cerrado (Brazilian savannah) biome. The maize hybrid Pioneer P4285 VYHR, resistant to pests and glyphosate-based herbicides, was used. Cropping seasons occurred between 2019 and 2021, with sowing dates in October 2019, October 2020, and March 2021 (off-season). Liming and fertilization practices followed the recommendations of the Agronomic Institute of Campinas (IAC). Each plot received different nitrogen topdressing rates (0%, 50%, 100%, and 200% of the recommended dose), while a uniform NPK (08-28-16) fertilization was applied at planting. Soil and yield sampling were performed on a 10 × 10 m grid, totaling 40 sampling blocks (Fig. 1). The analyses aimed to identify differences among plots, evaluate the influence of other macronutrients, and determine when yield differentiation occurred during crop development.

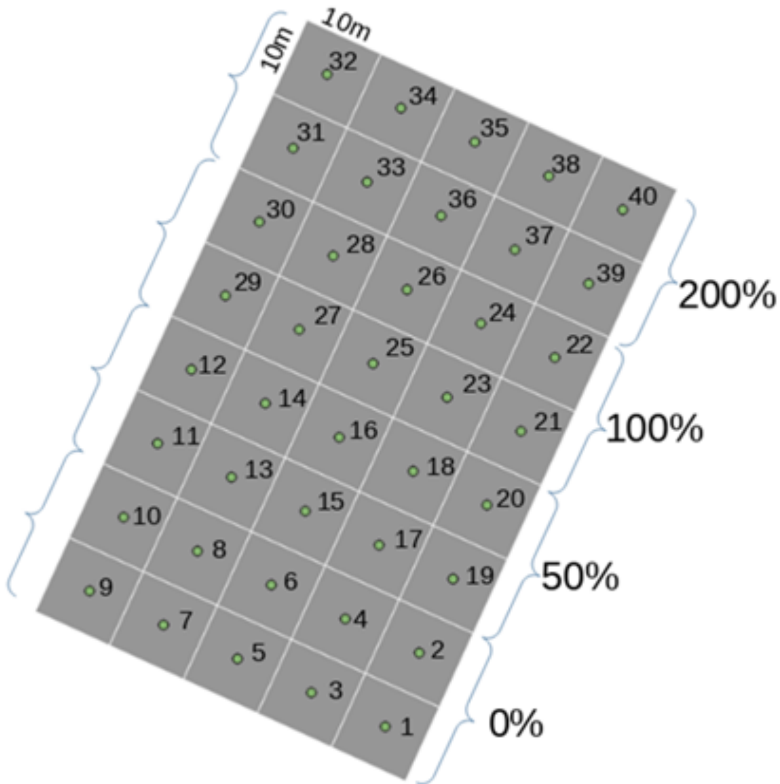


Fig. 1. Distribution of plots and sampling blocks in the experiment.

Field preparation, sowing, and harvesting were mechanized, whereas nitrogen topdressing was applied manually. Composite soil samples were collected at three depths (0–10 cm, 10–20 cm, and 20–30 cm) and analyzed in a certified laboratory. Grain yield was estimated from the average mass of ten plants per sampling block, ensuring representative results. For temporal analysis, eight drone flights were conducted during the 2019/2020 cycle using a multispectral camera, I.e., the Micasense RedEdge-M. In addition, ground control points (GCP) were considered in the experimental area using a high-precision GPS in conjunction with an RTK receiver that recorded their geographic coordinates to an accuracy of ± 1 cm. Images were processed in QGIS to calculate the Normalized Difference Vegetation Index (NDVI), which was correlated with yield data using statistical tests (Shapiro-Wilk, Spearman, and Kruskal-Wallis). This approach enabled monitoring of nitrogen fertilization effects throughout the crop cycle and identification of periods when NDVI showed stronger correlation with final yield. Interpolation maps were generated using kriging to complement the analysis. As illustrated in Figure 2, the experimental workflow encompassed all field operations and sampling stages, from soil preparation to harvesting. This sequence highlights the integration of conventional agronomic practices with precision agriculture tools, such as drone-based monitoring, to assess the spatial and temporal variability of maize productivity under different nitrogen fertilization rates.

Fig. 2. Experimental workflow: (a) field preparation; (b) soil sampling; (c) sowing; (d) nitrogen topdressing with different rates; (e) drone flights during crop growth; (f) harvesting after yield sampling.

Results and Discussion

Nitrogen fertilization is one of the main factors driving maize yield, making it essential to evaluate crop response under different application rates. Table 1 presents the statistical data for yield across seasons and treatments, while Figure 4a illustrates the distribution of values. A clear trend of increasing productivity was observed with higher urea doses. In 2019/2020, the 100% and 200% treatments showed similar averages (9216 and 9432 kg/ha), indicating no additional gains beyond the recommended rate. In 2020/2021, all treatments differed significantly, with continuous increases up to 200%. In the 2021 off-season, results were more heterogeneous but revealed substantial gains at higher doses, despite external influences such as shading from a eucalyptus row adjacent to the experimental field.

Table 2 summarizes the statistical tests used to verify assumptions of normality and homogeneity of variances, which are fundamental for selecting appropriate analytical methods. In 2019/2020, the Shapiro-Wilk ($p = 0.069$) and Levene ($p = 0.168$) tests confirmed that assumptions were met, allowing parametric analysis. However, in 2020/2021 and 2021/2021, both tests yielded $p < 0.001$, indicating lack of normality and homogeneity, thus requiring non-parametric methods. The Kruskal-Wallis test confirmed significant differences among treatments in all seasons ($p < 0.001$), demonstrating the effect of nitrogen fertilization on yield.

Multiple comparisons using the Dwass-Steel-Critchlow-Fligner method revealed that in 2019/2020 there was no difference between 100% and 200%, while in 2020/2021 all treatments differed. In 2021/2021, only 0% and 50% did not differ significantly, as shown in the boxplots of Figure 4a. These results reinforce that in normal seasons, increasing nitrogen beyond the recommended dose does not provide substantial benefits, but under adverse conditions such as the off-season, higher doses can lead to relevant yield gains, supporting evidence that nitrogen plays a decisive role under limited water availability.

Table 1. Statistical data of treatments applied in each season of the maize experiment.

Season	Treatment [%]	Mean [kg/ha]	Standard Deviation	Standard Error
2019/2020	**0**	5099.68	894.36	282.79
	50	6998.33	568.79	179.86
	100	9216.10	569.71	180.15
	200	9432.88	829.84	262.43
	Total	7687.75	1926.25	304.75
2020/2021	**0**	3933.00	41.92	13.28
	50	5238.25	64.86	20.53
	100	6560.75	69.35	21.91
	200	7337.00	93.90	29.67
	Total	5767.25	1316.75	208.15
2021/2021	**0**	484.73	209.24	66.18
	50	1633.00	821.56	259.79
	100	3734.63	1810.96	572.64
	200	6879.88	3180.27	1005.68
	Total	3185.50	3053.25	483.00

Table 2. Statistical data of treatments applied in each season of the maize experiment.

Season	Normality (Shapiro-Wilk)	Homogeneity (Levene)	Kruskal-Wallis (χ^2 / df / p)	Dwass-Steel-Critchlow-Fligner	Conclusion
2019/2020	Met ($p = 0.069$)	Met ($p = 0.168$)	$\chi^2 = 32.7$ df = 3 $p < 0.001$	0% < 50% < 100% ≈ 200%	N significant; P and K no effect
2020/2021	Not met ($p < 0.001$)	Not met ($p = 0.023$)	$\chi^2 = 36.6$ df = 3 $p < 0.001$	0% < 50% < 100% < 200%	N significant; P and K no effect
2021/2021	Not met ($p < 0.001$)	Not met ($p < 0.001$)	$\chi^2 = 21.8$ df = 3 $p < 0.001$	0% ≈ 50% < 100% < 200%	N significant; P and K no effect

Another important aspect was the evaluation of other macronutrients, such as phosphorus and potassium, to rule out possible interference in yield interpretation. Comparisons between productivity maps and residual distributions of these nutrients at different depths showed that only two results were significant, both in the superficial layer (0–10 cm). However, these findings were not consistent across seasons, despite some spatial similarity. Thus, phosphorus and potassium did not exert a relevant influence on yield, confirming nitrogen as the main differentiating factor. This aligns with studies highlighting nitrogen as the most limiting nutrient for maize in Cerrado (Brazilian savannah) soils.

For temporal analysis, spectral indices such as NDVI provide a non-destructive means of monitoring crop development and potentially predicting yield. Figure 3 shows orthomosaics generated for NDVI across drone flights, and Table 3 presents the Spearman correlation matrix between mean NDVI values and yield.

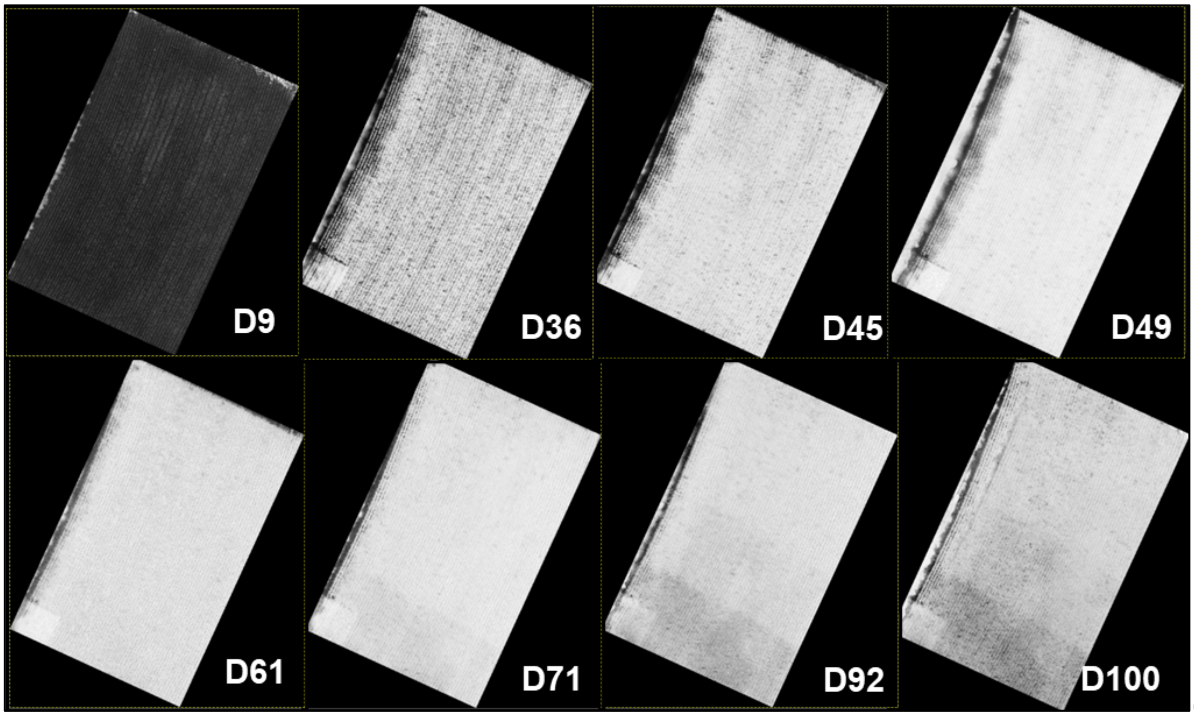


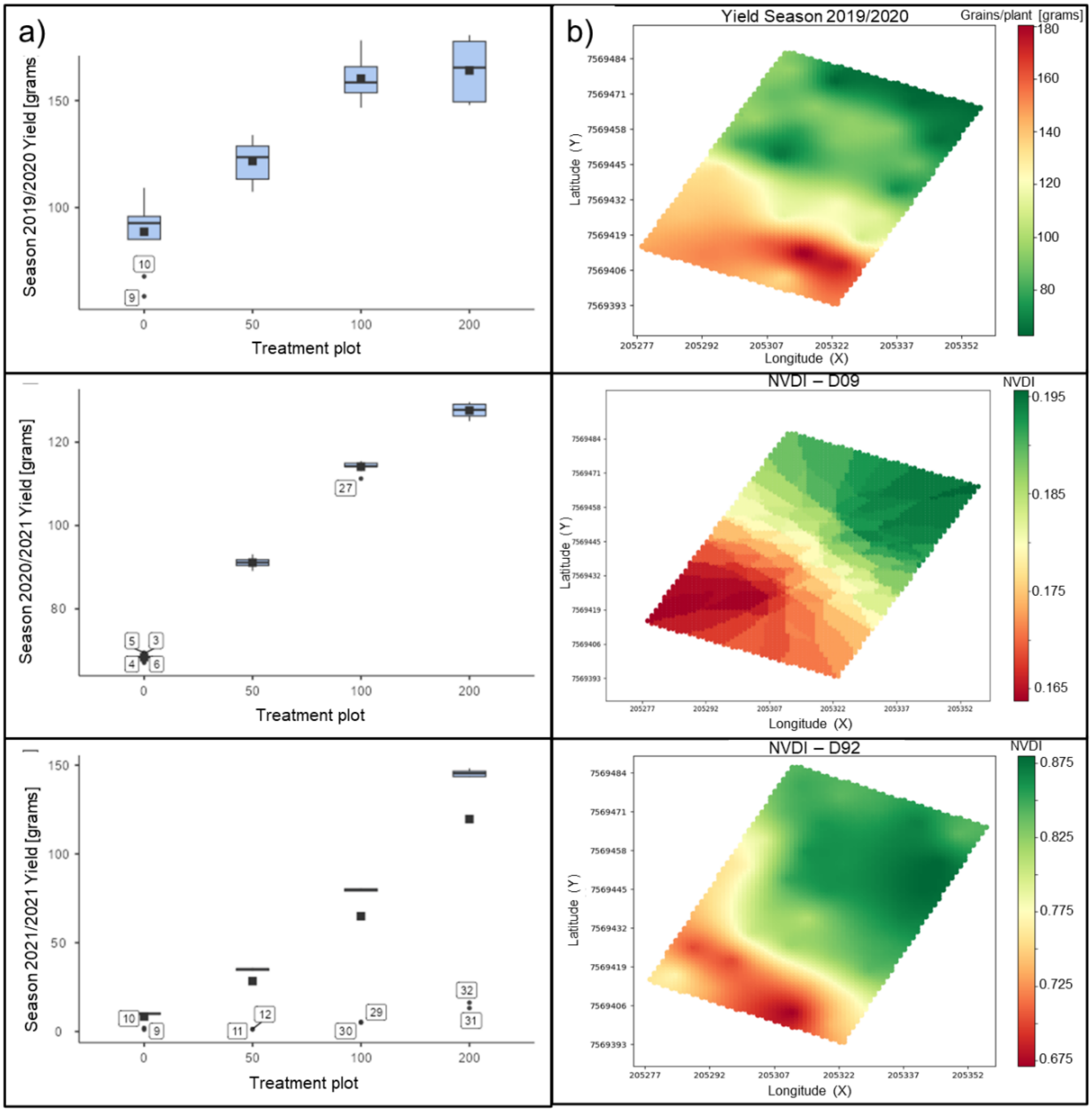
Fig. 3. Orthomosaics of NDVI indices from multiple drone flights conducted during the 2019/2020 maize season.

Table 3. Spearman correlation matrix between mean NDVI values at different dates and maize yield for the 2019/2020.

Correlation	D9	D36	D45	D49	D61	D71	D92	D100	Prod.
D9	—								
D36	0.282	—							
D45	-0.081	0.790***	—						
D49	0.028	0.803***	0.906***	—					
D61	0.077	0.601***	0.608***	0.603***	—				
D71	0.467**	0.736***	0.518***	0.576***	0.785***	—			
D92	0.761***	0.370*	0.002	0.079	0.341*	0.701***	—		
D100	0.719***	0.325*	-0.057	0.055	0.378*	0.703***	0.959***	—	
Prod.	0.544***	0.012	-0.301	-0.237	-0.053	0.317*	0.799***	0.771***	—

Note: * p <0.05, ** p<0.01, *** p<0.001

Subsequently, Figure 4b displays selected NDVI maps from different flight dates alongside the productivity map. From 92 days after sowing (final map in Figure 4b), a strong positive correlation (r > 0.6) was observed between NDVI and yield. At 9 days after sowing (middle map in Figure 4b), a moderate correlation (r = 0.54) was detected, suggesting potential for early use, albeit with lower precision. These results confirm that NDVI is more reliable in advanced growth stages but can already indicate yield trends in early stages. Similar studies also highlight NDVI as a promising tool for precision management and early decision-making.



Note: To obtain yield values in kg/ha, the results must be multiplied by 57.5, corresponding to a plant stand of 57,500 plants per hectare.

Fig. 4. Spatial and temporal analysis of maize yield: (a) Distribution of average grain yield (g/plant) across the three growing seasons under different nitrogen fertilization rates. (b) Temporal and spatial maps generated by kriging for the 2019/2020 season, illustrating yield distribution (top) and mean NDVI values obtained from drone flights at 9 days (D09) and 92 days (D92) after sowing.

Conclusion

Nitrogen fertilization proved to be the main factor influencing maize yield under Cerrado (Brazilian savannah) conditions. In regular seasons, yield gains plateaued at the recommended dose, while in the off-season higher rates provided significant benefits, confirming nitrogen's critical role under stress environments. Phosphorus and potassium showed no consistent effects, reinforcing nitrogen as the most limiting nutrient. The use of NDVI enabled effective, non-destructive monitoring of crop development, with strong correlations to yield in advanced stages and moderate associations even at early growth. These findings highlight the potential of integrating nitrogen management with remote sensing tools to enhance precision agriculture, optimize resource use, and support sustainable maize production.

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