Prediction of leaf nitrogen in corn cultivated under organomineral fertilization using machine learning and multispectral aerial imagery

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Abstract.
One of the main determining factors of corn productivity is nitrogen (N) fertilization. However, significant knowledge gaps still persist regarding plant responses to top-dressing nitrogen application with organomineral fertilizers. Conventional methods for assessing nutritional status, such as leaf tissue analysis and portable chlorophyll meters, although efficient, are limited by their point-in-time nature, failing to adequately represent the spatial and temporal variability throughout the crop cycle. In this context, the integration of artificial intelligence with high-resolution multispectral aerial imagery acquired by Unmanned Aerial Vehicles (UAVs) emerges as a promising alternative for predicting leaf nitrogen content and optimizing management strategies in precision agriculture. The objective of this study was to develop and evaluate machine learning models associated with multispectral aerial imagery to estimate leaf nitrogen in corn cultivated under organomineral fertilization. The experiment was conducted under a sprinkler irrigation system, in a randomized block design with four replications. The treatments consisted of five top-dressing nitrogen rates (0, 75, 150, 225, and 300 kg ha^{-1}), applied to plots with a density of 70,000 plants ha^{-1} and 0.5 m spacing between rows. Throughout the crop cycle, leaf chlorophyll indices (SPAD values) were measured weekly, from 10 to 107 days after sowing (DAS), on leaves C and C-1, with 30 leaves evaluated per plot. Multispectral remote sensing data were acquired with a DJI Matrice 350 RTK UAV equipped with an integrated Altum-PT multispectral camera, with image acquisition at a 60 m altitude, from which fifty-six vegetation indices (VIs) were derived. The model development employed the Random Forest (RF) algorithm, associated with Recursive

Feature Elimination (RFE) for variable selection, Leave-One-Out Cross-Validation (LOOCV), and Bayesian hyperparameter optimization. The predictive performance was evaluated using the coefficient of determination (R^2) and the mean absolute error (MAE). The spectral indices showed distinct relationships with chlorophyll values throughout the phenological stages of corn, with superior predictive performance in the V7–V8 and reproductive (R3) stages. The results demonstrate the potential of integrating machine learning and multispectral imagery as an efficient and viable tool for corn nutritional monitoring, representing a promising alternative for the sustainable management of this key nutrient.

Keywords.
Zea mays L., Precision Agriculture, Nutrient Management, Remote Sensing, Vegetation Indices, Random Forest, Crop Monitoring.

Introduction

Nitrogen (N) is one of the main determining factors of corn (*Zea mays* L.) productivity, given its central role in the biosynthesis of chlorophyll, proteins, and enzymes involved in photosynthesis and grain filling. Despite its critical importance, significant knowledge gaps persist regarding plant physiological responses to top-dressing N application with organomineral fertilizers, whose gradual nutrient release profile may differ substantially from conventional mineral sources in terms of synchrony with crop demand.

Conventional methods for assessing leaf nitrogen status, including destructive tissue analysis and portable chlorophyll meters (SPAD), although efficient, are limited by their point-in-time nature and inability to represent spatial and temporal variability throughout the crop cycle at field scale (Osco et al., 2020; Silva et al., 2025). These constraints limit the ability to implement timely and spatially differentiated management decisions, particularly in large-scale irrigated corn production systems.

In this context, the integration of artificial intelligence with high-resolution multispectral aerial imagery acquired by UAVs emerges as a promising, scalable, and non-destructive alternative for predicting leaf nitrogen content and optimizing management strategies in precision agriculture. Vegetation indices (VIs) derived from multispectral imagery are sensitive to canopy chlorophyll and nitrogen content across distinct phenological stages, enabling the development of predictive models that capture the temporal dynamics of crop N status (Yang et al., 2022).

Studies have demonstrated that Random Forest (RF) regression, combined with recursive feature selection from pools of spectral VIs, can achieve strong predictive performance for leaf nitrogen concentration in maize under varying N fertilization rates (Osco et al., 2020; Lee et al., 2020). The present study aimed to develop and evaluate RF machine learning models associated with multispectral aerial imagery to estimate leaf nitrogen in corn cultivated under organomineral fertilization, identifying the phenological stages and spectral indices most informative for nutritional prediction.

Materials and Methods

The The experiment was conducted under a sprinkler irrigation system in Minas Gerais, Brazil, in a randomized complete block design with four replications. Treatments consisted of five top-dressing N rates applied as organomineral fertilizer: 0, 75, 150, 225, and 300 kg N ha^{-1}, to plots with a density of 70,000 plants ha^{-1} and 0.5 m row spacing.

Leaf chlorophyll indices (SPAD values for total, a, and b chlorophyll) were measured weekly from 10 to 107 days after sowing (DAS) using a Falker chlorophyll meter, on leaves C and C-1, with 30 leaves evaluated per plot at the middle third of the leaf blade. Multispectral aerial imagery was acquired using a DJI Matrice 350 RTK UAV equipped with an Altum-PT multispectral camera, which captures Blue, Green, Red, RedEdge, NIR, and Thermal Infrared (TIR) bands, at a 60 m altitude. Radiometric calibration was performed using a reflectance panel before each flight, and georeferenced orthomosaics were generated through photogrammetric processing. A total of 56 vegetation indices (VIs) were derived per plot and per flight date.

Machine learning model development employed the Random Forest (RF) algorithm, implemented in Python 3, with three sequential steps: (1) variable selection via Recursive Feature Elimination (RFE) combined with Leave-One-Out Cross-Validation (LOOCV); (2) Bayesian hyperparameter optimization; and (3) model training and evaluation on an independent test dataset. Predictive performance was assessed using the coefficient of determination (R^2) and mean absolute error (MAE). Models were developed and evaluated independently for each phenological stage to identify the periods of highest predictive accuracy.

Results and Discussion

The spectral indices derived from multispectral UAV imagery exhibited distinct relationships with leaf chlorophyll (SPAD) values across the phenological stages of the crop cycle. Early vegetative stages (before V7) showed weaker spectral–chlorophyll associations, attributable to incomplete canopy closure and predominant soil background contribution to the multispectral signal, which reduces the sensitivity of vegetation indices to canopy N status. These limitations in early-stage prediction are consistent with findings reported by Osco et al. (2020) and Lee et al. (2020), who observed that model performance in maize is strongly conditioned by canopy development stage and cover fraction.

Superior predictive performance was achieved at the V7-V8 and reproductive (R3) stages, where canopy closure enables more reliable spectral characterization of leaf chlorophyll dynamics. These findings align with Yang et al. (2022), who identified intermediate vegetative and early grain-filling stages as the optimal phenological windows for UAV-based predictive modeling in maize, with spectral VIs showing markedly higher discriminatory power after full canopy closure compared to early vegetative stages. At these stages, the RF models incorporating RFE-selected vegetation indices and Bayesian-optimized hyperparameters demonstrated higher R^2 and lower MAE values, indicating improved capacity to capture chlorophyll variability driven by the contrasting organomineral N rates. These results are consistent with the phenological window identified by Silva et al. (2025), who reported that multispectral VIs such as GNDVI, GN, and TCARI showed the strongest correlations with leaf N content in corn at vegetative stages V6-V11 and at the reproductive R1 stage, precisely the periods of maximum N demand and active remobilization.

The use of RFE for variable selection from the pool of 56 VIs was critical to reducing model dimensionality and retaining only the most informative spectral predictors, mitigating overfitting in the relatively small experimental dataset structured around LOOCV. The Bayesian hyperparameter optimization further ensured that RF model configurations were tailored to each phenological stage, improving generalization. These methodological choices align with best practices identified in recent literature on UAV-based N estimation in cereals (Osco et al., 2020; Lee et al., 2020), and extend their application to the specific context of organomineral fertilization in irrigated corn production systems in Brazil.

Conclusion

The Random Forest models associated with multispectral UAV imagery demonstrated strong potential for estimating leaf nitrogen in corn under organomineral fertilization. Predictive performance was highest at the V7-V8 and R3 phenological stages. The proposed framework, combining RFE variable selection, LOOCV, and Bayesian optimization, proved effective for processing 56 vegetation indices and extracting the most informative spectral predictors across the crop cycle, supporting its application as a non-destructive tool for in-season nitrogen monitoring in irrigated corn production.

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