Evaluating Sentinel-2 vegetation indices for estimating corn nitrogen content and above ground biomass

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Abstract.

Nitrogen (N) fertilization plays a crucial role in corn production in the United States. Corn, being a major commodity crop, relies heavily on N fertilization throughout its growth cycle to achieve optimal yields and maintain profitability. During this period of rapid N uptake, it's imperative for farmers to supply sufficient N at the right time to support proper crop development. However, the use of N fertilizer comes with environmental considerations as it can be susceptible to loss through various mechanisms like volatilization, denitrification, and leaching. Effective modern nitrogen management necessitates the careful application of nitrogen at the appropriate rate and timing, striking a balance between the corn crop's needs and environmental and economic concerns. Using hyperspectral remote sensing to monitoring corn N status has the potential to provide timely and accurate information, allowing farmers to make informed decisions about nutrient management to improve N use efficiency, reduce N losses, and mitigate environmental impacts. The objective of this research is to assess in-season corn N status using Sentinel-2 Multi Spectral Instrument (MSI) vegetation indices (VI) with ground truth biomass and N contents data to establish the reliability and efficacy of RS approaches for N management. Three site-year corn (Zea mays L.) in Alabama commercial farms in 2022 and 2023 were used for this study. Plant tissue samples were collected at vegetation stage (V5-V7), tasseling / silking (R1), and at maturity (R6) for total nitrogen content analysis at multiple locations. Seventeen Sentinel-2 vegetation indices were evaluated for their performance in estimating N content. In central Alabama, the MERIS terrestrial chlorophyll index (MTCI) showed a notably strong positive correlation with crop nitrogen uptake at the V6 stage (R^2 = 0.8028). At southern site, where biomass is low, various indices, particularly those with the green band (ChlGreen and GNDVI), demonstrated strong associations with crop nitrogen uptake, exhibiting high R2 values (0.91–0.90) and low RMSE (1.38–1.45) at the corn V4 stage. With low above-ground biomass (AGB), VIs using NIR and Red bands (EVI2, MSAVI2, SAVI) exhibit higher R^2 values compared to those using Red Edge bands (MTCI, NDRE, ChlRE, CIre, SR(8a/8)). For the northern site, indices with the red edge band 8a (865 nm) showed R2 values above 0.5 and low RMSE. The results indicate the potential of using derived N distribution maps for site-specific corn nutrient management. The study confirmed that Sentinel-2 vegetation indices could rapidly return valuable information, with three red edge bands (705 nm, 740 nm, and 865 nm) *explaining the most variability. This information can be used to calibrate and validate agro-ecosystem models at multiple scales.*

Keywords.
remote sensing, precision agriculture, plant nitrogen, corn.

Introduction

As the global population continues to rise, the importance of optimizing maize production methods becomes increasingly paramount to meet the expanding demand for food. Corn (Zea Mays), stands as one of the world's most crucial cereal crops, serving as a staple food for millions while also contributing significantly to animal feed, biofuel production, and various industrial applications. However, ensuring the sustainability and productivity of maize cultivation poses multifaceted challenges, particularly in the context of nutrient management. Fertilizer, a fundamental component of modern agricultural practices, plays a pivotal role in enhancing crop productivity by replenishing essential nutrients in the soil (Scharf, et al., 2022). Among these nutrients, nitrogen (N) stands as a cornerstone for plant growth, development, and yield formation (White & Brown, 2010).

During the vegetative stage, corn plants require a substantial nitrogen supply to support the growth of leaves, stems, and roots. As corn transitions into the reproductive phase, the distribution of nitrogen shifts to prioritize the development of ears and kernels. Over-application of nitrogen fertilizers not only places financial burdens on farmers but also leads to nutrient runoff, soil acidification, and greenhouse gas emissions, posing significant threats to environmental sustainability and human health (Sutton et al., 2011). Conversely, insufficient nitrogen availability can result in diminished crop yields, jeopardizing food security and economic livelihoods. Inadequate nitrogen supply impedes the plant's metabolic processes, stunts growth, and reduces yield potential. Farmers confront the difficult challenge of navigating intricate agronomic decisions, encompassing the timing, rate, and method of nitrogen application, to optimize nutrient utilization efficiently while mitigating adverse environmental consequences. Moreover, the dynamic nature of nitrogen cycling in agroecosystems, influenced by soil properties, weather conditions, cropping systems, and management practices, underscores the need for adaptive and responsive nitrogen management strategies tailored to specific agro-climatic conditions and cropping contexts. Consequently, there is a crucial need for timely and efficient methods or tools to help farmers implement site- or field-specific nitrogen management strategies throughout the crop's growth period.

In recent years, technological advancements have revolutionized the field of agricultural monitoring and management, offering innovative solutions to address the challenges of nitrogen management in corn cultivation. Advancements in nondestructive estimation of crop N status have been made through the development of active crop canopy sensors such as GreenSeeker (Trimble Navigation Limited, Sunnyvale, California, USA), Crop Circle (Holland Scientific Inc., Lincoln, Nebraska, USA), and SPAD meter (Minolta Corporation, Ltd., Osaka, Japan). These active-light crop-canopy remote sensors, employed as ground-based sensing tools for in-season crop N management, possess the capability to measure spectral reflectance across the visible (VIS; 400–700 nm), near-infrared (NIR; 700–1000 nm), and red-edge (RE; 690–730 nm) portions of the electromagnetic spectrum (EMS). The combination of reflectance values from these portions in the form of Vegetation Indices (VIs) has proven effective in assessing multiple crop parameters. Several studies have successfully evaluated nitrogen requirements mid-season by pairing sensor readings with corresponding N fertilizer recommendation algorithms (Raun, et al., 2005; Sripada, et al., 2008; Dellinger, et al., 2008; Roberts, et al., 2009; Solari, et al., 2008; Solari, et al., 2010; Sharver, et al., 2011; Berker & Sawyer, 2012). These studies were conducted under control experimental condition with different Nitrogen treatment of fertilizer .

Remote sensing technologies, in particular, have emerged as powerful tools for assessing crop health, monitoring nutrient status, and optimizing agronomic practices (Mulla, 2013). Remote sensing satellites have emerged as indispensable tools, offering unparalleled insights and data for farmers and decision-makers. The integration of satellite imagery, unmanned aerial vehicles (UAVs), and ground-based sensors enables the real-time, high-resolution monitoring of crop growth, nutrient dynamics, and environmental conditions, thereby empowering farmers with actionable insights to enhance productivity, profitability, and sustainability. Furthermore, above-ground biomass (AGB) is closely correlated to grain yield (Hsiao, et al., 2009), serves as a critical indicator for monitoring crop growth stages. Various advanced remote sensing techniques, including optical spectral indices (SIs), have been developed to estimate AGB (Li, et al., 2020). However, challenges arise in corn cultivation as above-ground biomass increases rapidly after the V6 growth stage, affecting the sensitivity of red and green spectra-based indices at subsequent growth stages, especially under moderate to high biomass and high nitrogen rate conditions (Freeman, et al., 2007; Martin, et al., 2007; Mistele & Schmidhalter, 2008; Shaver, et al., 2010).

Despite the immense potential of remote sensing technologies, significant challenges remain in harnessing their full capabilities for nitrogen management in maize cultivation. The complex interplay between spectral signatures, crop physiology, and environmental factors complicates the interpretation and application of remote sensing data for nitrogen assessment. Furthermore, the scale-dependent nature of nitrogen dynamics, ranging from individual plants to entire landscapes, necessitates tailored approaches for data acquisition, processing, and analysis to ensure accuracy and reliability. The applicability of remote sensing for corn N status assessment on a broader scale, encompassing field or landscape dimensions, using satellite-based platforms, remains largely unexplored. In light of these challenges and opportunities, this study seeks to investigate the feasibility of leveraging Sentinel-2 satellite data for evaluating nitrogen status in commercial maize fields during the vegetation stage. By integrating spectral reflectance data from Sentinel-2 satellites with ground-based measurements and agronomic data, this research aims to develop robust methodologies for assessing nitrogen status, optimizing nitrogen management practices, and enhancing maize productivity and sustainability. Through empirical validation, statistical analysis, and spatial modeling, this study endeavors to advance our understanding of nitrogen dynamics in maize agroecosystems and contribute to the development of evidence-based nitrogen management strategies tailored to diverse agricultural contexts.

Material and Methods

Site description

The study was conducted across three distinct commercial cornfields in Alabama spanning the years 2021 and 2022 (Fig. 1). The North Alabama site encompasses a 120-hectare field (34°43'06.5"N and 87°23'13.5"W) located within the Town Creek Watershed of the Tennessee Valley Region. Characterized by Decatur silty clay loam soil, this site features a slope variation of 0–10% and elevations ranging from 169 to 180 meters. In Central Alabama, the study area covers an 8.5-hectare field (32°25'23.7"N 85°25'03.8"W) situated in Society Hill, Lee County. Here, the predominant Malboro loamy sand soil prevails, classified as fine, kaolinitic, thermic typic Paleudults, with slopes ranging from 0% to 5.5% and elevations fluctuating between 141 and 163 meters. South Alabama is the third site, positioned in Southeast Alabama with coordinates (31°07'03"N and 86°05'32"W). The prevalent soil type in this area is Eunola Sandy Loam, characterized by fine-loamy, siliceous, semiactive, thermic Aquic Hapludults. Key soil series identified include Eunola and Alpin, both exhibiting a substantial sand content (SSURGO, 2021). The research was conducted on a 16.3-hectare corn field (31°07'03.0"N, 86°05'32.3"W). Corn cultivation occurred in the North and South Alabama fields during the 2022 growing season, while the Central Alabama field was planted in the 2023 growing season. Essential dates pertaining to management practices are elaborated in Table 1.

Field sampling and measurements

During the growing season, comprehensive sampling and measurements were conducted on above-ground corn biomass at strategic growth stages. Specifically, sampling intervals were set between 40 and 46 days after planting, aligning with the V4-V7 growth stages, tasseling/silking (R1), and maturity (R6) stages of corn development. Sampling procedures were meticulously carried out within a 4-meter buffer surrounding central GPS points, encompassing four-meter rows. Each sample underwent meticulous separation into leaves, husks, ears, and stems to facilitate accurate analysis. Subsequently, these components underwent thorough oven-drying at 70°C until a constant mass was attained.

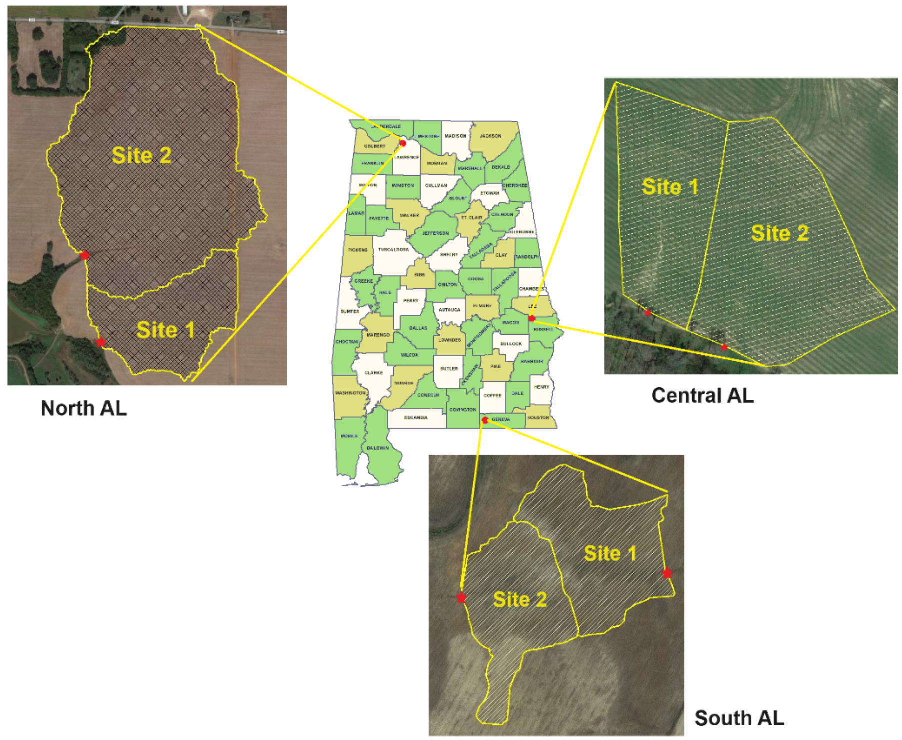


Figure 1. Location of the study area.

The total above-ground dry biomass was then converted from grams per square meter (g m^{-2}) to kilograms per hectare (kg ha^{-1}) to estimate biomass per unit area. Furthermore, for in-depth analysis, the dried crop samples underwent analysis at a reputable commercial laboratory to determine their nitrogen content. Dry matter and concentration measurements were used to compute the amount of nitrogen accumulation.

Table 1. Operating dates and growth stage of the corn for each site-year.

	North AL	South AL	Central AL
Planting	4/22/ 2022	3/6/2022	4/2023 Replanting 5/2/2023
Seeding rate	32,000	32,000	32,000
Row spacing	30	36	36
Harvest	8/25/2022	7/28/2022	9/14/2023
Corn hybrid	DK- 6916 Smart Stax	Corn Dyna Gro 58VC65	
Fertilization	Chicken litter at 2T/acre (03/28/22)		
	Urea at 420 lb/acre (05/13/22)	Urea at 30 units N (03/01/2022) Urea at 40 units N (03/31/2022) Urea at 75 units N (04/27/2022) Urea at 75 units N (05/07/2022) Potash at 210 units K (03/01/2022) DAP at 120 units P (03/01/2022)	150 units N at planting

Finally, the derivation of above-ground biomass (AGB) and nitrogen (N) uptake followed specific calculations:

Dry biomass for 1-meter row (g) = Sum (dry biomass leaf, stem) (1)

AGB (g m^{-2}) = Average (dry biomass of four 1-meter rows) * row spacing (m) (2)

$$AGB\ (kg\ ha^{-1}) = AGB\ (g\ m^{-2}) * 10 \quad (3)$$

$$N\ uptake\ (kg\ ha^{-1}) = Nitrogen\ percentage * AGB\ (g\ m^{-2}) \quad (4)$$

These rigorous methodologies ensured accurate assessment and quantification of key parameters, providing essential insights into corn growth and nutrient uptake dynamics. Temperatures and rainfall were recorded on site. GDU was computed using Eq. [5] and utilized as a time scale for AGB and N uptake. Table 2 displays the accumulated growing degree units (GDU) for each site when samples were taken.

$$GDU = (T_{min} + T_{max}) / 2 - 10 \quad (5)$$

where T_{min} is the minimum daily temperature or l0°C, whichever is larger, and T_{max} is the maximum daily temperature or 30°C, whichever is smaller.

Spectral data collection and vegetation indices calculation

The Sentinel-2 Multispectral Instrument images were obtained from the Copernicus Open Access Hub (https://scihub.copernicus.eu/). Cloud-free Sentinel-2 images were specifically selected, capturing data approximately 10 days before and after the vegetation stage sampling date. One image per site-year was chosen within this timeframe. Table 2 provides an overview of the dates when ground-based above-ground biomass (AGB) measurements and Sentinel-2 images were acquired.

Table 2. Date of sampling and selected Sentinel-2 images in the different years and location.

Site	Year	Sentinel-2 image	Field sampling date	GDD	Mazie growth stage
North AL	2022	June 11	June 1	464	V6 - V7
South AL	2022	April 19	April 21	336	V4
Central AL	2023	June 8	June 13	550	V6 - V7

To estimate corn N status and AGB, 17 Sentinel-2 Vegetation Indices (VIs) were computed. These VIs, carefully selected based on their proven efficacy in previous crop N studies, were instrumental in capturing key parameters related to vegetation health and vigor. Importantly, buffer zones ranging from 25 meters to 30 meters were established around the central GPS coordinates of field sampling points. Within ArcGIS, these buffer zones served as spatial reference points for the extraction of pixel values corresponding to different VIs.

Table 3. List of indices derived from Sentinel-2 data.

Sentinel-2 VIs	Formula	Reference
AVI	$(B8^* (1- B4)^* (B8- B4)^{-(1/3)}$	(Rikimaru, et al., 2002)
CIg	(B8/B3) - 1	(Gitelson, et al., 2003)
CIre	B5/B3-1	(Gitelson, et al., 2003)
Chlgreen	$(B7/ B3,-1)^{-1}$	
Chlred	$(B7/ B5 ,-1)^{-1}$	
EVI	2.5 * (B8 - B4) / ((B8 + 6.0 * B4 - 7.5 * B2) + 1.0)	(Huete, et al., 2002)
EVI2	2.4 * (B8 - B4) / (B8 + B4 + 1.0)	(Jiang, et al., 2008)
NDVI	(B8-B4)/(B8 + B4)	(Tucker, et al., 1985)
GNDVI	(B8- B3)/ (B8+ B3)	(Gitelson, et al., 1996)
SR	Simple ratio SR(B6/B8) = (B6/B8) SR(8a/8)= (B8a/B8)	(Jordan, 1969)
MTCI	(B7-B5)/(B5-B4)	(Dash & Curran, 2004)
MCARI	[(B5-B4)-0.2×(B5-B3)]×(B5/B4)	(Daughtry, et al., 2000)
NDVIre1	(B8-B5)/(B8 + B5)	(Shoko & Mutanga, 2017)
SAVI	(B8- B4)/(B8+ B4+0.428)*(1+0.428)	(Huete, 1988)
NDRE	(B8 – B5)/(B8 + B5)	(Barnes, et al., 2000)

Following the extraction of pixel values, statistical and correlation analyses were conducted to assess the relationships between the VIs and key agronomic parameters. Specifically, the associations between the VIs and measured AGB and N uptake data were quantified, providing invaluable insights into the utility of remote sensing-derived VIs for assessing crop health and nutrient status. Through rigorous analysis and validation of remote sensing-derived parameters, this methodology facilitated a comprehensive evaluation of crop performance and nutrient status, contributing to advancements in agricultural research and management practices.

Data analysis

Data analysis encompassed several key steps to assess crop nitrogen (N) status and above-ground biomass (AGB) utilizing field sampling and spectral reflectance data processing. Firstly, crop N status was evaluated based on comprehensive field sampling and measurements. This involved gathering data on N levels from various points within commercial corn fields.
Secondly, spectral reflectance data processing was conducted to calculate a range of vegetation indices (VIs). These VIs were utilized to assess their suitability as indicators of in-season corn N status and AGB. Specifically, general linear models were employed to establish relationships between field measurements of crop N status and Sentinel-2 Vegetation Indices.
To evaluate the accuracy of the regression models based on Sentinel-2 VIs, several metrics were utilized. The Coefficient of Determination (R^2) provided insights into the proportion of variance in crop N status explained by the VIs. Additionally, the Root Mean Square Error (RMSE) was calculated to assess the magnitude of error in the predictions. Furthermore, the indices with the highest R^2, the lowest RMSE, and the lowest Coefficient of Variation (CV) were identified. These indices exhibited a stronger likelihood for accurately predicting crop status, thereby providing valuable insights into the effectiveness of remote sensing-derived VIs for monitoring crop health and nutrient status throughout the growing season

Results and discussion

Crop N status and AGB

Samples were collected at 39, 42 and 46 DAP from North, Central and South AL respectively. The highest nitrogen concentration in a corn plant was found in the vegetative stage (V5-V7) for all sites (Fig.2). However, cumulative GDD was lower at South AL than the other sites., As a result, AGB at South AL was lower than the other sites. Nitrogen percentage at rapid plant growth (V5-V7) ranges from 2.9% to 4.1% with an average of 3.7% AGB. By reproduction stage, N percentage reduces to less than 2% of AGB.

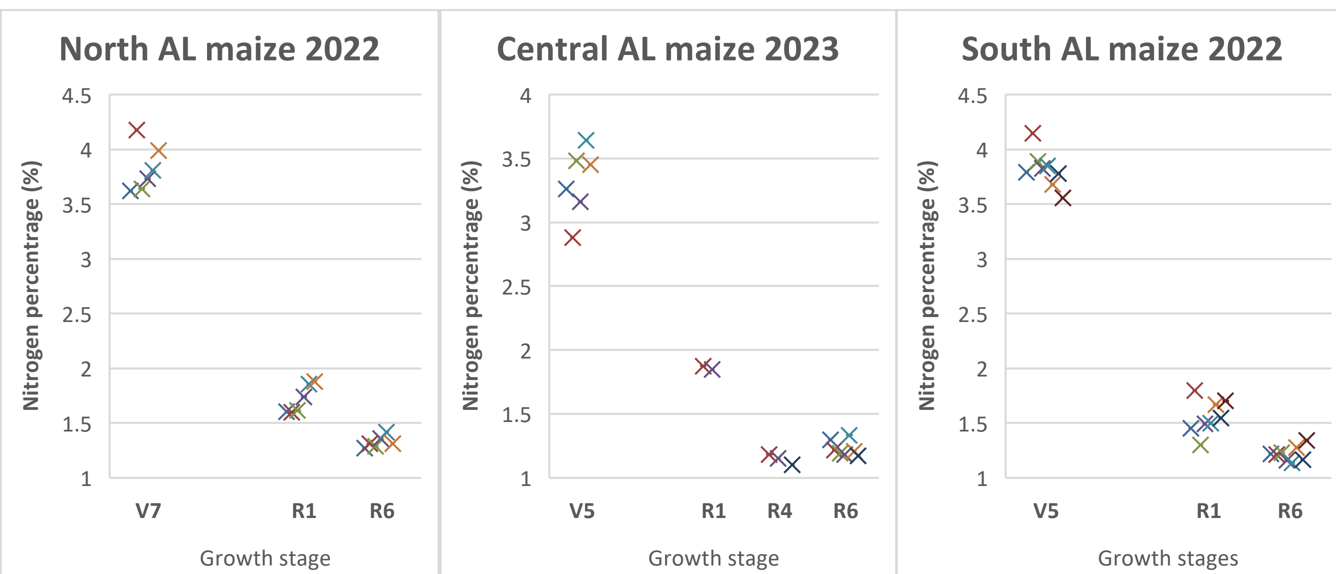


Figure 2. Nitrogen concentration measure from different growth stages.

The first step was to assess of ABG and crop N status based on field sampling and measurements. Figure 2 shows corn N content and AGB for the three site-year. Each point represents the average value, computed over sampling locations at 95% confidence intervals. The results from the SAS Tukey-Kramer Grouping for Site Least Squares Means (α=0.05) indicate that Lazenby N percentage is significant lower from the others (Fig.3). In terms of ABG, Samson

AGB is significantly different from both Lazenby and Posey. The highest nitrogen concentration in a corn plant is typically found in the vegetative stage, specifically during the rapid growth phase.

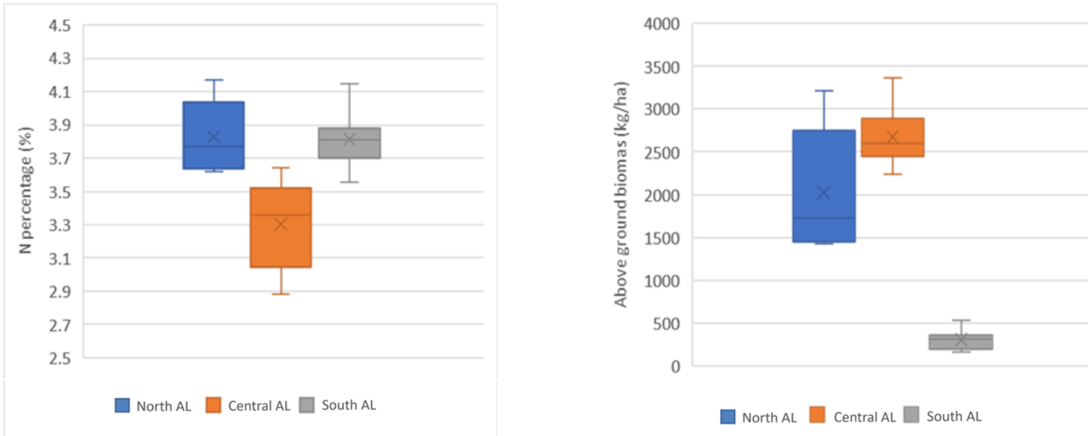


Figure 3. Plant N content and AGB average measurement at vegetation stage.

At harvesting stage, grain biomass account for 56% - 65% AGB (Fig.4). The Nitrogen Harvest Index (NHI) reflects the proportion of nitrogen harvested in the grain relative to the total nitrogen absorbed by the plant, introduced by (Moll, et al., 1982) to assesses the efficiency of nitrogen remobilization during grain filling and ripening stages. For these commercial fields, NHI ranges from 57% to 69%. The remaining of 31% - 43% uptake N stayed on the field as residue. Overall, there was no significant different of yield between fields. However, North site had higher N concentration in grain than the others, resulting the highest average NHI of 64%. Central site has higher average yield than South site but lower efficiency of remobilization (NHI of 58%).

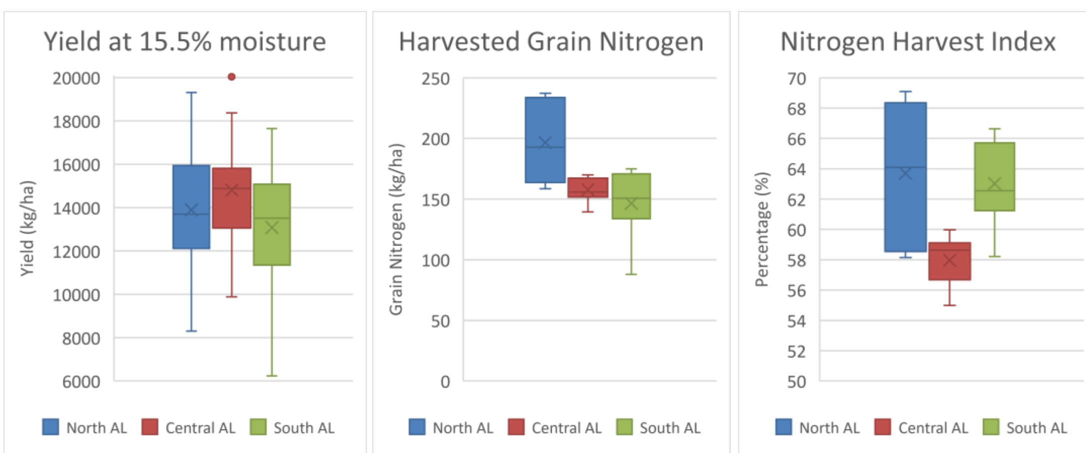


Figure 4. Yield at 15.5% grain moisture, harvested grain N and Nitrogen Harvested Index from all sites.

Evaluate goodness of fit as in-season crop status and Sentinel-2 VIs

The results of the correlation analysis between crop nitrogen uptake and various vegetation indices from remote sensing data show distinct patterns among the three sites: Central, North, and South (Fig.5).

In the Central site, the vegetation index MTCI exhibits a notably strong positive correlation with crop nitrogen uptake (R^2 = 0.8028), follow by SR(B6/B8) (R^2 = 0.6554), indicating its potential as a reliable indicator for assessing nitrogen levels in crops. Other indices, such as AVI, ChlGreen, and CIgreen, also show positive correlations, though with lower coefficients. Corn was sampling at V6 growth stage (42 DAP) with high biomass. However, this field was replanted in May, thus, upon V6 stage sampling, corn had 550 GDU resulting in higher biomass. MTCI has highest R^2 and lowest RMSE, follow by SR(6/8), then by VIs with green bands (Cigreen, GNDVI). For the North site, the correlation patterns are different. VIs with red edge band 8a (865 nm) have R^2

above 0.5 and low RMSE. These VIs display stronger positive correlations with crop nitrogen uptake. Other red edge VIs with other red edge bands (B5, B6, B7) have R^2 around 0.3. VIs without red edge bands have low correlation with N-Uptake. However, the overall model performance is lower compared to the Central site, as indicated by lower R^2 values and higher RMSE values. At South site, corn was sampling at V4 growth stage with low biomass and low GDD 336. There is a diverse range of positive correlations among various indices, with those VIs with green band (ChlGreen and GNDVI) showing particularly strong associations with crop nitrogen uptake with high R^2 (0.91 – 0.90) and low RMSE (1.38 – 1.45). The overall model performance in the South site is higher, with lower RMSE values. These variations in correlation patterns among sites highlight the site-specific nature of the relationship between vegetation indices and crop nitrogen uptake at different crop growth stage. With low biomass as at South field, VIs with NIR and Red (EVI2, MSAVI2, SAVI) have higher R^2 compare with those with Red Edge bands (MTCI, NDRE, ChlRE, Cire, SR(8a/8)). The differences observed in correlation patterns among sites emphasize the site-specific nature of the connection between vegetation indices and crop nitrogen uptake across various growth stages. Soil characteristics, climate variations, and management techniques are likely contributors to these site-specific discrepancies.

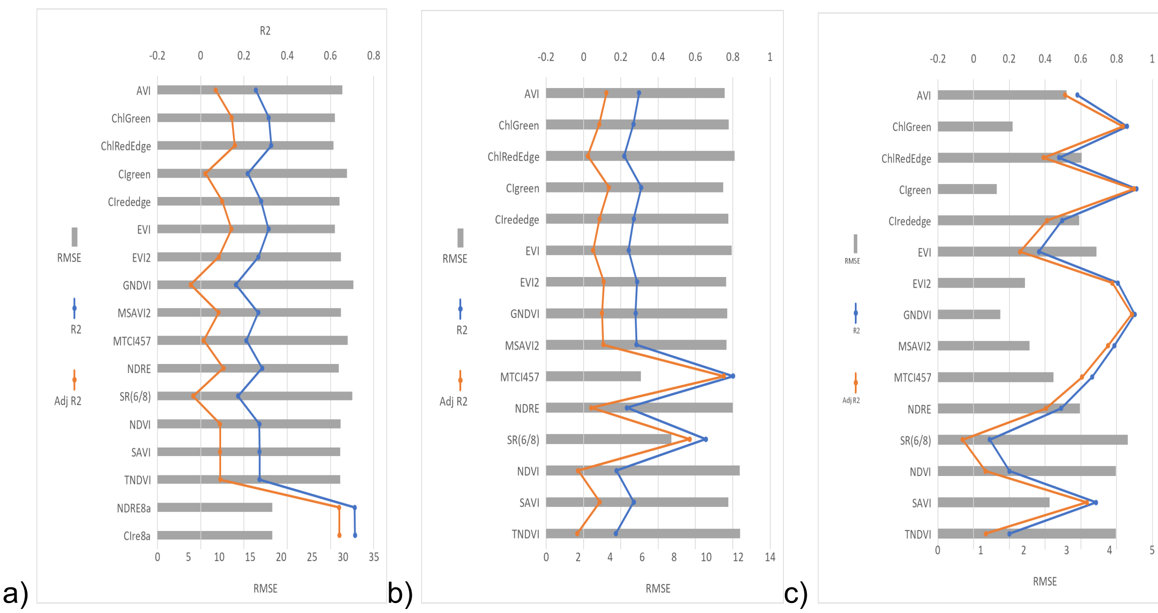
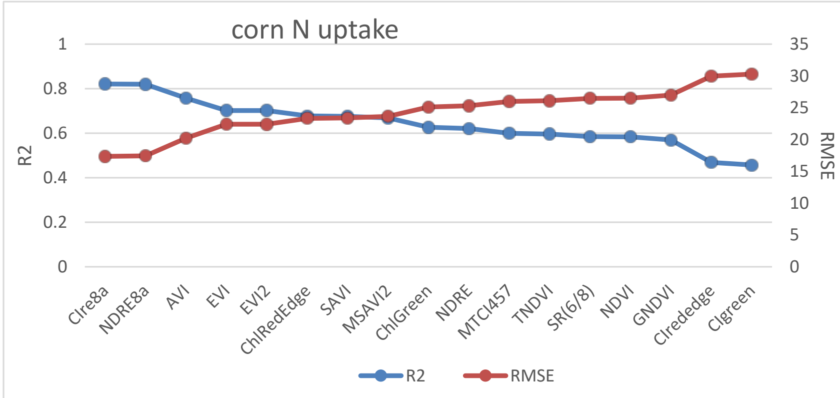


Figure 5. Performance of all indices across sites – (Corn) at earlier V stages: a) North AL, b) Central AL and c) South AL.

However, with combined all site-year data for analysis, it demonstrates strong performance indicating a robust correlation between the selected vegetation indices and the logarithm transform of crop AGB across all sites-year. Performance of all indices using all site data combine were shown in Figure 4. Two VIs with B8a exhibit the highest individual R^2 values (0.8219 and 0.8198 for Cire8a and NDRE8a respectively), suggesting their effectiveness as robust indicators of crop nitrogen status. Among the rest, AVI, ChlRedEdge, EVI, EVI2, and NDVI exhibit relatively higher R^2 values, ranging from 0.6267 to 0.7574. These indices contribute significantly to explaining the variance in crop nitrogen uptake, showcasing their potential as reliable indicators. These findings underscore the potential of utilizing remote sensing data and vegetation indices for accurate and efficient monitoring of crop AGB in diverse agricultural settings. The data derived from this study revealed variations in corn nitrogen concentration within the field with an average of 3.7% during the corn V4-V7 growth stage. The distinct corn nitrogen statuses observed were primarily attributable to the considerable variability in corn biomass across the different locations. This emphasizes the critical influence of biomass fluctuations on the corn nitrogen uptake at the specified growth stage. Further research and site-specific calibration can enhance the applicability and precision of such models, enabling tailored management strategies for improved crop productivity and environmental sustainability.

a) 

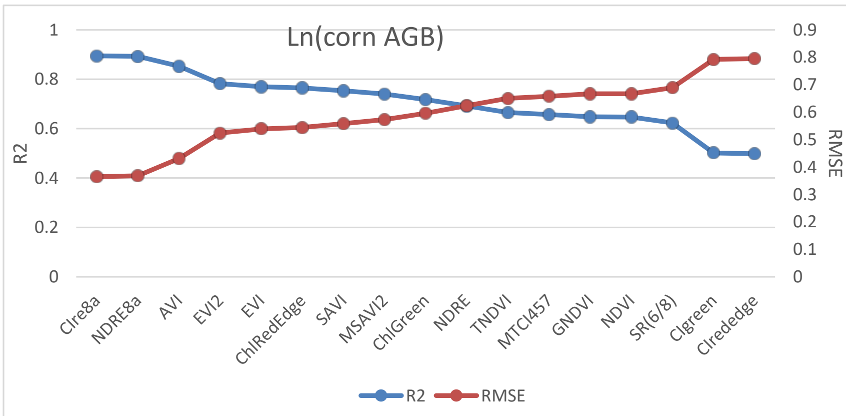
b) 

Figure 6. Performance of all indices (Corn) at earlier V stages using all site data combine.

Conclusion

This research evaluated the use of Sentinel-2 imagery to monitoring corn in commercial field in AL. Multiple VIs derived from Sentinel-2 imagery during growing season were compared in studying aboveground biomass (AGB) and N content. Overall, three red edge bands from Sentinel-2 explained the most AGB variability: 705 nm, 740 nm, and 865 nm. (Marshall & Thenkabail, 2015) also demonstrated the importance of the red-edge (700–740 nm) in crop biomass estimation. Most importantly, the Sentinel-2 vegetation indices can be used to return rapidly, estimates of crop AGB over large areas, which in turn can be used to calibrate/validate agro-ecosystem models at multiple scales.

Effective monitoring of crops is an essential aspect of ensuring a successful harvest. This process involves a systematic and attentive observation of crop growth, health, and environmental conditions throughout the cultivation period. Monitoring allows farmers to detect early signs of potential issues such as pest infestations, diseases, or nutrient deficiencies. For commercial agriculture fields, satellites offer cost-effective access to spatial and temporal information throughout the growing season. This enables the capture of crop status and spatial heterogeneity, providing valuable insights for efficient monitoring and management. As we continue to advance in satellite technology, the potential for further innovations and contributions to global food security remains vast. Embracing these advancements will undoubtedly shape the future of agriculture, ensuring a more resilient, productive, and sustainable food production system. By utilizing various tools and techniques, including advanced technologies like remote sensing and precision agriculture, farmers can gather valuable data for farm management (Hank, et al., 2019). This information enables informed decision-making, timely intervention, and the implementation of optimal agricultural practices. This proactive monitoring strategy ensures that there are no detrimental effects that could compromise the overall performance and quality of the final agricultural products.

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