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Evaluating a Satellite Remote Sensing and Calibration Strip-based Precision Nitrogen Management Strategy for Maize in Minnesota and Indiana

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Abstract.

Precision nitrogen (N) management (PNM) aims to match N supply with crop N demand in both space and time and has the potential to bring agronomic, economic, and environmental benefits. A remote sensing and calibration strip-based PNM technology (RS-CS-PNM) has been developed by the Precision Agriculture Center at the University of Minnesota. The objective of this research was to evaluate the benefits of this RS-CS-PNM technology under on-farm conditions compared with farmer's normal practice (FNP). Commercial fields in Minnesota and Indiana, USA were selected in 2021. A series of preplant N rate strips were set up based on the farmer's total N rate (FNR). Nitrogen rates included 35, 35, 70, and 100% FNR, with 3-5 replications depending on the field size, with the 130% FNR strip regarded as an N-rich strip. Strips were further delineated into smaller sections (grids) ranging from 45 to 60 m long by the original strip width. Adjacent grids that represented the range of all preplant N treatments were considered as one transect. For the RS-CS-PNM technology, normalized difference vegetation index (NDVI) was calculated from PlanetScope images (3 m resolution) around the V7-V9 corn stage. Response curves were created with NDVI and the applied preplant N rates for each

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transect. Then, the sidedress N rate for the 35% and 70% FNR treatments were determined for each grid from the transect-specific agronomic optimal N rate (AONR). The sidedress N rate for one of the two 35% FNR strips in each replication was determined by the commercially available Granular Nitrogen Management functionality powered by the Granular Crop Model (GCM) in Granular Insights software. The results suggested the RS-CS-PNM technology achieved higher grain yield and net economic return than the FNP despite lower N application rates for both fields in Minnesota and Indiana. The RS-CS-PNM and GCM strategies resulted in significantly higher partial factor productivity rates than FNP. The GCM statistically yielded a higher residual nitrate-N rate at harvest. Further analysis and on-farm trials under different weather and field conditions are required to evaluate the potential of PNM technology for the agronomic, economic, and environmental benefits

Keywords.
Precision nitrogen management, Satellite remote sensing, grain yield, Nitrogen use efficiency, Economic returns, Soil nitrate-nitrogen, On-farm trial.

Introduction

Improper management of nitrogen (N) fertilizers in the cropping systems of the United States Midwest has resulted in significant N leaching and pollution in the hydrosphere. Maize cropping systems have been identified as one of the dominant non-point sources of nitrate loads (Dinnes et al. 2002; Hussain et al. 2019). Precision agriculture contributes to better management of farm inputs by doing the right management practice at the right place and the right time (Mulla 2013). Precision nitrogen management (PNM) aims to match N supply with crop N demand in both space and time and has the potential to improve N use efficiency (NUE), increase farmer profitability, and reduce N losses and negative environmental impacts. However, the current PNM adoption rate is still quite low. One reason is that some PNM technologies require growers to provide historical yield and field management data which might not be available for some growers. The Precision Agriculture Center at the University of Minnesota has developed a remote sensing and calibration strip-based PNM (RS-CS-PNM) technology, which does not require historical data and can provide in-season N recommendation rates. Remote sensing has been proven to be effective for quantitative estimation and spatial variation identification of different canopy crop variables, including N status (Liu et al. 2010). Vegetative indices derived from aerial imagery have been used to assess field variability and crop responses throughout the growing season, which is key for management decisions and interventions (Hatfield et al. 2019).

The objective of this research was to systematically evaluate this RS-CS-PNM technology under diverse on-farm conditions in terms of maize yield, NUE, economic returns, and environmental impact compared with farmer's normal practice (FNP) and a commercially available crop growth model-based N management technology as in-season N strategy. (Main body text uses Normal style)

Materials and Methods

Study design

Commercial fields in Minnesota and Indiana, United States, were selected in 2021 for this study (Figure 1). The field in Minnesota (60 ha) was irrigated by a pivot system for water supply, while the field in Indiana (10 ha) was rainfed. A series of N rate strips across each field were set up before planting based on the total N rate a farmer conventionally applies (FNR) in a field during a growing season. Nitrogen rates included 35% FNR, 70% FNR, 100% FNR, and 130% FNR, with 3-5 replications depending on the field size. The 130% FNR strip can be regarded as an N rich strip. The 35% FNR was duplicated in each replication with the objective to compare the RS-CS-PNM technology with a commercially available crop growth model-based N management software developed by Pioneer (later Corteva) and implemented by Granular. Each strip dimension was equal to the farmer's fertilizer applicator's width by the length of the field. For sidedress N application purposes, the strips were further delineated into smaller sections (grids) ranging from 45 to 60 m long by the original width of the strip. Within each replication, adjacent grids that represented the range of all preplant N treatments (35, 70, 100 and 130% FNR) were considered as one transect. In the Minnesota field trial, some of the transects were set as "reference", which were designed to receive no sidedress N for evaluation purposes.

For the RS-CS-PNM technology, normalized difference vegetation index (NDVI) needs to be calculated from aerial images for each grid at V7-V9 growth stages. PlanetScope satellite imagery (Planet Labs, San Francisco, CA, USA) was chosen to derive NDVI maps because this commercial satellite platform offers daily multispectral imagery for any location in the world (Planet Team, 2018). The spatial resolution of the satellite data is 3 m and contains four bands, blue (B): 455–515 nm; green (G): 500–590 nm; red (R): 590–670; and near-infrared (NIR): 780–860 nm. Response curves were created with NDVI as a proxy of yield (dependent variable, y-axis) and the applied preplant N rates for each block (independent variable, x-axis) to determine the transect-specific agronomic optimal N rate (AONR). The sidedress N rate was determined for each grid by deducting the preplant N rate (35% and 70% FNR) from the transect-specific AONR.

The commercially available crop growth model-based N management technology, referred to as Granular crop model (GCM) from now on, was used to determine the sidedress N application rates for one of the two 35% FNR strips in each replication. GCM is a mechanistic, daily time-step crop growth model that simulates both the above- and below-ground physical, chemical, and biological sub-processes found in a field of maize. Developed by Pioneer (later Corteva) and implemented by Granular (the digital arm of Corteva) for N management, GCM utilizes weather, soils, management, and genetics information to simulate possible agronomic outcomes. As daily weather is fed into GCM, multiple sub processes are run to generate estimates, including soil moisture and temperature, nitrification, leaching, denitrification, volatilization, mineralization, root development, plant water, N uptake, plant biomass development, and yield. Soil information drives water availability, mineralization of organic matter, and affects soil temperature. Management inputs include seeding rate, timing, and density, along with N applications (rates, dates, N forms, and application methods). Genetic input parameters include vegetative and reproductive coefficients to denote different maize maturities, along with individual variety characteristics. GCM is used in the advisor-facing Granular N Management functionality of the Granular Insights software.

Yield data preparation and economic return calculation

Yield data were initially cleaned based on moisture content, travel speed, and location of the data within a grid. First, all yield data with moisture sensor readings that exceed 33% or fall below 10% (Luck et al. 2015). Second, data with travel speed less than 0.3 m/s or larger than 3.7 m/s was also removed. Third, data points in which the combine had a sudden change of speed 15% faster or slower than the previous point were excluded from our analysis. The moisture content recorded by a yield monitor was then used to adjust the yield mass weight based on 15% moisture content (Kleinjan et al. 2002). Fourth, any points outside three standard deviations from the average yield were deleted for each strip (Cummings et al. 2021). Last, only data within a grid 15.2 m (50 ft) away from both edges of each grid was used for our analysis to avoid areas with a lag in fertilizer application. The cleaned yield data (kg/ha) and total N applied (kg/ha) were used to calculate the partial factor productivity (PFP, kg grain/ kg N). Economic net return ($/ha) was calculated for each grid by the following formula:

$$Economic\ net\ return\ (\$/ha) = yield\ (kg/ha) * maize\ price\ (\$/kg\ grain) - total\ nitrogen\ applied\ (kg/ha) * fertilizer\ cost\ (\$/kg) - sidedress\ application\ cost\ (\$) \tag{1}$$

Soil residual nitrate-nitrogen

For the Minnesota field trial, soil samples from 0- to 15- and 15- to 60-cm depths were collected twice during a growing season for each treatment. The first sampling campaign took place in July at the reference transects where sidedress N was not applied. The second sampling campaign was conducted before harvest in October from transects where sidedress N was applied. The specific sampling locations were determined based on management zones, which were delineated based on soil types and topographic features. Soil nitrate-N was extracted by 0.01 M CaSO4 solution and measured on a Lachat Quikchem 8500 Flow Injection Analyzer after soil was air dried and passed through a 2 mm sieve (Gelderman and Beegle 2015; Henriksen and Selmer-Olsen 1970; Willis and Gentry 1987).

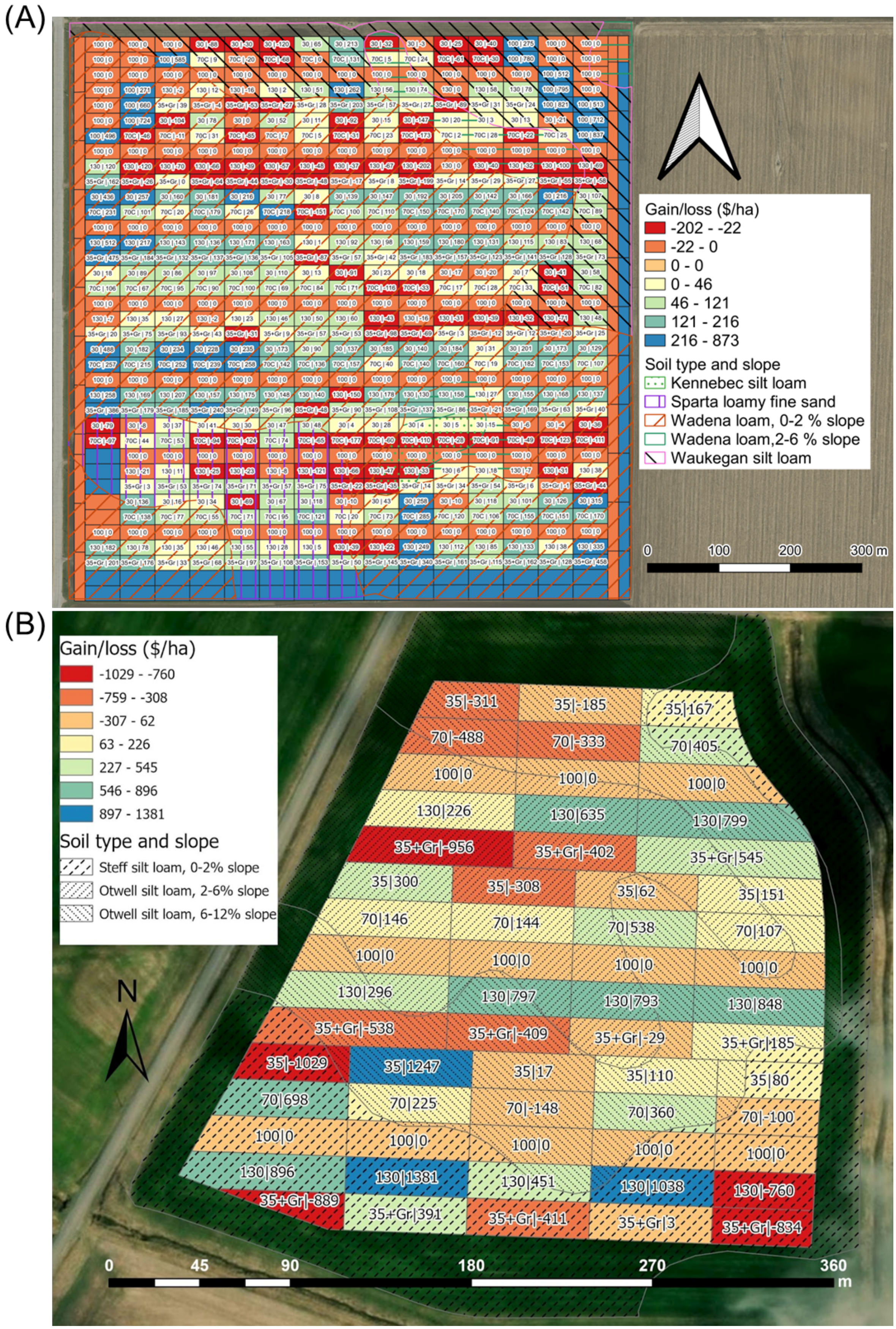

Figure 1. Spatial distribution of the study design, information of soil and topography, and economic gain/loss ($/ha) based on the net return of 100% FNR within a transect for Field A (A) in Minnesota and Field B (B) in Indiana. Note that 35 or 35+Gr is 35% FNR preplant followed by sidedress N derived from calibration strip model (+CS) or Granular's model. The numbers 70, 100, and 130 mean 70% FNR+CS, 100% FNR, and 130% FNR, respectively.

Statistical analysis

Conover's all-pairs rank comparison test was chosen to perform and analyze any statistical differences in yield, net return, PFP, and soil nitrate-N among treatments, considering the different numbers of grids (sample sizes) available for each treatment. The method was employed using the PMCMRplus package in R software (Ver. 4.1.0) based on a 90% confidence level.

Results and discussion

Evaluation of agronomic and economic benefits

Table 1 summarizes the agronomic and economic benefits of the RS-CS-PNM and GCM technology compared to the farmer's normal practice "FNP" (i.e., uniform applications of 100% FNR). Overall, the RS-CS-PNM (30% FNR+CS and 70% FNR+CS) strips showed higher grain yield and economic return than FNP for both fields in Minnesota and Indiana. Weather conditions in 2021 were favorable for Indiana, which contributed to a record-high corn yield in that year (USDA 2021). The RS-CS-PNM technology for both fields achieved net returns roughly $200/ha higher than FNP, although there were no statistical differences. The GCM technology also resulted in a higher grain yield and net return for Field A (Minnesota). The split application itself adds additional costs (USD 24.7/ha), but the strategy has the potential to reduce the excessive amount of N applied that is leached into aquifers. Our study shows that the result of PFPs for both RS-CS-PNM and GCM technologies were higher than the one of the uniform applications (FNP and 130% FNR) (Table 2), which suggests the improvement of N use efficiency by matching N supply with crop N demand in both space and time.

Table 1. Summary of on-farm nitrogen trials results for Minnesota (Field A) and Indiana (Field B) in 2021.

Field	N application strategy	Total N rate	Grain yield		Urea/UAN32 cost for preplant cost	Urea/UAN32 for sidedress cost	Net return[2]		Profit
		kg/ha	kg/ha*		---------------------$/ha----------------------------		*		rank
Field A, MN	35% FNR + CS	225	15,606	*a*	$227	$207	$4,395	*a*	1
	70% FNR + CS	293	15,751	*a*	$454	$136	$4,287	*a*	3
	100% FNR[1]	315	14,309	*a*	$643	$0	$3,807	*a*	5
	130% FNR	398	16,393	*a*	$833	$0	$4,266	*a*	4
	35% FNR + Granular	234	15,399	*a*	$228	$226	$4,311	*a*	2
Field B, IN	35% FNR + CS	158	15,761	a	$162	$139	$4,577	b	2
	70% FNR + CS	172	15,776	a	$321	$13	$4,549	b	3
	100% FNR[1]	225	15,480	a	$458	$0	$4,357	b	4
	130% FNR	282	18,400	b	$595	$0	$5,127	a	1
	35% FNR + Granular	147	14,227	a	$162	$112	$4,127	b	5

*Letters designate significant differences for all-pairs comparisons in a one-factorial layout with non-normally distributed residuals at the 90% confidence level.

[1]FNR: The total nitrogen rate the farmer normally applies for Field A was 263 N lb/ac under a maize-maize rotation. Ammonium sulfate of 67 kg/ha (14 kg N/ha) was uniformly applied at preplant and sidedress for Field A.

[2]Maize price: $0.3/kg; Urea $2.3/kg N; UAN28 $2.4/ kg N; UAN32 $2.4/ kg N

Table 2. Partial factor productivity (PFP) by treatment for Field A in Minnesota and Field B in Indiana.

Treatment	PFP (kg grain/ kg N)	
	Field A *	Field B *
35% FNR + CS	63.2 a	40.3 a
70% FNR + CS	49.2 b	37.5 a
100% FNR[1]	40.4 b	27.8 b
130% FNR	36.7 b	26.4 b
35% FNR + Granular	58.8 a	40.0 a

*Letters designate significant differences for all-pairs comparisons in a one-factorial layout with non-normally distributed residuals at the 90% confidence level.

Spatial evaluation of RS-CS-PNM performance

No statistical differences were overall found in grain yield or economic net return among treatments; however, the spatial distribution of economic gain/loss by different treatments was observed across the fields where RS-CS-PNM and GCM technologies outperformed/ underperformed FNP and 130% FNR (Figure 1). Site-specific field conditions, such as soil organic matter (SOM) content, may govern the agronomic and economic benefits of RS-CS-PNM and/or GCM technologies due to soil N mineralization supplying an additional source of N.

Evaluation of environmental benefits

Greater soil nitrate-N residuals were found in the precision application of split application treatments (30% FNR+CS and 70% FNR+CS) than uniform application treatments (100 and 130% FNR), especially 35% FNR + Granular for Field A (Figure 2).

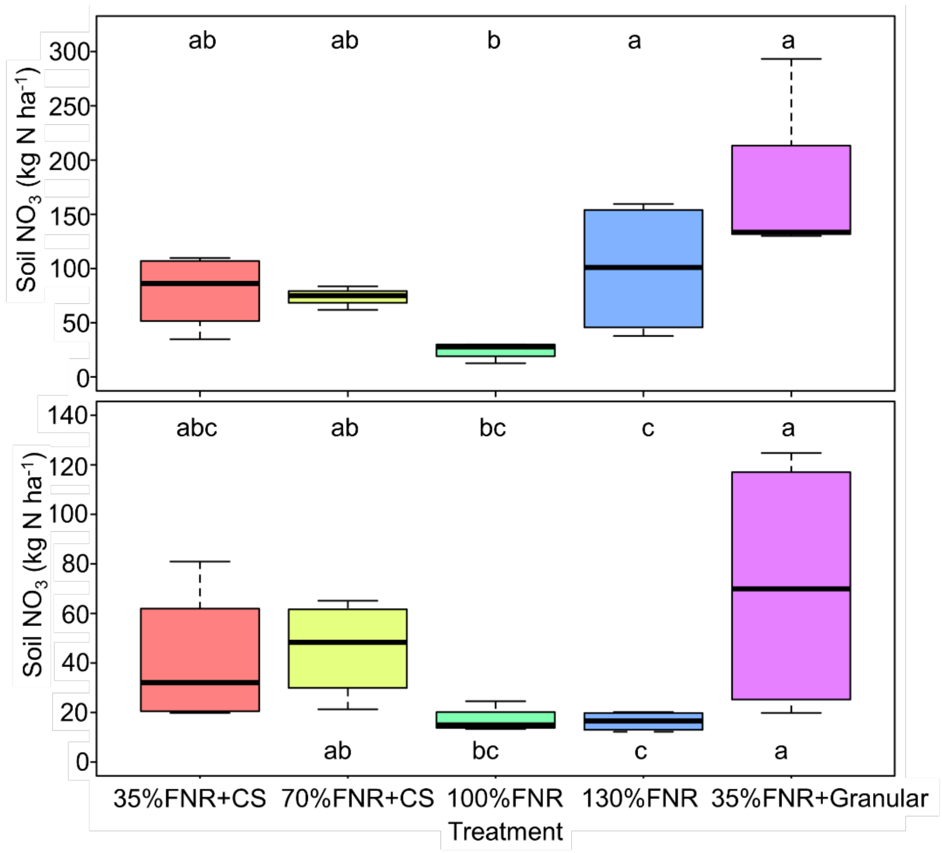

Figure 2. Soil NO3–N (lb N/ac) in the 0-to 60-cm depth in July (A) and October (B).

In addition to the PFP results (Table 2), the differences in soil nitrate-N residuals among treatments indicate that the RS-CS-PNM and GCM technologies were efficient in N application by matching N supply with crop N demand despite the heterogeneity of soil conditions in both space and time.

Precision application of split application has a low risk of N leaching for unexpected weather events (e.g., drought, rainstorms) by adjusting in-season N application, compared to a uniform application. Our results were consistent with the previous finding by Davies et al (2020) that the split application can increase maize grain yield, agronomic efficiency that can be regarded as a short-term indicator of economic return, and positive environmental impact by enhancing the efficiency of applied N.

Our study also revealed potential factors that affect the economic benefit of RS-CS-PNM technology, which include but are not limited to field conditions (e.g., soil organic matter content) and management (e.g., irrigation system, optimum level of FNR), weather conditions, and price of maize and fertilizers (Clark et al. 2019). For example, a higher price of fertilizer would reveal the significant level of economic benefit using RS-CS-PNM because the price would derive a multiplicative impact on the economic returns by the amount of N applied, as seen in Equation (1). The accuracy of the optimum level of FNR provided by a grower is another crucial factor. When FNR is greatly lower than the economic optimum N rate and the use of RS-CS-PNM technology further limits the amount of N applied, the optimum level of maize yield and economic return may not be achieved. This may be the reason why 130% FNR treatment for the Indiana field trial (Table 1) showed the highest grain yield and net return. Soil and weather data would also be the key factors to be considered in RS-CS-PNM technology because N mineralization rate driven by those factors may turn into another N source for crop and affect the outcomes of the technology (Clark et al. 2019; Oberle and Keeney 1990; Spackman et al. 2019). The spatial distribution of those factors related to growing environment together with grower's choice on FNR and maize hybrid can then be used to estimate a range of site-specific in-season N application rate for agronomic, economic, and environmental benefits.

Conclusions

The use of RS-CS-PNM and GCM revealed a great potential to optimize the in-season N application rate based on crop responses detected by remote sensing data. Spatial variability of the best management practices were observed, probably due to various field characteristics of soil, topography, weather, fertilizer, and crop and field management. Further study on the development of RS-CS-PNM technology across different growing environments and growers' "normal" field managements is necessary to enhance the optimization of site-specific N fertilizer management for agronomic, economic, and environmental benefits.

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