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Site-Specific Evaluation of Sensor-Based Winter Wheat Nitrogen Tools via On-Farm Research

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Abstract

Crop producers face the challenge of optimizing high yields and nitrogen use efficiency (NUE) in agriculture. Enhancing NUE has been demonstrated by adopting digital agricultural technologies for site-specific nitrogen (N) management, such as remote-sensing based N recommendations for winter wheat. However, winter wheat fields are often uniformly fertilized, disregarding the variability within the fields. Uniform N applications neglect the spatial variability within fields, leading to nitrogen losses and uneven yields. Soil physical and chemical properties can affect spatial variability, influencing nitrogen dynamics. Therefore, site-specific management strategies have the potential to overcome these variabilities across different management zones. Thus, an on-farm evaluation of sensor-based N tools is needed to promote the adoption of this technology among producers. We hypothesize that sensor-based nitrogen management will enhance NUE and achieve comparable or higher grain yields than conventional grower nitrogen management. Additionally, we hypothesize that the treatments will exhibit spatial heterogeneity across management zones, reflecting variations in soil properties that affect nutrient dynamics and crop response. We aim to (a) assess the impact of soil spatial variability on the performance of sensor-based nitrogen management technologies and (b) evaluate the effect of spatial variability within delineated management zones on the comparative performance of conventional grower N management versus sensor-based N management. We utilized commercially available N tools for in-season, variable-rate nitrogen management, such as active crop canopy sensors-based technologies. During the 2020-21, 2021-22, and 2022-23 growing seasons, we executed 8 on-farm randomized strip trials comparing sensor-based N technology against the conventional grower's N management. Precision N technology showed varied performance across fields, with significant differences in five of eight site-years; three of these demonstrated higher N use efficiency with sensor-based N management. Overall, our results

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have shown that there were no significant differences in grain yield between the grower and sensor-based N management across most site-years. However, an exception was observed in site-year 4, where grower N management achieved higher yield, surpassing sensor-based management by 1089.2 kg grain ha^{-1}. Notably, this increase coincided with a higher nitrogen application rate of +15 kg N ha^{-1}. Sensor-based N management applied about 11% less nitrogen in 75% of the site-years and was 6% more efficient in 60% of them compared to grower N management. Also, one out of eight site-years presented higher partial profit (+20%) for grower N management, suggesting that the economic performance of sensor-based N management was minimally penalized despite the reduced N input. This study indicates that sensor-based N management applies less N and often achieves higher efficiency across multiple site-years. This approach could enhance wheat production efficiency and reduce environmental impacts. The lack of interaction effect between treatments and zones may indicate a need for refined zone delineation to better capture soil property heterogeneities and optimize management strategies further. Future research should utilize grid sampling, remote sensing, and electromagnetic soil mapping to capture soil variability better and refine sensor-based N management. Evaluating the cost and practicality of these methods alongside the impact of soil properties is essential for optimizing agricultural practices.

Keywords. *Site-specific management, winter wheat, precision ag, digital ag, crop canopy sensors, nitrogen management*

Introduction

Adequate nitrogen (N) fertilizer management is crucial for maximizing yield and quality in winter wheat (*Triticum aestivum*) production while minimizing environmental impacts. Insufficient N fertilization can significantly reduce yield and protein content (Fischer et al., 1993; Scharf et al., 2011). However, determining the optimal N rate remains challenging due to substantial spatial and temporal variability in soil available N and crop N demand (Cassman et al., 2002). Therefore, N recommendations that consider soil characteristics, management practices, and weather conditions can help reduce the uncertainty in estimating the economic optimum N rate (EONR) within fields and across different years (Puntel et al., 2016).

In Nebraska, existing nitrogen recommendations for winter wheat, initially published in 2002 (Blumenthal and Sander, 2002) and updated in 2009 (Hergert and Shaver, 2009), may only partially meet the needs of modern winter wheat varieties and contemporary management practices. Despite achieving high yields, low protein values in winter wheat have decreased crop value for Nebraska producers (Baker et al., 2004). During times of high fertilizer prices, farmers often reduce N inputs to cut costs, typically leading to lower protein levels (Johansson et al., 2001) and reduced grain yields (Gastal et al., 2015). For optimal protein levels in wheat, N must be managed effectively to ensure its availability during grain development.

Recent advancements in digital agricultural technologies, particularly remote-sensing tools that utilize indices like Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red Edge (NDRE), offer potential improvements in nitrogen use efficiency (NUE) through site-specific nitrogen management. Site-specific management involves adjusting agricultural practices based on localized variations within fields to optimize resource use and crop yields (Pierce and Nowak, 1999). This method maximizes efficiency by addressing the unique needs of different field zones.

These tools assess plant health and vigor by measuring how plants absorb and reflect light, providing valuable insights into crop conditions (Bajocco et al., 2022; Zhao and Qu, 2024). Delineating management zones based on soil properties can capture this within-field variability, allowing for more precise N applications. By integrating spatial autocorrelation into the clustering process through methods like MULTISPATI-PCA and fuzzy k-means clustering, management zones can be effectively delineated, thereby improving site-specific N management (Córdoba et al., 2013).

Our research aimed to assess the impact of soil spatial variability on the performance of sensor-based nitrogen management technologies and evaluate the effect of spatial variability within delineated management zones, on the comparative performance of conventional grower nitrogen management versus sensor-based nitrogen management.

Material and Methods

On-Farm Experimental site-years

Eight replicated on-farm research trials were conducted on commercial dryland winter wheat fields across Nebraska during the 2020-2021, 2021-2022, and 2022-2023 growing seasons (Figure 1). These studies aimed to evaluate the effectiveness of sensor-based technologies (Sensor-based N management) by comparing treatments in terms of grain yield, total N, NUE, and partial profit.

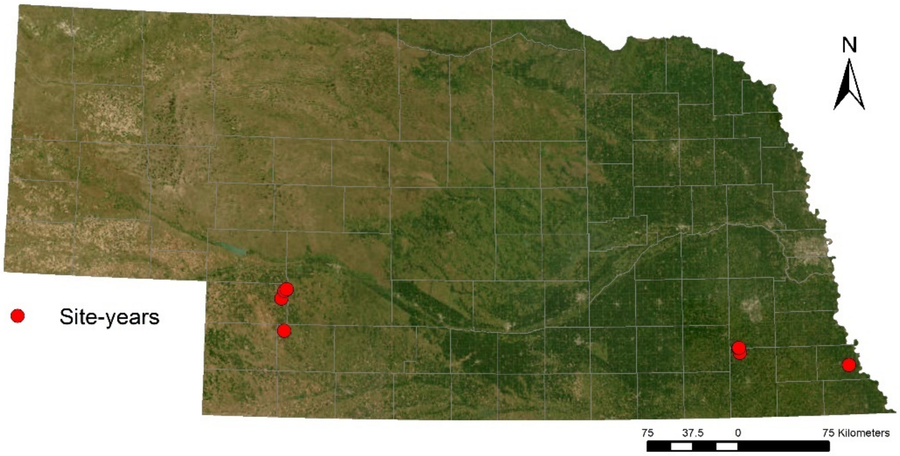

Figure 1. Map of on farm experimental trials and its spatial distribution across Nebraska. Red points represent each trial location, with some points overlapping due to proximity of trials. Grey lines delineate the county borders.

Treatments

In each site-year, two N management strategies and three management zones were compared utilizing field-length strips (

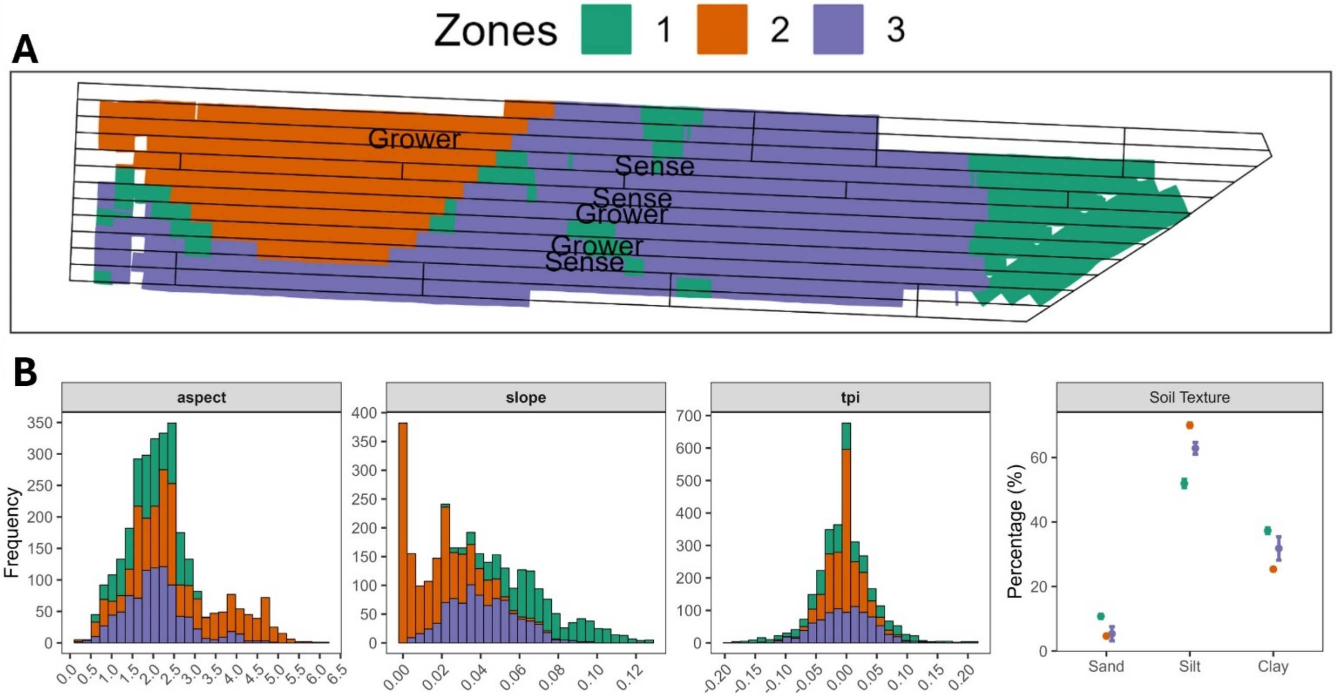

Figure 2. Management zones and soil properties' distributions in Nemaha County, Nebraska (site-year 2): A) Layout of field treatments displaying zones delineated for grower's and sensor-based N management, and predefined management zones (Zones 1, 2, and 3). B) Distribution of soil properties (aspect, slope, topographic position index (TPI), and soil texture) across different management zones.

): grower N management and Sensor-based N management. Management zones were defined based on soil properties such as aspect, slope, TPI, and texture. These zones were divided into three distinct categories, as shown in Figure 2. Treatments were located at contrasting landscape positions to capture variation in soil properties due to elevation, soil N, apparent electrical conductivity (ECa), previous crop, and soil properties.

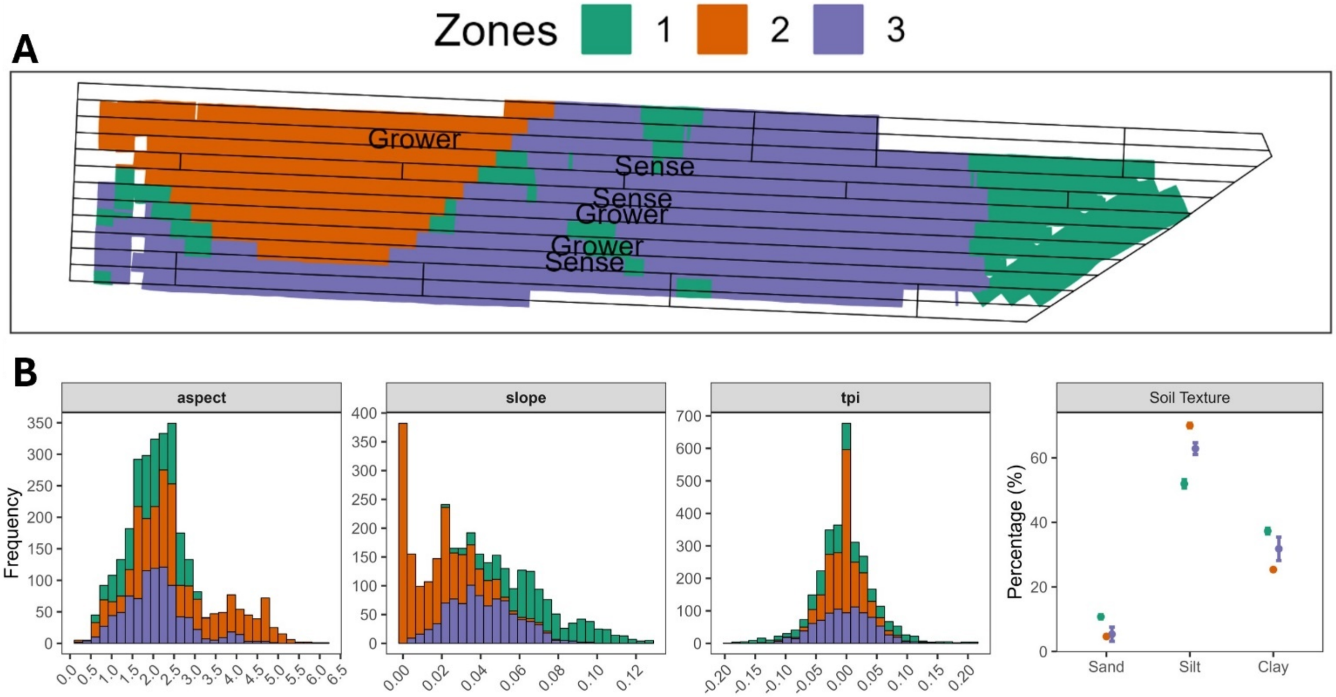

Figure 2. Management zones and soil properties' distributions in Nemaha County, Nebraska (site-year 2): A) Layout of field treatments displaying zones delineated for grower's and sensor-based N management, and predefined management zones (Zones 1, 2, and 3). B) Distribution of soil properties (aspect, slope, topographic position index (TPI), and soil texture) across different management zones.

Mixed-effects models were fitted to assess the effects of treatments and clusters on grain yield, total nitrogen, nitrogen use efficiency, and partial profit. These models were fitted for each site-year using the '*nlme'* package in R (R Core Team, 2023). In the model treatments, zones, and their interaction were designated as fixed effects, while repetition was designated as a random effect. Estimated marginal means and pairwise comparisons for the fixed effects were calculated using the '*emmeans'* package.

Grower N management:

Traditional N rates were defined from grower to grower depending on their preferences and it ranged from 58 to 162 kg N ha^{-1}. Timing applications occurred during Fall (Feekes 2-3), Spring (Feekes 4-6), or split (Fall and Spring) according to the grower's preference. The distribution of application timings across all site-years included one full Fall application (100%) and seven Split applications, with Fall contributions ranging from 25% to 58% and applications at the jointing stage ranging from 42% to 82%.

Sensor-based N management:

The sensor-based N management treatments were administered using either the OptRx sensor or the Ninja Ag platform. The OptRx sensor, mounted on a high-clearance applicator (Ag Leader®), captures and records real-time crop health data through light reflectance. It uses NDVI or NDRE algorithms to formulate nitrogen recommendations based on specified inputs such as minimum and maximum N rates, N credits, and pre-topdress fertilizer levels. Conversely, the Ninja Ag platform relies on NDVI measurements from high-resolution imagery acquired either by the Planet® SkySat satellite (0.5 m resolution) during the growing seasons. This imagery is downloaded, pre-processed, and inputted into the Ninja Ag platform to generate tailored nitrogen recommendations. In both approaches, variable-rate nitrogen application was performed using UAN (32-0-0) at the jointing stage (Feekes 6) of crop growth.

Sensor application

For all site-years, NDRE or NDVI indexes were obtained at jointing (Feekes 6), and it varied from 0 to 0.38 and the Total N target varied from 6 to 176 kg N ha^{-1} with a mean of 103 kg N ha^{-1}. For example, in site-year 2 (Figure 3), the NDRE varied between 0.09 to 0.36 with a mean of 0.162. The N target rate varied from 22 to 126 kg N ha^{-1}. Figure below shows NDRE values and its corresponding nitrogen application rates targeted for each value.

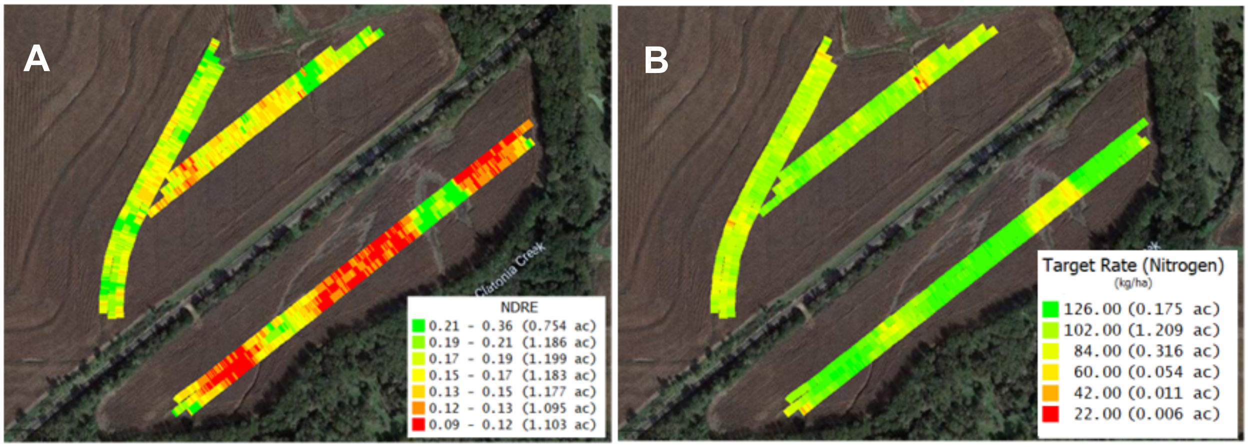

Figure 3. Example of Normalized Difference Red Edge (NDRE) values from Ag Leader® OptRx® sensors (A) and variable-rate nitrogen directed by sensors (B) from winter wheat at jointing (Feekes 6) at Gage county, Nebraska (site-year 2). Adapted from Laura Thompson, 2021, On-Farm research results (Page 108).

Zone delineation

To delineate management zones within each site-year, we selected variables that significantly influence crop growth and soil variability, including slope, aspect, and the topographic position index (TPI). These variables were extracted from the Soil Survey Geographic (SSURGO) database, which provides detailed soil and landscape information for agricultural applications.

In our analysis, a weighted mean of these variables was calculated across all observations within the dataset rather than within predefined management zones. This approach ensures a comprehensive assessment of the soil properties across each site-year, facilitating accurate zone delineation.

The clustering process to delineate the management zones was implemented using the '*paar*' package in R. The function applies the KM-sPC method (Córdoba et al., 2013), a spatial clustering analysis that incorporates spatial autocorrelation to enhance traditional principal component analysis (PCA).

This approach led to the creation of management zones and reduced variance within each class, thereby laying a solid foundation for targeted crop management practices that can better respond to site-specific conditions.

Crop measurements

The phenological stages of winter wheat were monitored using the Feekes scale (Large, 1954). At Feekes 6 growth stage, canopy reflectance was measured with the OptRx sensor (Ag

Leader®). Harvesting was performed using the grower's combine, which was equipped with yield monitors to collect data.

Total N, NUE and Partial Profit calculation

To compare the total N applied using traditional and sensor-based N management methods, data were collected from application reports (also known as "as-applied files") obtained from the variable rate equipment. NUE (kg grain kg N^{-1}) was calculated as the ratio of grain yield to the amount of nitrogen fertilizer applied, based on the following equation (Eq. 1):

$$NUE = \frac{Grain\ Yield}{Applied\ N} \qquad \text{(Eq. 1)}$$

where 'Grain Yield' (kg grain ha^{-1}) is the yield obtained from the yield monitor and 'Applied N' is the total N applied (kg N ha^{-1}). This method assesses the efficiency of nitrogen utilization in producing grain yield directly from the applied fertilizer. In addition, we calculated the partial profit by multiplying the grain yield by the grain market price minus the total N applied multiplied by the fertilizer cost (US\$ ha^{-1}; (grain yield*grain yield market price) – (total N applied*fertilizer cost)). Partial profit was based on \$0.27 kg grain $wheat^{-1}$ and \$1.43 kg N^{-1}. These metrics provided insight into the efficiency of N use in the study and helped us evaluate the impact of different N management on winter wheat productivity and profitability.

Data Analysis

Mixed-effects models were fitted to assess the effects of treatments and clusters on grain yield, total nitrogen, nitrogen use efficiency, and partial profit. These models were fitted for each site-year using the '*nlme'* package in R (R Core Team, 2023). In the model treatments, zones, and their interaction were designated as fixed effects, while repetition was designated as a random effect. Estimated marginal means and pairwise comparisons for the fixed effects were calculated using the '*emmeans'* package.

Results

Management Zones

Analysis of management zones revealed no consistent impact on grain yield, total N, NUE, or partial profit across most site-years (Table 1, Appendix). While significant effects on these variables were observed in certain site-years, these were not consistently aligned with specific management zones or treatments. Notably, the only significant interaction between treatment and zones was observed in site-year 8, specifically for Total N (Figure 8B; $p < 0.05$) and NUE (Figure 8C; $p < 0.05$), indicating a unique instance where zone delineation influenced treatment efficacy. For other variables like grain yield and partial profit, no significant interactions were detected, suggesting that management zones did not consistently capture the variability necessary for optimizing nitrogen management strategies. The SSURGO data used for delineating these zones often have a coarser spatial resolution. They may not reflect finer soil variability, which could explain the lack of consistent influence on treatment outcomes across other site-years. This limitation underscores the need for integrating more detailed and dynamically updated data sources such as grid sampling, remote sensing, and electromagnetic soil mapping to enhance the precision of management zones.

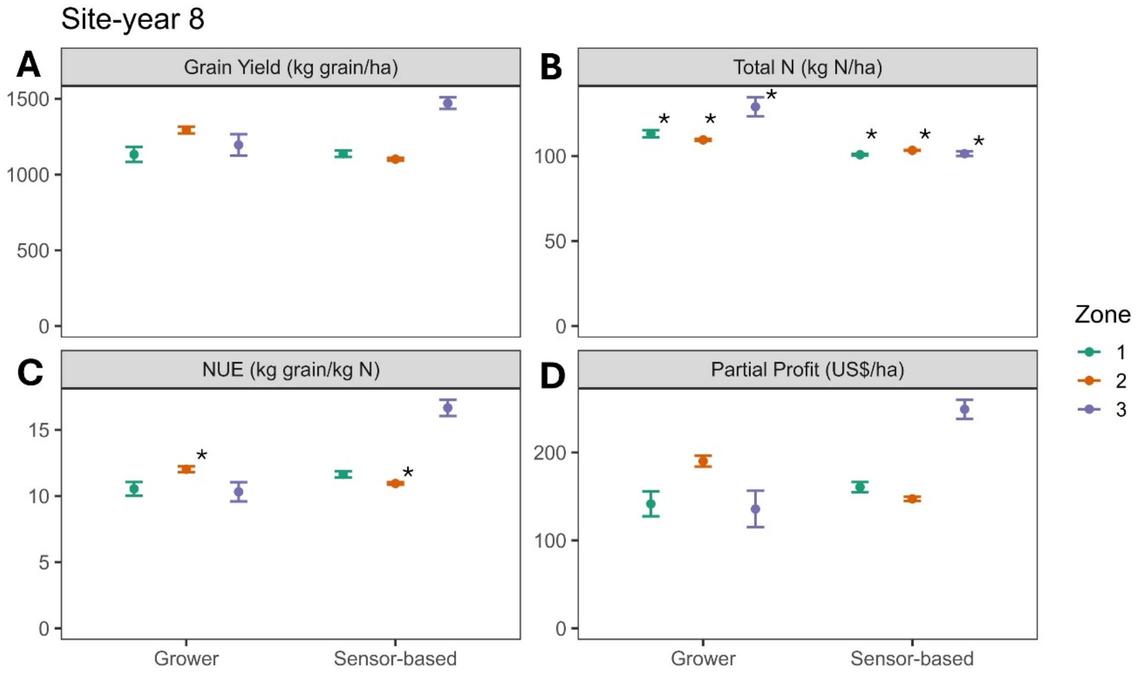

Figure 4. Grain Yield (A), Total N rate (B), NUE (C), and Partial profit (D) between Grower N management and Sensor-based N management from only site-year 8. Yield values are from cleaned monitor data expressed at 13.5% moisture. Partial profit was calculated using $0.27/kg wheat and $1.43/kg N. ANOVA was run by site. For each site, asterisk (*) indicates significant differences between treatments at 95% confidence level.

Grain yield

Grain yields ranged from 1272.1 to 8299.2 kg grain ha^{-1} with a mean of 4556.3 kg grain ha^{-1} across all site-years for Grower N management. While for Sensor-based N management, grain yield ranged from 1235.9 to 8658.8 kg grain ha^{-1} with a mean of 4460.9 kg grain ha^{-1} across all site-years. No statistically significant yield differences were observed between the treatments in seven site-years (Table 1, Appendix). In site-year 4 (Figure 5A), the Grower N management treatment had a significantly higher yield compared to the Sensor-based N management treatment, with a difference of 1089 kg grain ha^{-1} ($p < 0.01$; Table 1, Appendix). While not statistically significant on an aggregated level, analyses conducted independently across site-years revealed a consistent trend where the Grower N management treatment typically yielded slightly more (on average +35.4 kg grain ha^{-1}) than the Sensor-based N management. Regarding the management zones, their interaction with the treatments did not significantly influence the grain yield. However, in five site-years zones were statistically significant (site-years 2, 3, 4, 5, 6; Table 1, Appendix).

Total N applied

Total N ranged from 67 to 123 kg N ha^{-1} with a mean of 97 kg N ha^{-1} across all site-years for Grower N management. For Sensor-based N management, on average Total N ranged from 75 to 131 kg N ha^{-1} with a mean of 96 kg N ha^{-1} across all site-years. In six of the eight site-years, the sensor-based N management treatment recommended lower rates (on average -11 kg N ha^{-1}; Table 1, Appendix and Figure 5B). However, for the two remaining site-years (2 and 3), sensor-based N management recommended higher rates (on average +26 kg N ha^{-1}; Table 1, Appendix and Figure 5B). Additionally, the interaction between treatments and management zones had significantly affected only site-year 8 (Figure 4B) for Total N application. However, management zones were significant on site-year 3 ($p < 0.05$; Table 1, Appendix)

Nitrogen use efficiency

NUE ranged from 11.8 to 84.1 kg kg^{-1} with a mean of 48.6 kg kg^{-1} across all site-years for Grower N management. For Sensor-based N management, NUE ranged from 14.1 to 67.6 kg kg^{-1} with a mean of 47.9 kg kg^{-1} across all site-years. In two out of eight site-years (site-years 2 and 3; Table 1, Appendix and Figure 5C), the Grower N management treatment demonstrated significantly higher efficiency ($p < 0.05$; Table 1, Appendix). Conversely, site-years 1, 6 and 7 showed greater efficiency under the Sensor-based N management treatment ($p < 0.001$; Table 1, Appendix). Site-years 4, 5, 8 have shown no statistical differences in NUE ($p = 0.250$, $p = 0.125$, and $p = 0.224$, respectively; Table 1, Appendix). Furthermore, there was significant interaction between treatments and delineated management zones affecting NUE only on site-year 8 (Figure 4C). However, site-years 3, 4, and 5 presented statistical differences between zones (Table 1, Appendix).

Partial profit

Partial profit ranged from 179.65 to 2084.7 US$ ha^{-1} with a mean of 1082.8 US$ ha^{-1} across all site-years for Grower N management. For Sensor-based N management, Partial profit ranged from 188.4 to 2134.8 US$ ha^{-1} with a mean of 1059.6 US$ ha^{-1} across all site-years. In one out of eight site-years (site-year 4; Figure 5D), the Grower N management was significantly more profitable in terms of partial profit with an average difference of 272 US$ ha^{-1} ($p < 0.001$). The remaining site-years did not show statistical differences for Grower and Sensor-based N management ($p > 0.05$; Table 1, Appendix). Interactions between management zones and treatment had no significant impact on partial profits as shown in Table 1 from Appendix.

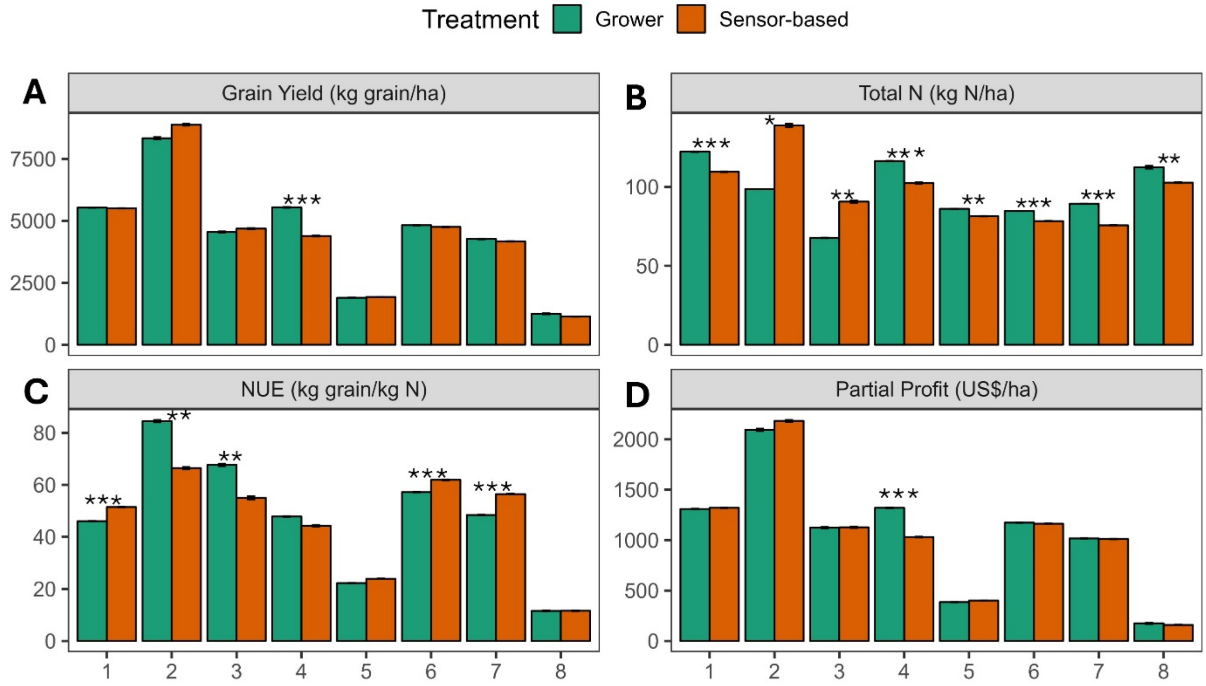

Figure 5. Grain Yield (A), Total N rate (B), NUE (C), and Partial profit (D) between Grower N management and Sensor-based N management across all site-years. Yield values are from cleaned monitor data expressed at 13.5% moisture. Partial profit was calculated using $0.27/kg wheat and $1.43 /kg N. ANOVA was run by site. For each site, asterisk (*) indicates significant differences between treatments at 95% confidence level.

Conclusion

In 75% of the site-years analyzed, sensor-based nitrogen (N) management applied approximately 11% less N while achieving similar or greater NUE (~6% more efficient) in 60% of the site-years compared to traditional grower N management. In addition, only one out of eight site-years presented higher partial profit (+20%) for grower N management, suggesting that the economic performance of sensor-based N management was minimally penalized despite the reduced nitrogen input. Although yield differences were not consistently significant, the data indicates that sensor-based N management can achieve comparable yields with reduced N input, highlighting the potential of sensor technologies to optimize N use while minimizing environmental footprints.

Although the results of this study are promising, the yield differences were not consistently significant. While SSURGO remains a valuable resource for soil property data, a finer resolution may be necessary to delineate management zones more effectively. The lack of significant interactions between treatments and management zones could be due to the coarse resolution of the SSURGO data, which may not adequately capture finer soil variability. Future analyses will aim to assess the homogeneity of the fields more accurately. These findings are pivotal for wheat growers, offering a foundation upon which to refine their nitrogen management strategies, thereby enhancing efficiency and minimizing the environmental impact of surplus N.

Future research should explore methods such as grid sampling, remote sensing, and electromagnetic soil mapping to capture soil variability better. While these approaches hold promise for aligning agricultural practices more closely with local soil conditions, their practicality and cost must also be considered in large-scale applications. Additionally, investigating factors that influence the efficacy of sensor-based N management, such as soil properties, is crucial. Understanding these dynamics has the potential to refine the application of this technology and promote its adoption, especially in fields where the return on investment might be most favorable. This strategic approach could improve the immediate effectiveness of the technology and contribute to sustainable management practices.

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Appendix

Table 1. ANOVA table summarizing the effects of treatment and zone on Grain Yield, Total Nitrogen (N), Nitrogen Use Efficiency (NUE), and Partial Profit across three different site-years. The table displays the sum of squares, mean squares, numerator degrees of freedom (Num DF), denominator degrees of freedom (Den DF), F values, and p-values for each factor and their interactions, highlighting the statistical significance of each effect. The notation 'Treatment*Zone' indicates the interaction between the treatment and zone variables, assessing whether the effect of one variable depends on the level of the other.

Grain Yield (kg grain ha^{-1})							
Site-year		Sum Sq	Mean Sq	Num DF	Den DF	F value	p-value
1	Zone	5.63	0.23	2	25	0.23	0.8
	Treatment	0.01	0.10	1	25	0.10	0.985
	Treatment*Zone	56.22	2.25	2	25	2.25	0.126
2	Zone	355.94	177.97	2	25	177.97	<0.001***
	Treatment	18.02	9.01	1	25	9.01	0.095

	Treatment*Zone	15.67	7.83	2	25	7.83	0.113
3	Zone	96.26	9.63	2	10	9.63	<0.01**
	Treatment	11.88	1.19	1	10	1.19	0.301
	Treatment*Zone	6.08	0.61	2	10	0.61	0.563
4	Zone	232.47	8.02	2	29	8.02	<0.01**
	Treatment	3612.11	124.56	1	29	124.56	<0.001***
	Treatment*Zone	13.42	0.46	2	29	0.46	0.634
5	Zone	36.45	1.46	2	25	1.46	0.252
	Treatment	6.93	0.28	1	25	0.28	0.603
	Treatment*Zone	5.08	0.2	2	25	0.2	0.817
6	Zone	12.01	0.4	2	30	0.4	0.674
	Treatment	26.63	0.89	1	30	0.89	0.354
	Treatment*Zone	0.48	0.02	2	30	0.02	0.984
7	Zone	1133.88	28.35	2	40	28.35	<0.001***
	Treatment	91.18	2.28	1	40	2.28	0.139
	Treatment*Zone	69.94	1.75	2	40	1.75	0.187
8	Zone	376.01	10.44	2	36	10.44	<0.001***
	Treatment	2.96	0.08	1	36	0.08	0.776
	Treatment*Zone	30.61	0.85	2	36	0.85	0.436
			Total N (kg N ha^{-1})				
Site-year		Sum Sq	Mean Sq	Num DF	Den DF	F value	p-value
1	Zone	66.87	2.67	2	25	2.67	0.089
	Treatment	812.51	32.5	1	25	32.5	<0.001***
	Treatment*Zone	12.37	0.49	2	25	0.49	0.616
2	Zone	0.65	0.32	2	25	0.32	0.756
	Treatment	85.53	42.77	1	25	42.77	<0.05*
	Treatment*Zone	3.61	1.8	2	25	1.8	0.357
3	Zone	70.48	7.05	2	10	7.05	<0.05*
	Treatment	181.49	18.15	1	10	18.15	<0.01**
	Treatment*Zone	10.62	1.06	2	10	1.06	0.382
4	Zone	18.82	0.65	2	29	0.65	0.53
	Treatment	1120.41	38.63	1	29	38.63	<0.001***
	Treatment*Zone	10.53	0.36	2	29	0.36	0.699
5	Zone	59.85	2.39	2	25	2.39	0.112
	Treatment	266.78	10.67	1	25	10.67	<0.01**
	Treatment*Zone	9.71	0.39	2	25	0.39	0.682
6	Zone	12.17	0.41	2	30	0.41	0.67
	Treatment	1874.18	62.47	1	30	62.47	<0.001***
	Treatment*Zone	2.63	0.09	2	30	0.09	0.916
7	Zone	46.49	1.16	2	40	1.16	0.323
	Treatment	1577.06	394.27	1	40	394.27	<0.001***
	Treatment*Zone	75.43	1.89	2	40	1.89	0.165
8	Zone	1.01	0.03	2	36	0.03	0.972
	Treatment	350.37	9.73	1	36	9.73	<0.01**
	Treatment*Zone	139.71	3.88	2	36	3.88	<0.05*

NUE (kg grain kg^{-1} N)

Site-year		Sum Sq	Mean Sq	Num DF	Den DF	F value	p-value
1	Zone	19.25	0.77	2	25	0.77	0.474
	Treatment	786.19	31.45	1	25	31.45	<0.001***
	Treatment*Zone	49.27	1.97	2	25	1.97	0.16
2	Zone	4.95	2.48	2	25	2.48	0.288
	Treatment	236.26	118.13	1	25	118.13	<0.01**
	Treatment*Zone	4.8	2.4	2	25	2.4	0.294
3	Zone	110.74	11.07	2	10	11.07	<0.01**
	Treatment	67.97	6.8	1	10	6.8	<0.05*
	Treatment*Zone	6.36	0.64	2	10	0.64	0.549
4	Zone	143.68	4.95	2	29	4.95	<0.05*
	Treatment	39.96	1.38	1	29	1.38	0.25
	Treatment*Zone	16.06	0.55	2	29	0.55	0.581
5	Zone	23.04	0.92	2	25	0.92	0.411
	Treatment	62.97	2.52	1	25	2.52	0.125
	Treatment*Zone	2.61	0.1	2	25	0.1	0.901
6	Zone	1.72	0.06	2	30	0.06	0.944
	Treatment	718.81	23.96	1	30	23.96	<0.001***
	Treatment*Zone	0.55	0.02	2	30	0.02	0.982
7	Zone	1157.05	28.93	2	40	28.93	<0.001***
	Treatment	1788.39	44.71	1	40	44.71	<0.001***
	Treatment*Zone	72.51	1.81	2	40	1.81	0.176
8	Zone	152.68	4.24	2	36	4.24	<0.05*
	Treatment	55.04	1.53	1	36	1.53	0.224
	Treatment*Zone	109.78	3.05	2	36	3.05	<0.05*

Partial Profit (US$ ha^{-1})

Site-year		Sum Sq	Mean Sq	Num DF	Den DF	F value	p-value
1	Zone	1.77	0.07	2	25	0.07	0.932
	Treatment	27.88	1.12	1	25	1.12	0.301
	Treatment*Zone	64.37	2.57	2	25	2.57	0.096
2	Zone	360.59	120.2	2	25	120.2	<0.001***
	Treatment	10.61	3.54	1	25	3.54	0.157
	Treatment*Zone	15.09	5.03	2	25	5.03	0.11
3	Zone	92.88	9.29	2	10	9.29	<0.01**
	Treatment	0.79	0.08	1	10	0.08	0.785
	Treatment*Zone	4.92	0.49	2	10	0.49	0.625
4	Zone	232.17	8.01	2	29	8.01	<0.01**
	Treatment	3130.8	107.96	1	29	107.96	<0.001***
	Treatment*Zone	13.27	0.46	2	29	0.46	0.637
5	Zone	32.86	1.31	2	25	1.31	0.287
	Treatment	15.51	0.62	1	25	0.62	0.438
	Treatment*Zone	4.47	0.18	2	25	0.18	0.837
6	Zone	10.3	0.34	2	30	0.34	0.712
	Treatment	4.6	0.15	1	30	0.15	0.698

	Treatment*Zone	0.54	0.02	2	30	0.02	0.982
7	Zone	1151.86	28.8	2	40	28.8	<0.001***
	Treatment	17.04	0.43	1	40	0.43	0.518
	Treatment*Zone	68.34	1.71	2	40	1.71	0.194
8	Zone	288.12	8	2	36	8	<0.01**
	Treatment	3.8	0.11	1	36	0.11	0.747
	Treatment*Zone	52.6	1.46	2	36	1.46	0.245