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Variable fertilizer application in wheat using remote sensors in southern Sonora, Mexico

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Abstract
The southern region of the state of Sonora is Mexico's main wheat-producing area, where fertilization represents one of the highest production costs. The use of nitrogen fertilizers, although it increases grain yield and quality, has significant environmental impacts, and its cost has risen notably in recent years. This study evaluated variable nitrogen application in wheat using remote sensors during the 2022–2023 fall–winter growing season, with the aim of optimizing input efficiency and improving crop productivity and quality. The research was conducted at CENEB-INIFAP in the Yaqui Valley, Sonora. Two experimental strips with differences in biomass were identified through satellite imagery, and different nitrogen doses were applied according to the detected biomass index. The results showed that the high-biomass and low-biomass zones responded differently to fertilization, with unfertilized yields of 5.169 and 1.749 t ha^{-1}, respectively. The economically optimal nitrogen rate was 184 kg ha^{-1} for the high-biomass zone and 322 kg ha^{-1} for the low-biomass zone. Grain protein content and the incidence of white belly improved with fertilization. This study demonstrates that variable fertilizer application based on remote sensors is an effective tool for adjusting fertilization according to crop needs, optimizing costs, increasing yield, and improving quality, while also contributing to more sustainable and environmentally friendly agricultural practices.

Keywords: Precision agriculture; Nitrogen; Variable rate application; Yield; Protein

1. Introduction
Sonora is the main wheat-producing state in Mexico. Over the past ten years, an average of 246,450 hectares have been planted, with a yield of 6.73 t ha^{-1}. In southern Sonora—comprising the municipalities of Cajeme, Navojoa, Benito Juárez, Etchojoa, Huatabampo, Bácum, San Ignacio Río Muerto, and Guaymas—90% of the wheat sown in the state was established, with an average yield of 6.67 t ha^{-1} [1]. Until the 2020–2021 growing season, fertilization was the main production cost in wheat, accounting for 25% of total expenses. However, during the 2021–2022 season fertilizer costs tripled, representing up to 45% of the crop's total production costs. Mineral fertilizers have been a key factor in increasing agricultural yields, feeding a growing population, and mitigating pressure for land-use change. At the same time, the use of nitrogen fertilizers is associated with the annual emission of 700 million tons of carbon dioxide equivalent (Gt CO_2e), along with other forms of nitrogen pollution [2]. Fertilizers have a significant impact on wheat yield, protein content, and production costs. However, the environmental impact of nitrous oxide and NH_3 emissions into the atmosphere, and nitrate leaching into aquifers and water bodies, is a major concern in the context of climate change and global warming [3]. Therefore, nitrogen optimization is crucial for both economic and ecological reasons [4]. In the United Kingdom, the government has sought to improve air quality and the environment, stating that reducing ammonia emissions is essential to achieving both goals. For this reason, in 2022 three measures related to the use of

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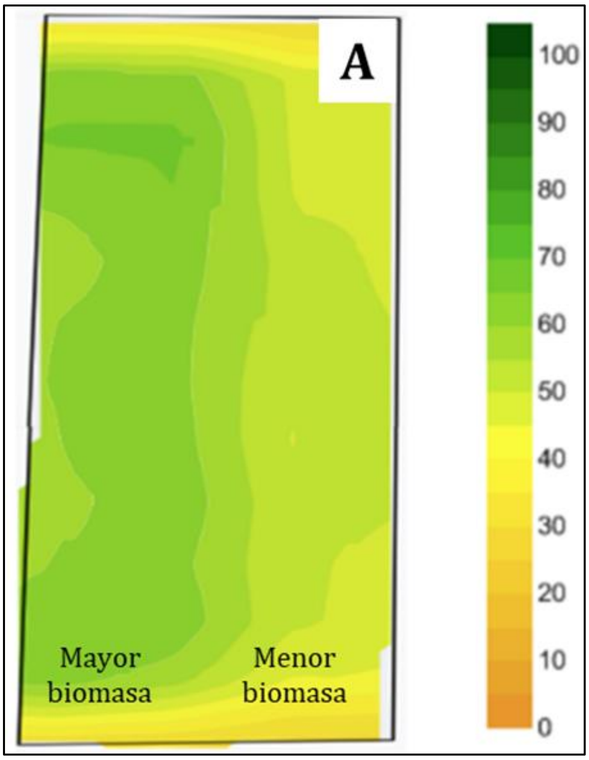
urea in agriculture were put out for consultation: (1) an outright ban; (2) a requirement to treat solid urea with urease inhibitors (UI); and (3) a restriction on applying solid urea only from January 15 to March 31 [5]. These actions illustrate the measures being taken to reduce greenhouse gas emissions.

Nitrogen is the most deficient element in the soils of this region. Wheat crops receive up to 350 units of nitrogen, and phosphorus rates range from 100 to 150 kg ha^{-1} of monoammonium phosphate. Soil analysis is a tool that is seldom used in the region, and when it is used, the recommended random sampling method for obtaining a composite sample generates a single recommendation to be applied across the entire field, without considering within-field variability—which can exceed 30% for phosphorus and 20% for nitrogen [6]. Today, satellite imagery can be used to identify zones that respond homogeneously to fertilizers, allowing the right dose to be applied in the right place. However, adoption is still limited, mainly due to the lack of variable-rate application equipment. Moreover, the magnitude of the crop response within these zones still needs to be validated, considering the timing of fertilization, the fertilizer source, application method, yield, and grain quality. The objective of this study was to evaluate the capability of remote sensors to estimate wheat yield in the Yaqui Valley, Sonora, Mexico.

2. Materials and methods

During the 2022–2023 fall–winter cycle, homogeneous response zones to nitrogen application in wheat were identified using remote sensors. The study was conducted at the Norman E. Borlaug Experimental Station (CENEB) of INIFAP, located in Block 910 of the Yaqui Valley, Sonora, at 27.36805 N and –109.92771 W, on a clay-textured soil. The site has a hot arid climate [BW(h)] with episodes of extreme heat, according to the Köppen classification modified by García [7]. Sowing took place on December 2 using the variety Don Lupe Oro 2020 [8], in furrows spaced 80 cm apart, with a seeding rate of 100 kg ha^{-1} and two plant rows spaced 30 cm apart. One pre-sowing irrigation and three supplemental irrigations were applied. The experimental field had not been fertilized during the two previous cropping cycles.

In January 2023, two experimental units were selected, each consisting of 12 furrows in width and 110 meters in length, which visually differed in wheat color and biomass. It has been reported that crop biomass is closely related to wheat grain yield [9, 10, 11 and 12]. To estimate wheat yield, processed NDVI (Normalized Difference Vegetation Index) images were obtained from Agrosat Chile [13] at 49 days after sowing, confirming that both experimental units had different biomass levels (Figure 1).



Source: (Agrosat Chile; Jan 19, 2023).

Figure 1 Wheat biomass index.

Figure 2 Visual appearance of the wheat (Jan 19, 2023). Left: high-biomass area. Right: low-biomass area

Before the first supplemental irrigation, the nitrogen treatments based on urea were broadcast-applied (Table 1). It was established that lower biomass indicated greater nitrogen deficiency; therefore, a higher nitrogen dose was applied in those areas. The first irrigation was carried out 50 days after sowing. A randomized block design with four replications per treatment was used, considering as the experimental unit four furrows, each 10 meters long. The evaluated variables included wheat aboveground biomass, from which grain yield was estimated, protein content on a dry basis and at 12% moisture, and the percentage of kernels with white belly.

Table 1 Fertilization treatments applied before the first supplementary irrigation to the zone with higher and lower biomass index. CENEB-INIFAP, Autumn–Winter 2022–2023 cycle

Treatment Number	Zone with higher biomass		Zone with lowest biomass	
	Urea kg ha^{-1}	Nitrogen kg ha^{-1}	Urea kg ha^{-1}	Nitrogen kg ha^{-1}
1	0	0	0	0
2	300	138	400	184
3	400	184	500	230
4	500	230	600	276
5	600	276	700	322

3. Results and discussion

Grain yield in the treatments without nitrogen, in the zones diagnosed as having higher and lower biomass index according to the satellite images, is reported in Table 2. A clear contrast was observed between the average grain yield obtained in both zones, 5.169 and 1.749 t ha^{-1}, respectively. The greater variability detected in the low-biomass-index zone in the satellite image was reflected in a larger variation in grain yield. This high variability confirms that traditional composite sampling does not capture the significant spatial heterogeneity of soils and crops. Similar findings have been reported in other precision agriculture studies, where field variability strongly influences crop response to fertilization and nitrogen use efficiency [14, 15].

Table 2 Description of wheat grain yield in t ha^{-1} in the treatments without fertilization in the areas of highest and lowest biomass index. CENEB-INIFAP, Autumn–Winter 2022–2023 cycle

Remote sensor diagnosis	Descriptive statistics			
	Mean	Maximum	Minimum	Range
Higher biomass index	5.169	5.649	4.629	1.020
Lower biomass index	1.749	2.049	1.522	0.527

In Figure 3 and Table 3, the results for the area with the highest biomass index are reported. Significant differences (P≤0.05) were only detected between the control and the other treatments. In the case of protein, the nitrogen-free control showed significantly lower values than the other treatments. The highest value was observed with the highest nitrogen dose. Considering a wheat price of $6,000 per ton and a nitrogen unit cost of $21.3 using urea, the economically optimal dose was 184 units of nitrogen.

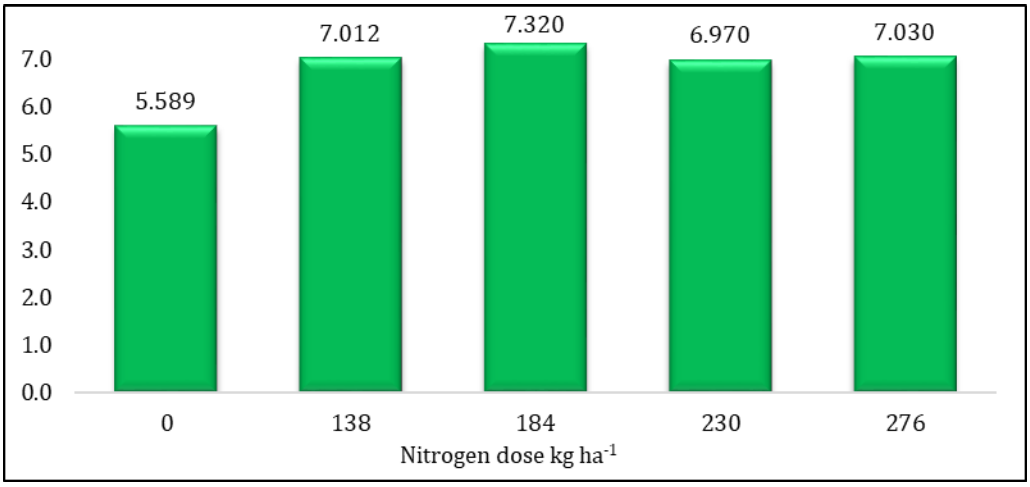


Figure 3 Nitrogen dose and wheat yield in the area with the highest biomass index.

Table 3 Dry matter protein, 12% moisture basis protein, and white belly percentage in the area with the highest biomass

Nitrogen Dose kg ha^{-1}	Dry basis protein %	Protein Basis 12% Moistur	Yellow berry %
0	8.525 c	7.38	99
138	10.565 b	9.30	47
184	11.277 b	9.93	19
230	11.443 ab	10.08	17
276	12.420 a	10.93	11
Tukey 0.05	1.102		

For both the local industry and export, it is specified that hard or vitreous wheat must have a maximum of 15% of grains with white belly. Based on this criterion, the dose required to achieve the quality necessary for marketing in the area with the highest biomass was 276 units per hectare, a quantity that does not qualify for the protein premium in the local market, since it is granted starting from 12.3% on a 12% moisture basis [16].

In Figure 4 and Table 4, the results for the area with the lowest biomass index are reported. In terms of yield, the control had a significantly lower value than the other treatments. Both yield and quality increased as a function of the nitrogen dose. The economically optimal nitrogen dose was 322 kg ha^{-1}, with a benefit/cost ratio of 1.94. It was considered feasible that a higher nitrogen dose could elicit a response. From the perspective of grain quality, the increase in protein content with higher nitrogen doses was consistent with the literature, where adjusted nitrogen doses correlate positively with protein in wheat [17].

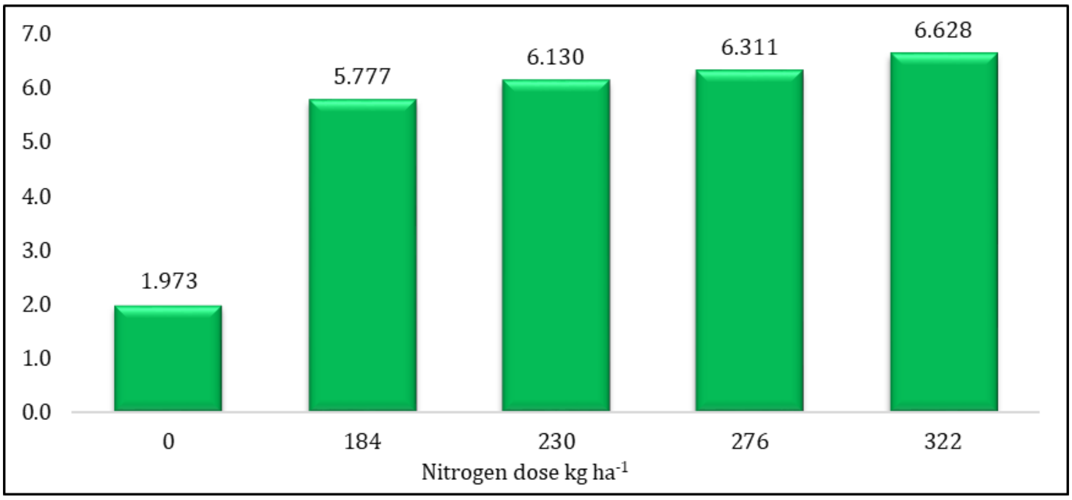


Figure 4 Nitrogen dose and wheat yield in the area with the lowest biomass index

Table 4 Dry matter protein, 12% moisture basis protein, and white belly percentage in the area with the lowest biomass

Nitrogen Dose kg ha^{-1}	Dry basis protein %	Protein Basis 12% Moistur	Yellow berry %
0	8.553 c	7.65	97
184	10.265 b	9.05	33
230	11.697 a	10.30	23
276	11.805 a	10.38	20
322	12.590 a	11.08	5
Tukey 0.05	1.072		

For protein, the nitrogen-free control showed a significantly lower value than the other treatments. Based on the white belly criterion, the dose required to achieve the quality needed for marketing was 322 units per hectare, a quantity that does not qualify for the protein premium in the local market [16].

Figure 5 Left: wheat grain with white belly and low protein content. Right: wheat grain without white belly and high protein content

The use of remote sensors is an integral part of what is now understood as precision agriculture. Through multispectral or hyperspectral images captured by these platforms, key variables such as biomass, plant vigor, crop phenology, water stress, evapotranspiration, soil moisture, and even the presence of pests or diseases can be estimated. This information allows for the detection of zones with different productive potential within the same field, which in turn enables differentiated management of irrigation, fertilization, or other agronomic practices, optimizing resources and increasing sustainability [15].

In this context, remote sensors play a crucial role, as they are tools capable of capturing information about the field and crops from platforms such as satellites, manned and unmanned aircraft, without the need for direct physical contact with the object of study. The data captured by these sensors, which may include multispectral, hyperspectral, or thermal images, allow the estimation of relevant agronomic variables such as plant vigor, water stress, and biomass variability—information essential for guiding water management, nutrition, and crop protection practices in each zone of the field [18].

Numerous studies have employed satellite imagery. For example, in one study, satellite data and clustering were used to delineate wheat management zones for the purpose of applying nitrogen fertilizer at variable rates [19]. Romano et al. [20] propose a method using time series of satellite images and a potential biomass index to define stable and homogeneous yield zones over the years, allowing the identification of high- and low-productivity areas and optimizing fertilization. Another study evaluated NDVI and soil parameters, observing significant correlations, suggesting that NDVI can serve as a variable to delineate homogeneous fertilization zones in crops [21]. In maize cultivation, soil sampling combined with geostatistics and clustering can define homogeneous fertility zones, facilitating site-specific nutrient management [22]. Another work demonstrates that biomass estimates from satellite data can be used to generate field maps zone by zone, supporting their use in fertilization or localized management [23].

However, there are also important limitations. One of them is the dependence on atmospheric conditions, especially for optical sensors, where frequent cloud cover reduces image quality or availability, affecting monitoring continuity [24]. Additionally, the processing of hyperspectral and multitemporal data requires advanced computational infrastructure and trained personnel, which can be a barrier for farmers with limited resources [25]. For satellites, spatial resolution may not be sufficient for highly heterogeneous crops or small plots, while drones, although highly detailed, require investment, maintenance, and compliance with flight regulations [26, 27].

4. Conclusion

It was concluded that the use of remote sensors allows for predicting wheat response to nitrogen application and represents a viable and necessary tool in the context of rising input costs and the growing demand for more efficient and sustainable agricultural systems.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that No conflict of interest.

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