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Factors influencing the adoption of modern nitrogen dose reduction technologies: the case of wheat in the Yaqui Valley

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ABSTRACT

Objective: The article examines the factors influencing the adoption of nitrogen dose reduction technologies among wheat farmers in the Yaqui Valley, Mexico.

Design/methodology/approach: Through the analysis of a sample of 336 farmers, the study identifies key factors associated with technology adoption, including gender, educational level, farm size, and land tenure. Additionally, factors such as access to technical advice and a positive perception of the technology's adaptability and relevance also play a crucial role. A random utility model was used to determine the probability that a wheat farmer would decide to adopt the described technology.

Results: The findings suggest that the male farmers male, higher education levels, technical advice, prior knowledge of the technology, and a positive perception of its adaptability, usefulness, and relevance influence the likelihood of adopting the proposed technology. Additionally, adoption is less likely when production is carried out without the support of technical advisors or when the farmers is not legally constituted as a legal entity.

Limitations on study/implications: The research focuses on a specific type of technology and a particular region.

Findings/conclusions: The use of new technologies among agricultural farmers is a high-impact tool in public policy aimed at supporting rural areas. Additionally, it is suggested that further actions, such as establishing demonstration plots with the proposed technology and inviting regional associations and farmers, as well as accompanying the technological proposals with certified technical advisors, can lead to a higher adoption rate, offsetting low educational levels and small plot sizes.

Keywords: Agriculture 4.0, technology adoption, wheat, logit.

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INTRODUCTION

The sustainability of wheat production is increasingly challenged by environmental concerns and the need for efficient resource management. Nitrogen, a key nutrient in wheat cultivation, plays a crucial role in yield and quality; however, its excessive and inefficient use leads to economics losses and severe environmental impacts, such as soil degradation water contamination, and greenhouse gas emissions (Matson *et al*., 1998; Beman *et al*.,

2005). Addressing this problem requires the adoption of modern technologies, known as Industry 4.0 (Schwab, 2017), that optimize fertilizer application and maintain productivity.

This study examines the factors influencing the adoption of nitrogen dose reduction technologies among wheat farmers in the Yaqui Valley during the Fall-Winter 2022/2023 cycle.

The Yaqui Valley, located in northern Mexico, in the states of Sonora and Chihuahua, has historically been a center for agricultural innovation. It was a pivotal region during the Green Revolution, introducing high-yield wheat varieties, mechanization, and expensive fertilizer use (Cerutti, 2019). While these advancements increased productivity, they also contributed to nitrogen overuse, which remains a challenge today. Nitrogen use efficiency in the region is reported to be approximately 31%, highlighting the need for improved management strategies (Millar *et al.*, 2018; CIMMYT, 2021). Modern precision agriculture technologies, such as optical sensors, have been developed to optimize nitrogen application by detecting the crop's specific nutrient needs and adjusting fertilizer doses accordingly (Ortiz *et al.*, 2007; Ruan *et al.*, 2005; Santillano *et al.*, 2013; Crain *et al.*, 2012). Therefore, these technologies can reduce nitrogen application rates while maintaining or even improving wheat yields. Despite their potential benefits, adoption rates among farmers in the Yaqui Valley remain low.

However, it is noteworthy that access to the new technologies has not been widespread, and the conditions for accessing them are unequal (Mehrabi *et al.*, 2021), whether due to indispensable factors for suppliers to expand them, or due to demand factors that limit adoption, such as educational, digital capabilities, or tradition and inertia in production methods (Elizondo *et al.*, 2023).

Lapidus (2017) points to some impediments to its adoption, highlighting the dependence on donor resources to transfer the technology to farmers through advisors. On the other hand, it is common that when it comes to adopting input-saving technologies, incentives tend to interfere between input-supplying companies that provide credit, and farmer organizations. By identifying the economic, technical, and institutional barriers to adoption, this research seeks to provide valuable insights for policymakers, researchers, and stakeholders interested in promoting sustainable nitrogen management practices in wheat production. The hypothesis of the study was that The adoption of nitogen dose reduction technologies among wheat farmers in the Yaqui Valley is influenced by a combination of economic, technical, and institutional factors. Specifically, it is hypothesized that farmers with greater financial resources, higher levels of technical knowledge, and stronger institutional support are more likely to adopt these technologies. Conversely, traditional farming practices, limited access to credit, and weak extension services act as barriers to adoption.

MATERIALS AND METHODS

The concurrence of high fertilizer prices resulting from the beginning of the Russia-Ukraine war, in the fall-winter (F-W) 2022/2023 cycle, motivated the Fideicomisos Instituidos en Relación con la Agricultura (FIRA) to implement a support scheme to encourage the adoption of efficient fertilization practices. FIRA absorbed 65% of the cost of the technological proposal corresponding to equipment rental, training and hiring of field advisors, diagnostic, recording in field logs, coordination of the application, supervision and validation of its use.

Proposed agricultural technology and practice

The first element inherent to the technology evaluated in this study was the diagnosis of the need for nitrogen by means of images taken by remote sensors integrated to drones. The images make it possible to estimate the quantity and quality of vegetation by measuring the intensity of radiation in the red and infrared bands of the electromagnetic spectrum emitted by the vegetation. The imaging varies according to the desired resolution. Related to the choice of technology (Späti *et al.*, 2021) have found that drones are more effective for fields with high spatial heterogeneity although not at any cost compared to other available alternatives, such as satellite imagery or handheld devices (*e.g.* green seeker).

The second element consisted of more efficient fertilizer application practices that considered no nitrogen use prior to planting, then an application of a maximum of 100 units of nitrogen, buried and solid, in the first fertilization at the time of planting. Then, prior to the first irrigation, the crop was diagnosed by means of a multispectral image obtained by the drone. Based on the interpretation of the image taken, recommendations were generated for the dose of nitrogen required to cover the needs in the strongest stage of crop development. Finally, in a subset of farmers, a second crop diagnosis using the drone was proposed prior to the second irrigation to determine a possible additional nitrogen requirement in order to ensure the quality of the grain.

Target population and study sample

The population of farmers for whom the Yaqui irrigation district issued permits in the F-W 22/23 cycle corresponds to 138,252 hectares of wheat managed by 11,073 irrigation users. In addition, the local ministry of agriculture (SAGARHPA) identified, in addition to irrigation users, 5,648 farmers who used irrigation permits in the F-W 22/23 cycle. Since the collection of information requires the estimation of various parameters, the most relevant of which is the proportion of farmers adopting the technology, a sample size was used to reach a confidence level of 95% and precision in the estimator of technology adoption of 3% for the population described resulting in sample size of 321 farmers (Cochran,1977).

Technology promotion

In the first phase, the local association of farmer unions AOASS (Asociación de Organismos de Agricultores del Sur de Sonora) promoted the technological program to the representatives of each of the farmer unions that make up the association and provided institutional support for its subsequent dissemination to the respective farmers. In the second phase, the representatives of each association disseminated the technology and FIRA's institutional support to the farmers of their respective union. Finally, AOASS held a meeting in each of the respective premises to further explain the technology, its benefits, the work plan and the respective cost reduction support.

Data collection

The data collection process was designed following established methodologies for studying technology adoption in agriculture. To ensure scientific rigor, we incorporated elements from meta-analyses by Mwangi and Kariuki (2015) and Ruzzante *et al.* (2021), which synthesize a wide array of studies on farmer's decisions to adopt new technologies. These studies highlight four key dimensions relevant to adoption processes: i) exposure of the farmer to the technology, ii) economic- productive characteristics of the farmers, iii) institutional support elements for the application of the technology and iv) socioeconomic profile of the farmer's household. Based on these dimensions, a structured survey was developed and validated through expert consultation with agricultural economists and extension specialists. The survey was administered through in-person interviews by trained enumerators at the end of the 2022-2023 fall-winter agricultural cycle. The sample consisted of 336 farmers from the Yaqui Valley who had been exposed to the initial offer of nitrogen reduction technologies. The selection process followed a stratified random sampling approach to ensure representation across different farm sizes, production systems, and access to institutional support.

Data collection adhered to standardized protocols to minimize bias, ensuring that all enumerators received training in survey administration. The data were then digitized and verified for consistency before analysis. This methodological approach ensures that the findings accurately reflect the factors influencing the adoption of nitrogen reduction technologies among wheat farmers in the region.

Diagnostic method

A random utility model (Ben-Akiva *et al.*, 1985) was used to determine the probability that a wheat farmer would decide to adopt the described technology. The model is defined as:

$$U_{in} = V_{in} + \varepsilon_{in},\ \ i = 1,\ldots,I \wedge n = 1,\ldots,N \qquad (1)$$

Where U_{in} is the expected utility of alternative i for farmer n, V_{in} is the deterministic component of the utility and ε_{in} is the random component. In the hypothetical case that V_{in} contains perfect information about the determinants of utility, the farmer would choose the highest alternative. Therefore, the probability that farmer n chooses alternative i over alternative j is:

$$\begin{aligned} P_{\square}(i) &= \Pr\left(U_{in} \geq U_{jn}\right) \\ &= \Pr\left(V_{in} + \varepsilon_{in} \geq V_{jn} + \varepsilon_{jn}\right) \\ &= \Pr\left(\varepsilon_{jn} - \varepsilon_{in} \leq V_{in} - V_{jn}\right),\ for\,all\ i, j \in C_n \end{aligned} \qquad (2)$$

where C_n is the set of options for farmer n, which in the present case is considered as $\left[C_n = \left\{i, j\right\} = \left\{Adopt,\ Not\,adopt\right\}\right]$.

Equation (1) assumes that the random errors are independently and identically distributed across the I alternatives and N individuals $(n=1,\ldots,N)$ and follow an extreme value distribution meaning $\varepsilon_n=\varepsilon_{jn}-\varepsilon_{in}$ in equation (2) is logistically distributed. The probability of choosing i is obtained by integrating equation (2) over a continuum of all possible values for ε_n. Thus, the probability that farmer n chooses alternative i is given by:

$$P_n(i)=\frac{e^{\mu V_{in}}}{\sum_{j\in C_n} e^{\mu V_{jn}}} \tag{3}$$

where μ is a positive scale parameter, $\mu>0$. The choice probability model with two probability options ($i=1$ y $j=0$) has a more succinct expression as follows:

$$\begin{aligned} P_n(i=1) &= \frac{e^{\mu V_{in}}}{e^{\mu V_{in}}+e^{\mu V_{jn}}} \\ &= \frac{1}{1+e^{-\mu\left(V_{in}-V_{jn}\right)}} \\ &= \frac{1}{1+e^{\mu\beta' x_{jn}}} \end{aligned} \tag{4}$$

where β' is the vector of parameters to be estimated.

RESULTS AND DISCUSSION

The results are grouped according to farmer characteristics as follows: i) socioeconomic profile, ii) economic-productive characteristics and iii) knowledge and previous exposure to technology.

Socioeconomic profile

Adoption rates show significant differences according to gender and schooling level. The odds ratio presented in Table 1 show that gender significantly influences technology adoption, with an OR of 0.057 meaning that male are 94.3% less likely (1-0.057) to adopt technology compared to women, all other variables being constant.

Regarding women's participation, the finding is consistent with some similar studies such as Ndiritu *et al.* (2014) which noted that women farmers in Kenya are less likely to adopt intensified farming practices such as minimum tillage and use of animal fertilizer. However, it should be noted that the present study highlights structural differences in the economic-productive characteristics of men and women, since female have on average smaller landholdings (34 hectares) compared to men (79 hectares), in addition to the fact that land tenure is their own in 28% of cases compared to 50% in the case of men. These facts are interpreted as proxies for other potential explanatory factors in the low adoption rate shown by women.

Thus, farmers with basic and secondary less school likely to adopt technology compared to those with higher education.

According to Ruzzante *et al.* (2021) farmer education is positively correlated with adoption motivation. Similarly, Feder *et al.* (1985) concludes that "the most educated farmers are the first to adopt modern technologies". On the other hand, Knight *et al.* (2003) find that schooling positively influences the adoption of modern inputs both directly and indirectly, through a reduction in risk aversion. These results reinforce current findings in the context of the Yaqui valley wheat producers.

Economic-productive characteristics

The size of the plot is one of the variables with the greatest theoretical and practical support with respect to its importance in terms of the decision to adopt new technologies. This hypothesis has been identified by Feder *et al.* (1985) and is generally linked to a proxy role for other potentially determining factors, such as the ability to withstand greater risks, access to essential inputs, information on technologies, access to specialized labor, among others.

Although it is common to elaborate on the "scale neutrality" of technologies, *i.e.* that technologies are of equal benefit to small and large-scale farmers, data from the sample revealed that plot size was critical in explaining adoption in favor of farmers with larger size of land. There also seems to be a trade-off between scale and form of access to land, since farmers that commonly lease land to third parties as a way to increase scale and thus make technology adoption attractive, in this sample, renting land decreases the propensity to adoption. This behavior seems to be associated with the idea that "the returns to investment for the use of these technologies are lower as time horizon of the exploitation of a given area is shortened" (Lachman *et al.*, 2022), due to the high turnover that can occur on rented land. The first studies regarding this association were

Table 1. Socioeconomic characteristics associated with technology adoption.

Independent variable	Category	Adopter	Non-adopter	Odds Ratio (OR)	p-value
		(a)	(b)	a/b	
		(c)	(d)	c/d	
Gender	1: Female	1	72	0.057	0.005***
	0: Men (ref.)	49	214		
Age	1: <30 years (*ref.*)	3	26		
	2: 30 to 40 years old	7	31	1.957	0.364
	3: 40 to 50 years old	6	44	1.182	0.824
	4: 50 to 60 years old	11	60	1.589	0.504
	5: ≥60	23	125	1.595	0.473
Schooling	0: No studies	0	2		
	1: Basic	7	86	0.294	0.005***
	2: Secondary	4	57	0.247	0.012**
	3: Higher (*ref.*)	39	141		

***p-value<0.01; ** p-value<0.05; *p-value<0.10

Table 2. Economic and productive characteristics associated with technology adoption.

Independent variable	Category	Adopter	Non-adopter	Odds Ratio (OR)	p-value
		(a)	(b)	a/b	
		(c)	(d)	c/d	
Land tenure	1: Rented (ref.)	33	130	2.285	0.010**
	0: Own	17	153		
Production Form	1: Individual (ref)	25	204	0.397	0.003***
	2: Legal entity	25	81		
Plot size (ha)	1: <20 ha (ref.)	4	114	0.131	0.000***
	0: ≥20 ha	46	172		
Access to credit	1: Yes	48	256	2.813	0.166
	0: No	2	30		
Technical Advisor[2]	1: Yes (ref.)	44	204	2.948	0.017**
	0: No	6	82		
Wheat yield	(ton/ha)	50	284	1.776	0.002***
% of total income from wheat		50	284	1.005	

***p-value<0.01; ** p-value<0.05; *p-value<0.10

carried out in the context of the green revolution, for example, Vyas (1975) found that the form of land tenure did not significant influence adoption of technologies and, rather, as these technologies showed their potential, they were gradually adopted by all farmers. However, with the emergence of new and more diverse technologies, the phenomenon was further explored and farmers with owned land were found to more often adopt those technologies with higher costs (*e.g.* stone terraces in Ethiopia; Gebremedhin and Swinton, 2003) or with positive medium and long-term sustainable effects on land (*e.g.* natural resource management technologies, especially prevention of soil erosion; Ruzzante *et al.*, (2021). It is worth mentioning that the technology addressed in the present study has positive effects on cost reduction in the short term and generates medium- and long-term environmental benefits by making less intensive use of nitrogen and mitigate soil erosion.

Adoption is less likely when farmer's production is carried out without the support of technical advisors or when the farmer is not established as a legal entity. These findings suggest the presence of "network effects", where interactions with other actors could be enhancing the adoption of these technologies, which are not necessarily easily assimilated independently and autonomously by farmers. This highlights the crucial role of external information sources and peer influence in the diffusion and adoption process of these and other technologies, as emphasized by Lachman *et al.* (2022).

Prior knowledge of technology

The farmer's prior knowledge of the technology, as well as the farmer's revealed perceptions regarding its positive adaptability, usefulness, and relevance, make them more likely to adopt it.

Table 3. Characteristics of prior knowledge of technology.

Independent variable	**Category**	**Adopter**	**Non-adopter**	**Odds Ratio (OR)**	**p-value**
		(a)	**(b)**	**a/b**	
		(c)	**(d)**	**c/d**	
Complexity	1: Yes	4	40	0.535	0.254
	0: No	46	246		
Useful	1: Yes	32	88	4.000	0.000***
	0: No	18	198		
Relevance	1: Yes	46	233	2.616	0.077*
	0: No	4	53		
Adaptation	1: Yes	45	215	2.972	0.026**
	0: No	5	71		
Pre-application	1: Yes	15	19	5.030	0.000***
	0: No	35	223		
Previous results	1: Yes	19	48	3.039	0.001***
	0: No	31	238		
Test	0: No test	20	81	0.593	0.099*
	1: With test	30	205		

*** p-value<0.01; ** p-value<0.05; *p-value<0.10

Joint impact assessment

The proportion of farmers that used the nitrogen dose reduction technology in the sample is 14.8%. In order to jointly test the effects that significantly explain this behavior, the various groups of variables were tested simultaneously therefore enhancing their precision and the nature of their statistical significance reducing the possibility of error in the interpretation of individual parameters. The estimates of all parameters revealed an association consistent with the direction suggested by the individual analysis.

The estimates of all parameters used in the model revealed their expected signs (Table 4). They also confirmed statistical significance with respect to their univariate counterparts. In general, farmers' characteristics show, through their respective parameters, a lower impact on the probability of adoption if they are considered jointly. For instance, schooling shows that a greater number of years of education increases the probability of adoption by 1.52% for each additional year of schooling and not by 2.70% as suggested when considered individually. However, of greater relevance is the comparison of marginal effects for impact variables, particularly those that are of a non-idiosyncratic nature. Noteworthy is the fact that having previous exposure to the new technology in a neighboring plot increases the probability of adoption in 14.5% while, for example, a smaller plot size reduces it by only 11.4%. In this way, small farmers previously exposed to the new technology can be compensated for other limiting characteristics and enhanced on their probability of adoption. A similar result is obtained if a technical advisor is present to support the farmer in the normal course of his activities.

Table 4. Parameter Estimates and Marginal Effects of the multiple variable Logit Model.

Independent variables	Category	Estimation (standard error)	Average marginal effects
Socio-economic characteristics			
Gender***	Female (ref.)	−2.740	−16.18%
	Men	(1.042)	
Age		−0.008	−0.08%
		(0.013)	
Schooling**		0.160	1.52%
		(0.070)	
Productive economic characteristics			
Land Tenure*	Own (ref.)	0.644	6.12%
	Rented	(0.389)	
Production Form	Individual (ref.)	−0.331	−3.26%
	Legal entity	(0.383)	
Plot size (ha)**	<20ha (ref.)	−1.399	−11.36%
	>20ha	(0.595)	
Access to Credit	Yes (ref)	1.215	9.24%
	No	(0.860)	
Technical Advisor*	Yes (ref)	0.954	8.24%
	No	(0.499)	
Wheat yield (ton/ha) **		0.548	5.24%
		(0.234)	
% Wheat of total productive plots**		0.020	0.19%
		(0.009)	
Prior knowledge of the technology			
Previous results***	No (ref)	1.299	14.52%
	Yes	(0.406)	
Const.		−11.092	
		(2.713)	

***p-value<0.01; **p-value<0.05; *p-value<0.10

The reference class for the estimation of the respective parameter is highlighted in parentheses (ref).
Number of observations=329. Likelihood ratio test: −100.730. McFaden R^2=0.281. ROC=0.855.
The variables Age and Schooling are treated as discrete numerical variables.
The marginal effect indicates the change in the expected probability of adopting the technology for a unit change in an explanatory variable.
Technical advisor: Farmers with declared availability of technical advisor during previous productive activities.

Effectiveness of the technology

Figure 1 illustrates the changes with respect to the previous cycle in terms of fertilizer use and in terms of crop production (tons per hectare). As for the fertilizer, various nitrogen molecules were used, such as urea (67%), ammonia (23.3%) and phosphonitrate (2.9%), among others. As can be seen, the majority (57%) of adoptive farmers are in quadrant (II), which simultaneously shows an increase in yield and a decrease in fertilizer use. On

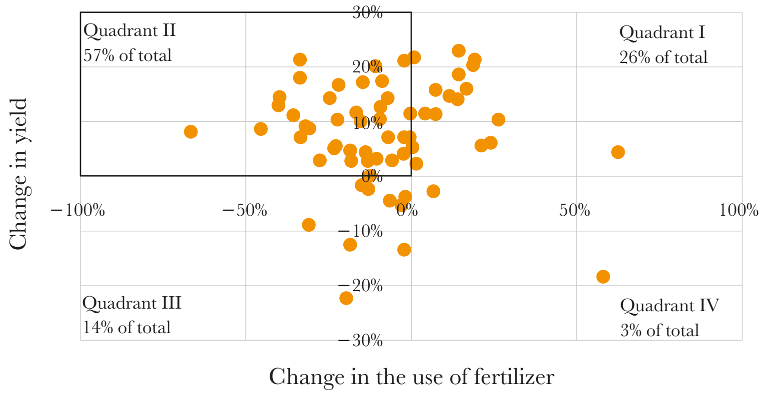

Figure 1. Change *vs*. previous cycle in fertilizer use and yield (tons per hectare).

average, within this quadrant there is a 20% lower use of fertilizer, and a 10% higher yield compared to the previous cycle.

Likewise, the evaluation of field results shows that wheat production is more profitable with the technology tested in this study with respect to the traditional technology. If we consider the Benefit/Cost ratio for the farmer as proposed in Table 5, we conclude that the farmer increases revenues as compared to costs from 1.055 to 1.149, even considering the additional cost for the crop diagnosis with drone and field advisory and consulting services. This is due to the fact that the technology allowed reducing on average the cost of the crop by saving fertilizer, in addition to increasing, on average, wheat yield.

Table 5. Profitability of wheat cultivation through traditional technology and Optimal Fertilization.

Concept	Traditional technology	Nitrogen dose reduction technology without Support	Nitrogen dose reduction technology with support
Total Cost $ per ha	36,938.00	36,418.05	35,764.00
1. Cost per ha:	36,938.00	35,502.05	35,502.05
(of which Fertilization)	15,747.00	14,311.05	14,311.05
2. Drone/ha	-	153.50	30.70
3. Advice/ha	-	500.00	100.00
4. Consultancy/ha	-	262.50	131.25
Income $ /ha	38,967.50	41,834.20	41,834.20
-Yield tn/ha	7.15	7.68	7.68
-Price / tn	5,450.00	5,450.00	5,450.00
B/C ratio	1.055	1.149	1.170

1/ Traditional technology: Cost of cultivation (www.FIRA.gob.mx)
Price: Price per ton of crystalline wheat during harvest at the end of May/2023 (310 dis/tn)

CONCLUSIONS

The adoption of new agricultural technologies is crucial for agricultural development, especially in Mexico, as it enhances nitrogen use reduction in wheat production in the Yaqui Valley and consequently improves overall agricultural productivity. However, the decision and associated risks fall on farmers, which limits implementation. This study identified key adoption barriers, including lack of education, technical assistance, and financial resources. Farmers with higher education levels, access to credit, and technical support are more likely to adopt these technologies. at the adoption rate was 14.8%, but it could increase through strategies such as field demonstrations and specialized technical assistance.

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