

GENERATING NITROGEN RECOMMENDATIONS FOR MAIZE: ECONOMIC CONSIDERATIONS

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ABSTRACT

The use of excessive amounts of nitrogen fertilizers in crops usually results in nitrogen (N) losses, increasing environmental pollution and contributing to climate change, while also elevating crop production costs. This study aimed to determine in maize (*Zea mays* L.): (1) the economic optimal nitrogen rate (EONR), economic optimal yield (EOY), and N use efficiency (NUE) utilizing the current N/maize (grain) price ratio (N/MPR) for attainable yield levels; and (2) the effect of an increase in the N/MPR on the EONR, EOY, net income (NI), NUE, and the loss of N. Data from 140 maize response experiments to increasing rates of N, conducted between 2010 and 2019 across 18 states in Mexico under rainfed and irrigated conditions, were analyzed. In these experiments, the average maximum yields were 4.971 ± 2.716 Mg ha⁻¹ under rainfed conditions and 11.776 ± 2.366 Mg ha⁻¹ under irrigated conditions. The EONR, EOY, and NUE were determined with the current N/MPR for attainable yield levels. At these levels, both the EONR and NUE increased with higher EOY and decreased with increased yield without N treatment. An increase in N/MPR reduced EONR and its associated costs without significantly affecting EOY and NI. The reduction in EONR resulted in higher NUE and, consequently, lower N losses. By utilizing N/MPR in economic optimization, recommended N rates for maize can be reduced, leading to decreased N losses and environmental pollution.

Keywords: *Zea mays* L., economic optimal nitrogen rate, nitrogen/maize price ratio, economic optimal yield, nitrogen use efficiency.

INTRODUCTION

Given the extensive global cultivation of maize, there has been growing interest in recent decades in achieving greater precision in nitrogen (N) recommendations, for two main reasons: (1) the relatively high amounts of N required by the crop to reach potential yields result in substantial N applications (Ciampitti *et al.*, 2013; Castellanos *et al.*, 2019); and (2) the efficiency of N recovery by maize is relatively low, leading

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to N losses that increase production costs and environmental pollution, thereby contributing to climate change (Woli *et al.*, 2016; Lu *et al.*, 2019; Banger *et al.*, 2020b). Various approaches have been developed for generating N fertilization recommendations for maize. These differ in terms of the required information, the accuracy of the generated recommendations, and the associated time and cost (Morris *et al.*, 2018). The primary approaches include: (1) considering the attainable yield of the crop, which depends on soil and climate conditions, as well as the production system (Sawyer *et al.*, 2006; Morris *et al.*, 2018); (2) conducting field experiments with increasing N rates to estimate a response function through regression analysis, followed by economic analyses to determine economic optimal N rates (EONR), and generating a recommendation for production systems under similar soil and climatic conditions (Sawyer *et al.*, 2006; Morris *et al.*, 2018); and (3) using soil and plant analysis to derive crop-specific recommendations at the individual farmer's field level (Sela *et al.*, 2016; Morris *et al.*, 2018).

Not all approaches consider an economic analysis for generating maize N fertilization recommendations. When such analysis is incorporated, the economic criterion of maximizing net income per unit area (MNIS) is generally used. This is done in different ways, considering: (1) the crop yield achieved with increasing N rates or the same yield but subtracting the yield without N (Sawyer *et al.*, 2006; Wang *et al.*, 2020b); (2) fixed costs, with or without fixed production costs (Morris *et al.*, 2018; Wang *et al.*, 2020b); and (3) net incomes, based on net income (NI) or yields and the subsequent calculation of NI (Morris *et al.*, 2018; Wang *et al.*, 2020b).

According to the economic theory, maximization of NI with the MNIS economic criterion is linked to maximization of the amount of N that is economically viable to use in production, which consequently implies the highest fertilization costs. In this sense, this economic criterion is most appropriate for use in contexts where there is sufficient capital availability and low risk, or where agricultural insurance is in place. The recovery of N from fertilizer in maize generally ranges between 35 and 75 %, with the remainder being lost through various pathways such as leaching, volatilization, denitrification, and surface runoff (Morris *et al.*, 2018). This low applied N use efficiency (NUE) implies that higher N rates will result in greater losses (Sela *et al.*, 2016; McLellan *et al.*, 2018; Millar *et al.*, 2018). Since the MNIS economic criterion generates higher EONR than other economic criteria, it also tends to result in greater N losses.

The MNIS economic criterion allows working with different input/output price ratios, which can fluctuate due to changes in the prices of inputs or products. For N, as expected, an increase in the N/maize (grain) price ratio (N/MPR) will reduce the EONR (Sawyer *et al.*, 2006; Morris *et al.*, 2018). This reduction of EONR leads to decreases in the optimal economic yield (OEY) and NI, which, within certain limits, may not be significant (Banger *et al.*, 2020a; Wang *et al.*, 2020a). Conversely, lower EONRs imply higher NUEs and, therefore, reduced N losses (Millar *et al.*, 2018; Wang *et al.*, 2020b). This study utilized data from field experiments on the response of maize to increasing

N rates, conducted under both rainfed and irrigated conditions in areas with varying yield potentials. This study aimed to determine in maize: (1) the economic optimal N rate, economic optimal yield, and N use efficiency using the current N/maize (grain) price ratio for attainable yield levels; and (2) the effect of an increase in the N/maize (grain) price ratio on the economic optimal N rate, economic optimal yield, net income, N use efficiency, and the loss of N.

MATERIALS AND METHODS

Data from 140 maize response experiments to increasing N rates were analyzed. The experiments were conducted by the International Maize and Wheat Improvement Center (CIMMYT) in 18 states in Mexico between 2010 and 2019, under both rainfed and irrigated conditions with the maize-maize production system. The states were grouped into distinct climatic regions. The prevalent agricultural soils included Phaeozems, Vertisols, Cambisols, and Luvisols, characterized mainly by medium and fine textures, and sandy soils in some states like Puebla and Tlaxcala (INEGI, 2007). The climate across these regions varied with latitude, altitude (ranging from 10 to 2250 m), relief (including coastal plains, mountainous areas, and high plateaus), and proximity to the coast (INEGI, 2018).

In the coastal plains, the climate is very warm, ranging from dry in the north to subhumid in the center and south of the country. In mountainous areas and high plateaus, the climate is temperate, subhumid, semidry, or dry, depending on their distance from the coast (INEGI, 2018). Rainy season occurs during the summer months, between June/July and September/October. The experiments were established: (1) at the onset of the rainy season (June/July) under rainfed conditions with supplemental irrigation when rains are scarce (spring-summer cycle); and (2) in October/November under irrigation in warmer areas with limited rainfall (autumn-winter cycle). The states, altitude, average annual rainfall, and number of experiments across rainfed and irrigated conditions were grouped by climatic region (Table 1).

Of the experiments, 107 were conducted in the spring-summer cycle and 33 in the autumn-winter cycle, with some experiments being replicated at the same sites in different years. The maize used included 131 experiments with improved varieties and nine with landraces. Five N rates were used in most experiments and, in some, seven rates, ranging from a treatment without N to 300 kg N ha⁻¹ under rainfed conditions (based on the expected yield) and to 360 kg N ha⁻¹ under irrigated conditions. The N fertilizer was urea, applied at sowing, as the experiments were specifically designed to estimate the optimal N rate for application at this time.

The experimental design was a randomized complete block, with each treatment replicated three or four times, subject to space availability. The size of the experimental plots was set at 5.6 x 8 m, including six rows with 0.8 m spacing between them. All experiments included a base phosphorous fertilization, with sowing, dates, seed doses, and the management of weeds, pests, and diseases carried out in accordance with the

Table 1. Altitude, average annual rainfall, and number of maize experiments under rainfed and irrigated conditions by climatic region.

Region	Altitude (m)	Average annual rainfall (mm) [†]	Number of experiments	
			Rainfed	Irrigated
Sinaloa, Sonora	25–50	250–450, 450–650	3	26
San Luis Potosi	100–150	800–1500	2	0
Guanajuato, Jalisco, Michoacan, Queretaro, Zacatecas	1300–1600, 1600–1900, 1900–2200	300–500, 500–700, 700–800, 800–1000	11	46
Hidalgo, Mexico, Puebla, Tlaxcala	2100–2500	300–500, 500–700, 700–1000	7	1
Morelos	900–1100	800–1000	10	1
Oaxaca	1500–2150	750	5	0
Chiapas, Guerrero	500–800	650–1050	15	2
Campeche, Quintana Roo, Yucatan	50–100	600–800, 800–1200, 1200–1400	11	0

[†]Source: INEGI (2018).

guidelines provided by the National Forestry, Agricultural and Livestock Research Institute (INIFAP). The response variable measured was grain yield at 14 % moisture. Data analysis for each experiment included a regression analysis to estimate a grain yield equation as a function of N rate, complemented by an economic analysis to calculate the EONR and EOY. The regression analysis included two key steps: (1) specifying models based on the observed graphical crop response to N; and (2) using the SAS (Statistical Analysis System) program to estimate the regression equation, eliminating possible outliers, when necessary ($p = 0.01$) (Freund and Littell, 2000), and selecting the model with the smallest mean square error as the most appropriate. With the fitted regression equation, EONR and EOY were determined using a SAS program designed for this purpose (Briones-Encinia *et al.*, 2009).

The economic optimization criterion applied was the MNIS, where the EONR is determined at the point where the marginal net income (the increase in net income from an additional unit of input) equals the marginal cost (the cost of one unit of input). The price of fertilizer and maize was based on May 2020 figures. Given the prevalent use of urea and ammonium sulfate as N sources by farmers, the prices per kilogram of N for both fertilizers were averaged to USD \$1.06 N kg⁻¹, considering individual prices of USD \$0.955 and 1.165 N kg⁻¹, respectively. Transportation and application costs, as well as invested capital were added to this value, resulting in a price of USD \$1.25 N kg⁻¹. The net price of maize, after deducting harvest and transportation costs, was set at USD \$175 Mg⁻¹. With these prices, the N/MPR was equal to 7.14. All other costs related to crop production were considered fixed, amounting to USD \$425 and 575 ha⁻¹ for rainfed and irrigated conditions, respectively.

The experiments were grouped based on moisture regime and attainable EOY into levels: (1) for rainfed maize, < 2, 2–3, 3–4.5, 4.5–6, 6–8, and 8–10 Mg ha⁻¹; and (2) for irrigated maize, 8–10, 10–12, 12–14, 14–16, and greater than 16 Mg ha⁻¹. For these attainable EOY levels, mean EONR, EOY, yields without N (Y_0), and NUE were determined. The NUE was estimated using the formula: $NUE = ((EOY - Y_0) / EONR) \times 20$, where, the factor 20 represents the average amount of N (kg N) needed to produce 1 Mg of maize grain (14 % moisture) including stalk, assuming a harvest index of 0.5 for improved maize (Castellanos *et al.*, 2019).

This approach does not account for the possibility that Y_0 may have a lower N concentration in the grain (Ciampitti and Vyn, 2014; Wang *et al.*, 2020b), resulting in the NUE estimated being somewhat higher. With the N/MPR increased by 25, 50, 75, 100, 125, and 150 %, for maize experiments in both rainfed and irrigated conditions, EONRs were calculated similarly to the current N/MPR. Using the recalculated EONR, EOY, NI, and NUE were determined for these increased N/MPRs. Furthermore, based on the determined EONR, the potential N saving from using a lower rate was also estimated, thereby reducing both costs and environmental impact.

RESULTS AND DISCUSSION

Yields

The yields observed in the maize experiments, both with and without N application, show variations under rainfed and irrigated conditions. These differences can be attributed to the diverse soil types and climate conditions in which the experiments were established, and, when applicable, to the varying intensity of irrigation. The average yields and their standard deviations were: under rainfed conditions, 2.952 ± 2.136 Mg ha⁻¹ (without N) and 4.971 ± 2.716 Mg ha⁻¹ (with N); and under irrigated conditions, 5.816 ± 3.317 Mg ha⁻¹ (without N) and 11.776 ± 2.366 Mg ha⁻¹ (with N).

Models and fitting of regression equations by experiment

The regression equations from experiments differed in the number of N variables included, ranging from one to three, such as $N^{0.25}$, $N^{0.50}$, $N^{0.75}$, N , N^2 , and N^3 , depending on maize response to N. The most frequent models were square root (in 24 experiments) and quadratic (in 68 experiments). The fit of these regression equations, indicated by the R^2 value, ranged from 0.222 to 0.982, excluding experiments with no response to N. The correlation between the ordinate of the regression equations and the yield of the treatment without N was strong, with $r = 0.998$ ($p \leq 0.01$).

Economic optimal rate of nitrogen by level of attainable yield

The results show that in both moisture conditions (Table 2), an increase in Y_0 , EOY, and EONR is followed by an attainable yield level increase, with a smaller increase in Y_0 under irrigated condition. The relationship tends: (1) to be linear, except for attainable

Table 2. Yields without nitrogen (Y_0), optimal economic yields (EOY), and economic optimal nitrogen rate (EONR) by level of attainable yield for rainfed and irrigated maize.

Moisture condition	Yield level (kg ha ⁻¹)	Yield (Mg ha ⁻¹)		EONR (kg N ha ⁻¹)
		Y_0	EOY	
Rainfed	< 2.0	1.020	1.150	9
	2.0–3.0	1.224	2.539	72
	3.0–4.5	1.881	3.768	99
	4.5–6.0	2.278	5.557	142
	6.0–8.0	3.129	6.888	157
	8.0–10.0 [†]	5.199	8.978	154
Irrigated	8.0–10.0	4.838	9.356	187
	10.0–12.0	5.126	10.850	221
	12.0–14.0	5.451	13.381	269
	14.0–16.0	5.647	14.955	303

[†]The 8–10 kg ha⁻¹ yield level in the rainfed condition displayed high without nitrogen and economically optimal yields, and for this, a relatively low economic optimal N rate, for which there is no response.

yield levels below 2 Mg ha⁻¹ and from 8 to 10 Mg ha⁻¹ under rainfed conditions that do not follow this trend; and (2) under irrigated conditions, this relationship follows a similar trend to rainfed conditions but with higher EONR and EOY values (Figure 1).

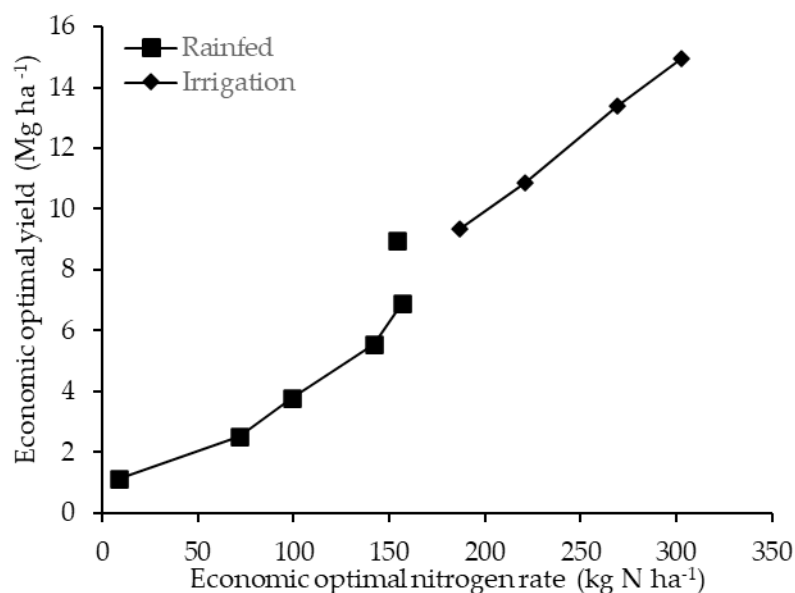


Figure 1. Relation between the economical optimal yield and the economic optimal nitrogen rate by level of attainable yield for rainfed and irrigated maize.

This study found that the relationship between EONR and EOY is similar to those reported by Sánchez-Roldán *et al.* (2022) in their study across 16 Mexican states, involving 67 experiments on maize response to N in soils with 2 % of organic matter. In the 67 experiments, N application was split into one-third at sowing and two-thirds at 30–45 days for expected yields below 4 Mg ha⁻¹ and all the N was applied at 45–60 days for expected yields above 4 Mg ha⁻¹. In the current 140 experiments, all N was applied at sowing. According to this, the time of N application would not have significantly influenced the response of maize to N.

It could be assumed that the maize response to N is mainly determined by yield and N supply from the soil. In 67 experiments, this N supply was estimated by soil organic matter content, and in 140 experiments, this was done by the yield of the treatment without N. The organic matter in the soil requires to be mineralized, and this process is influenced by soil and climate factors, as well as crop management (Wang *et al.*, 2020b). In this case, crop management was referred to as the maize-maize system, but the soil types were different, as were the climate conditions.

In general terms, one way to reduce the effect of soil and climate variations on the crop response to N in a region is by mapping relative similar soils and climates in geographic areas (Sawyer *et al.*, 2006; Morris *et al.*, 2018). For climate variations, it is necessary to estimate the variation over the long term, excluding atypical years, or using a probabilistic distribution for more accuracy (Morris *et al.*, 2018). In these geographic areas, experiments on the response of maize to N are carried out, and the average optimal rate of N are determined.

The EONR determined for maize yield levels can have the advantage that farmers know the yield their crop can achieve, unless it is limited by poor crop management. However, N recommendations determined for similar soil and climate units, as well as for stable management systems, may have some inherent lack of precision due to variations in soil N input by the production system (Wang *et al.*, 2020b). These variations are due to differences in both the content and mineralization of soil organic matter, typical of any production system (Morris *et al.*, 2018).

Relationship of the economic optimal nitrogen rate with the yields without nitrogen and the economic optimal yield

In order to deepen into the relationship between EONR against Y_0 and EOY (Table 2), regression equation for EONR was estimated as a function of Y_0 and EOY for both the rainfed and irrigated conditions. The estimated regression equations are as follows:

$$EONR_{rainfed} = 9.338 + 54.803 Y_{os} - 2.201 Y_{os}^2 - 61.906 Y_0 + 3.195 Y_0 Y_{os}$$

(MSE = 154.115, $R^2 = 0.979$, $n = 64$, 5 outlier points removed),

$$EONR_{irrigation} = 44.301 + 48.776 Y_{os} - 1.598 Y_{os}^2 - 52.657 Y_0 + 0.533 Y_{o0}^2 + 2.196 Y_0 Y_{os}$$

(MSE = 321.131, $R^2 = 0.971$, $n = 71$, 7 outlier points removed),

where EONR is the economic optimal nitrogen rate (kg N ha^{-1}), Y_{oe} is the economic optimal yield (Mg ha^{-1}), Y_0 is the yield without N (kg ha^{-1}), MSE is the mean square error, and R^2 is the coefficient of determination.

The regression equations have a good fit, expressed by high R^2 values for both rainfed and irrigated conditions, which could have been favored by the elimination of outlier points. These regression equations show: (1) that EONR increased with increasing EOY (positive decreasing relationship) and decreased with increasing Y_0 (negative relationship); and (2) a positive interaction between Y_0 and EOY, which indicates that the greater the EOY, the smaller the negative effect of Y_0 .

The rise in EONR with yield level suggests that higher yields lead to more N being extracted from the fertilizer by the maize plants, with the amount of N extracted largely dependent on biomass production and its N concentration. This concentration depends on genetic factors (Ciampitti and Vyn, 2012) and can be modified by N contribution from the soil and N fertilization (Ciampitti and Vyn, 2014; Wang *et al.*, 2020b), as well as by factors that limit crop yields (Morris *et al.*, 2018). For improved maize with a harvest index of 0.5, concentration normally varies by about 20 kg of N for every 1 Mg of grain (plus stalk) (Castellanos *et al.*, 2019).

In this study, the EONR displayed a correlation with yield level, suggesting that higher yields require more N, and therefore, a higher EONR might be necessary. There is information that corroborates this relationship (Morris *et al.*, 2018; Wang *et al.*, 2020b); however, it has also been observed that improved maize varieties with higher yields do not necessarily demand significantly more N from fertilizers, leading to a higher EONR. This is attributed to: (1) more developed root systems in newer maize generations that absorb N more efficiently, from both the soil and the fertilizer (Peng *et al.*, 2010; Feng *et al.*, 2016); and (2) the fact that the latest improved maize varieties produce more biomass per unit of absorbed N; therefore, a higher yield does not cause a proportional increase in the N demand (Ciampitti and Vyn, 2012; Woli *et al.*, 2016). On the other hand, the reduction in the EONR with an increase in Y_0 could be linked to a higher contribution of N from the soil due to a greater organic matter content derived from crop residues and root production. This was observed in the study, where the correlation between Y_0 and EOY was $r = 0.691$ ($p \leq 0.01$) in rainfed experiments and $r = 0.402$ ($p \leq 0.01$) in irrigated experiments. However, the residual N content in the soil may also be related to this (Wortmann *et al.*, 2011; Morris *et al.*, 2018).

The attainable yield, represented here by the EOY, has been the basis of the model for generation N recommendations in maize, as utilized in many states in the USA between 1970 and 2005 (Morris *et al.*, 2018). This model, however, has been questioned for overlooking economic considerations in its recommendations and for the attainable yield not being related to the EONRs (Sawyer *et al.*, 2006; Morris *et al.*, 2018). In this latter point, it is worth considering the relationship to consider the relationship between EOY and EONR alongside the N contribution from the soil, estimated in this study by Y_0 . Thus, a similar yield might be achieved with either a higher N contribution

from the soil and a lower EONR or a lower N contribution from the soil and a higher EONR. This was substantiated by the regression analysis, where the EOY as a function of EONR showed R^2 values of 0.334 ($p \leq 0.01$) for experiments under rainfed conditions and 0.002 ($p \leq 0.74$) for experiments under irrigated conditions. However, when incorporating both EONR and Y_0 , the R^2 values increased to 0.93 ($p \leq 0.01$) and 0.676 ($p \leq 0.01$), respectively.

Applied nitrogen use efficiency

In addition to the crop, the applied N use efficiency (NUE) is influenced by several factors, including soil characteristics (mainly texture), climate (the frequency and distribution of rainfall, and temperature), and the management of fertilization (its chemical form, application method, timing, and the amount applied relative to the soil N contribution). These factors contribute to variations in NUE both within and between production systems (Morris *et al.*, 2018). For diverse conditions soil, climate and N fertilizer management, mean NUE values between 0.35 and 0.75 are reported for maize (Morris *et al.*, 2018), and as high as 0.85 in maize under optimal irrigation conditions (Castellanos *et al.*, 2019).

In this study, the NUE for EONR increased with the level of attainable yield in both moisture conditions, as values: (1) under rainfed, 0.29, 0.37, 0.38, 0.46, 0.48, and 0.49 for yield levels < 2, 2–3, 3–4.5, 4.5–6, 6–8, and 8–10 Mg ha⁻¹, respectively; and (2) under irrigated, 0.48, 0.52, 0.59, and 0.61 for yield levels 8–10, 10–12, 12–14, and 14–16 Mg ha⁻¹, respectively. These estimated efficiencies are relatively low in comparison with values obtained with split N applications in other studies. For example, in irrigated maize, Wortmann *et al.* (2011) report an average NUE of 0.67 for a mean yield of 13.3 Mg ha⁻¹ obtained with a mean rate of 171 kg N ha⁻¹, and Davies *et al.* (2020) report a value of 0.63 for a yield of 13.7 Mg ha⁻¹ obtained with a rate of 202 kg N ha⁻¹. In rainfed maize: (1) Wang *et al.* (2020b) report mean NUEs between 0.56 and 0.58 for mean yields between 10.45 and 10.34 Mg ha⁻¹ obtained with rates of 225 and 187 kg N ha⁻¹, respectively; and (2) Meena *et al.* (2020) report a NUE of 0.36 and 0.39 for yields of 3.88 and 4.66 Mg ha⁻¹ obtained with rates of 90 and 120 kg N ha⁻¹, respectively, which are similar values to those found in this study. However, the NUEs estimated in this study were obtained by applying N at sowing, which could partially explain the relatively low NUE values reached.

In order to deepen into the relationship between NUE vs. EONR and EOY, regression equations of the NUE were estimated as a function of such variables for both the rainfed and irrigated conditions. The estimated regression equations are as follows:

$$NUE_{rainfed} = 0.216 + 0.167 Y_{os} - 0.148 Y_0 - 0.000932 N_{oe} - 0.000323 Y_{oe} N_{oe} + 0.000174 Y_0 N_{oe}$$

(MSE = 0.00322, $R^2 = 0.778$, $n = 43$, 6 outlier points removed),

$$NUE_{irrigation} = 0.208 + 0.123 Y_{os} - 0.108 Y_0 - 0.000906 N_{oe} - 0.000155 Y_{oe} N_{oe} + 0.000889 Y_0 N_{oe}$$

(MSE = 0.00578, $R^2 = 0.960$, $n = 60$, 4 outlier points removed),

where NUE is the nitrogen use efficiency, Y_{oe} is the economic optimal yield (kg ha^{-1}), Y_0 is the yield without N (kg ha^{-1}), N_{oe} is the economic optimal nitrogen rate (kg N ha^{-1}), MSE is the mean square error, and R^2 is the coefficient of determination.

Both regression equations show that NUE increased with increasing EOY and decreased with increasing EONR and Y_0 . Also, EOY has a negative interaction with EONR, and Y_0 has a positive interaction with EONR. The increase in NUE due to higher EOY coincides with greater biomass production by the plants, leading to an efficient root system that can utilize applied N more efficiently (Peng *et al.*, 2010; Feng *et al.*, 2016). Conversely, as the rate of applied N increases, its relative use efficiency tends to decrease, as indicated by numerous studies on the matter (Wortmann *et al.*, 2011; Millar *et al.*, 2018).

Economic optimal nitrogen rate obtained with increased nitrogen/maize price ratios

The N/maize price ratio (N/MPR) has been utilized to determine the EONR based on maximizing economic income, considering variations in the prices of N and maize (Dobermann *et al.*, 2011; Morris *et al.*, 2018). In this study, EONRs were calculated using regression equations from experiments, considering both the current N/MPR and increased N/MPR by 25, 50, 75, 100, 125, and 150 %. The analysis was applied to 19 experiments with yield ranges between 5 and 8.5 Mg ha^{-1} under rainfed conditions and 29 experiments with yield ranges between 10 and 14 Mg ha^{-1} under irrigated conditions. The resulting EONRs were then used to determine EOY, cost of N, and NI for respective attainable yield levels, and an average value was estimated for each N/MNR (Table 3).

An increase in N/MPR led to a decrease in the related EONR and costs of N fertilization, as well as reductions in EOY and NI (Table 4). However, the percentage reductions in EONRs and their associated costs were more significant than the percentage reductions in EOYs and NIs. For instance, with a 100 % increase in N/MPR: (1) under rainfed conditions, EONR was reduced by 38 kg N ha^{-1} (21.5 %) and its cost by USD \$47.5 ha^{-1} (21.5 %), compared to a decrease of 0.397 Mg ha^{-1} (5.8 %) in EOY and USD \$21.95 ha^{-1} (4 %) in NI; and (2) under irrigation conditions, EONR was reduced by 45 kg N ha^{-1} (18.8 %) and its cost by USD \$56.25 ha^{-1} (18.8 %), compared to a decrease of 0.475 Mg ha^{-1} (4 %) in EOY and USD \$26.85 ha^{-1} (2.5 %) in NI. These reductions in EONRs with increased N/MPR have both economic and environmental implications. Economically, they decrease the cost of N fertilization without significantly reducing NIs, within certain limits. Environmentally, they contribute to reducing N losses by applying lower amounts of N to crops, thus mitigating environmental contamination. Practically, it is necessary to consider how much the N/MNR can be increased without significantly affecting yields and net incomes.

The higher the rate of N applied to the crop, the greater the potential losses through processes such as leaching, volatilization, denitrification, and surface runoff (McLellan

Table 3. Economic optimal nitrogen rate (EONR), economic optimal yield (EOY), cost of nitrogen (N), and net income (NI) from an increase in the N/maize price ratio (N/MPR) in maize under rainfed and irrigated conditions.

Moisture condition	Increase in N/MPR (%)	EONR (kg N ha ⁻¹)	EOY (Mg ha ⁻¹)	Cost of N (USD \$ ha ⁻¹)	NI (USD \$ ha ⁻¹) [§]
Rainfed [†]	0	177	6.861	221.25	554.40
	25	167	6.777	208.75	552.20
	50	157	6.687	198.75	548.95
	75	148	6.574	185.00	540.45
	100	139	6.464	173.75	532.45
	125	131	6.337	163.75	520.20
	150	122	6.172	152.50	502.60
Irrigated [‡]	0	240	11.771	300.00	1184.90
	25	229	11.681	286.25	1182.90
	50	217	11.568	271.25	1178.15
	75	206	11.437	257.50	1168.95
	100	195	11.296	243.75	1158.05
	125	185	11.133	231.25	1142.00
	150	175	10.967	218.75	1125.45

[†]Yield between 5 and 8.5 Mg kg ha⁻¹. [‡]Yield between 10 and 14 Mg ha⁻¹. [§]Fixed costs, USD \$425 for rainfed, USD \$575 for irrigation.

Table 4. Reduction of the economic optimal nitrogen rate (EONR), economic optimal yield (EOY), cost of nitrogen (N), and net income (NI) due to the increase in the N/maize price ratio (N/MPR) in rainfed and irrigated maize.

Moisture condition	Increase in N/MPR (%)	EONR (kg N ha ⁻¹)	EOY (Mg ha ⁻¹)	Cost of N (USD \$ ha ⁻¹)	NI (USD \$ ha ⁻¹)
Rainfed	0	0	0.000	0	0
	25	10	0.084	12.5	2.2
	50	20	0.174	50.0	5.4
	75	29	0.287	36.2	13.9
	100	38	0.397	47.5	21.9
	125	46	0.524	57.5	34.7
	150	55	0.689	68.7	51.8
Irrigated	0	0	0.000	0	0
	25	11	0.090	13.7	2.0
	50	23	0.203	28.7	6.7
	75	34	0.334	42.5	15.9
	100	45	0.475	56.2	26.9
	125	55	0.638	68.7	42.9
	150	65	0.804	87.2	59.4

et al., 2018; Millar *et al.*, 2018). In this study, N losses were reduced based on economic considerations with the increase in N/MPR. However, strategies to reduce N losses and practices related to the use and management of N fertilizers should also be considered. Depending on the crop, soil, and climate, N losses are related to the management of the N fertilizer in relation to its chemical form, application time, application method, and the level of N rate relative to the soil N contribution (Morris *et al.*, 2018; Banger *et al.*, 2020b; Wang *et al.*, 2020a). In addition, the use of soil and plant analysis leads to more accurate N recommendations, thereby reducing N losses (Morris *et al.*, 2018). For example, in the United States and China, which are leading producers of maize, there have been issues with N management. In 2011, in the USA, 71 % of drained lands did not have proper management in terms of rates, application time, and application methods (Ribaud *et al.*, 2011). Also, considering that de N fertilizer should be applied when the maize requires it: (1) in 2012, 91 % of farmers in Minnesota, USA, applied N in a single application (either in autumn or spring pre-planting) (Bierman *et al.*, 2012), and (2) in China, in 2019, 51.4 % of farmers applied N in a single application to average rates of 248 kg N ha⁻¹, achieving mean yields between 9.1 and 10.9 Mg ha⁻¹ (Chen *et al.*, 2019).

The practice of applying excessive amounts of N to crops, particularly maize, is prevalent in several countries (Huang *et al.*, 2012; Ribaud *et al.*, 2015; Flores-Sánchez *et al.*, 2019). The change to practices that reduce N losses is a complex process that covers not only economic and environmental aspects but also social ones. In this regard, there may be several factors and beliefs among farmers: (1) higher N rates would produce higher yields without considering that the relationship between both variables is not linear (positive, decreasing) (Chen *et al.*, 2019); (2) farmers who have previously achieved satisfactory results applying high N rates are likely to continue using such rates (Sawyer *et al.*, 2006); (3) farmers primarily focused on maximizing income, often at the expense of environmental considerations (Ribaud *et al.*, 2015); and (4) adopting improved technologies that increase NUE can be complex and difficult to adopt (Chen *et al.*, 2019).

Various programs aimed at making N use more efficient in crops have been primarily voluntary, focusing on encouraging farmers to adopt practices that reduce N losses and, with some exceptions, have had limited impact (Ribaud *et al.*, 2015; McLellan *et al.*, 2018). An alternative approach could be that farmers from support programs (such as agricultural insurance, services, and subsidies) should comply with recommended practices for management of N fertilizers (Ribaud *et al.*, 2015).

Increase in the nitrogen/maize price ratio and applied nitrogen use efficiency

The losses of N applied to crops are often indirectly inferred through NUE measurements, where higher NUE indicates lower N losses (Wortmann *et al.*, 2011; Millar *et al.*, 2018; Lu *et al.*, 2019). In the experiments discussed earlier, under both rainfed and irrigated conditions, NUE was calculated with increased N/MPR values (Table 5). As the EONR decreased due to the increase in N/MPR, the NUE correspondingly increased. For instance, with the N/MNR increasing from 0 to 150 %,

Table 5. Nitrogen use efficiency based on the increase in the nitrogen/maize price ratio in rainfed and irrigated maize.

Moisture condition	Increased nitrogen/maize price ratio (%)						
	0	25	50	75	100	125	150
Rainfed	0.47	0.49	0.51	0.54	0.56	0.58	0.61
Irrigated	0.53	0.55	0.58	0.60	0.62	0.63	0.67

the NUE increased from 0.47 to 0.61 under rainfed conditions and from 0.53 to 0.67 under irrigated conditions (Table 5). Therefore, utilizing the N/MNR in line with the MNIS economic criterion not only leads to a reduction in EONR but also an increase in NUE, thereby reducing N losses. (Table 4).

CONCLUSIONS

Based on maize yield data obtained from experiments with increasing N rates under diverse climate and soil conditions in Mexico, economic optimal N rates (EONR) were determined for attainable maize yield levels under rainfed and irrigated conditions, which may have practical applications at a regional level. An increase in the N/maize (grain) price ratio (N/MPR) led to a decrease in the economic optimal N rates (EONR), resulting in lowered costs of N fertilization without significantly impacting yields and net incomes (NI). The N use efficiency (NUE) increased with: (1) the rise in the level of economic optimal yield (EOY); and (2) the decrease in the economic optimal N rate related to an increasing N/maize (grain) price ratio. The use of N/maize (grain) price ratios was a way to reduce both the economic optimal N rates and, consequently, the N losses, thereby mitigating environmental pollution.

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