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NITROGEN FERTILIZATION FOR MAIZE BASED ON ATTAINABLE YIELD AND SOIL ORGANIC MATTER CONTENT

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ABSTRACT

Agricultural soils generally do not provide enough N to satisfy crop needs, so it is necessary to apply it as fertilizer. This supply can be estimated by chemical analysis of the soil and, based on this and the needs of the plant, nitrogen fertilization recommendations are made for the crops. The objective of this study was to determine economic optimum N rates for maize (*Zea mays* L.), based on attainable yield and soil organic matter content as an estimator of soil N supply, with the current and increased N/maize price ratio, to reduce economic optimum N rates and fertilization costs, as well as N losses and environmental pollution. In 2011, 2012, and 2013, 67 experiments on maize response to N were distributed and conducted in five edaphoclimatic regions of Mexico, with native and improved maize in rainfed and irrigation conditions. The treatments were: (1) fertilization with N, P, and K; (2) omission of each nutrient; and (3) no fertilization. The experimental design was a randomized complete block design, without replications. Production functions were estimated for rainfed and irrigation conditions in edaphoclimatic regions, for yield as a function of attainable yield classes, amount of N applied, and soil organic matter content. The production functions were used to estimate economic optimum N rates, with: (1) the current N/maize price ratio for the attainable yield classes and soil organic matter contents, as well as optimum economic yields and net income; and (2) the increased N/maize price ratio, that reduced the economic optimum N rates and fertilization costs, without significantly decrease of the economic optimum yields and the net income; this also reduces N losses and environmental pollution.

Keywords: *Zea mays* L., production function, N/maize price ratio, economic optimum nitrogen rate, economic optimum yield, net income.

INTRODUCTION

In Mexico, maize is grown on approximately 7.5 x 10^6 ha, of which about 21.5 % is irrigated and 78.5 % rainfed. Agricultural and Livestock and Fisheries Information and Statistics Service (SIAP) estimated in 2018 a national average yield of 1870 kg ha^{-1} in rainfed crops and 8760 kg ha^{-1} under irrigation, with variations among maize-producing states between 580 and 6470 kg ha^{-1}, and between 2490 and 11460 kg ha^{-1}, respectively (SIAP, 2018). This information does not indicate the causes of the low yields obtained. This can be attributed, in addition to possible deficient crop management, to limiting soil and climate conditions in rainfed, and to the shortage of water in irrigation conditions, without excluding the fact that limiting climate conditions can also occur.

Crop management includes several technological components, among which fertilization is one of the most important when the soil does not have sufficient capacity to meet the nutrient requirements of the crop. Thus, as is generally known, on the one hand, low fertilization will cause lower crop yields than potentially possible, and lower farmer incomes; on the other, over-fertilization will result in higher production costs and lower farmer incomes, as well as higher environmental pollution.

Among the nutrients normally supplied to crops by fertilization, N stands out in importance because of the amount required by them (Ciampitti and Vyn, 2014; Bak *et al*., 2016), and because of the losses that occur in its use, which for maize are estimated on average between 35 and 65 % (Morris *et al*., 2018). These losses occur through leaching (as $N\text{-}NO_3$), volatilization (as NH_3), denitrification (as N_2, N_2O), and surface runoff (Grajeda-Cabrera *et al*., 2011; Morris *et al*., 2018), of which N_2 and N_2O are strong greenhouse gases (McLellan *et al*., 2018; Millar *et al.,* 2018). Factors affecting losses are soil and weather conditions, and the chemical form and management practices of the fertilizer, but one practice that increases losses is the application of high and excessive amounts of N to crops (Wortmann *et al*., 2011; McLellan *et al*., 2018).

Different approaches have been used to determine the amount of N to be applied as fertilizer to maize (Morris *et al*., 2018). One is based on the attainable crop yield, considering or not the supply of N by the soil and the production system (Morris *et al*. 2018). And another one is based on field experiments of crop response to two or more N rates, in which economic optimum N rates are estimated, and associated with N supply by soil and the production system, or recommendations are generated for similar soil and climate units and production systems (Moreno-Ramos *et al*., 2014; Morris *et al*., 2018).

One way to estimate the N supply by the soil is as soil analysis when properly calibrated, for which there are different methods of chemical analysis. The values determined by the analysis method are an approximate indicator of the soil capacity to supply a certain amount of a nutrient to the crop, since various factors (soil, climate, production system) can modify its expression. For N, among soil analyses, the following have been considered: available N ($N\text{-}NO_3$+$N\text{-}NH_4$) (Hartmann *et al*., 2014; Morris *et al*., 2018), potentially mineralizable N (Sharifi *et al*., 2007; Murphy *et al*., 2009), total N (Wang *et al*., 2012; Ren *et al*., 2015) and organic matter (OM) (Janssen *et al*.,1990; Morris *et al*., 2018). Among these, OM has the advantage of being determined within a routine soil analysis (SEMARNAT, 2002), though its mineralization is affected by several factors.

Organic matter mineralization depends on soil (pH, texture) and climate (precipitation, temperature) conditions, type of OM (C/N ratio), presence of irrigation, and the production system (crops and their management) (Clivot *et al*., 2017; Crzyb *et al*., 2020). This implies that the relationship between crop response to N and the N supply by OM must be estimated under different soil and climatic conditions and production systems (Moreno-Ramos *et al*., 2014; Morris *et al*., 2018).

In the optimization to determine economic optimum rates of a nutrient, the economic criterion of maximization of net income per hectare has been used. This economic criterion determines the maximum economically optimum rates, and since high N rates increase N losses (Dobermann *et al*., 2011; Morris *et al*., 2018), it is associated with higher N losses. One way to decrease the economic optimum N rates determined by this economic criterion is with an increase in the N/maize price ratio in economic optimization (Chen *et al*., 2011; Dobermann *et al*., 2011; Morris *et al*., 2018), but provided that yields and net returns do not decrease significantly.

The objective of this study was to determine economic optimum N rates for maize in edaphoclimatic regions of Mexico, based on attainable yield and soil OM content as an estimator of soil N supply, with the current and increased N/maize price ratios, to reduce economic optimum N rates and fertilization costs, as well as N losses and environmental pollution.

MATERIALS AND METHODS

The information was obtained from 67 experiments on maize response to N, conducted by the MasAgro Program of the International Maize and Wheat Improvement Centre (CIMMYT), in 2011, 2012, and 2013 in Mexico. The experiments were located in fields of local farmers and maize-maize production systems. Treatments consisted of fertilization with N, P, and K (complete fertilization), the omission of each nutrient, and a control treatment with no fertilization (Wang *et al*., 2012; Ren *et al*., 2015). The experiments were distributed in five edaphoclimatic regions, as follows: 16 in Bajio (Guanajuato, Jalisco, Michoacan, Queretaro), 19 in Tropico (Chiapas, Guerrero, Oaxaca, Quintana Roo), 22 in Valles Altos (Mexico, Hidalgo, Puebla, Tlaxcala), eight in Pacifico (Sinaloa, Sonora), and two in Intermedia (San Luis Potosi). Seventeen experiments were established under irrigated conditions and 50 under rainfed conditions. In irrigated conditions, improved maize was sown, while in rainfed conditions, native (21) and improved (29) maize were sown. In the edaphoclimatic regions, there are differences in altitude and soil and climate types, which affect crop yields, while in the Pacifico region and some states, production is carried out with irrigation. The predominant agricultural soils are classified as Phaeozems, Vertisols, Cambisols, and Luvisols, with textures ranging from loamy to clayey, and there are sandy textures in some states (Puebla, Tlaxcala) due to volcanic eruptions (INEGI, 2007). The types of climate present are associated with latitude, altitude, relief, and distance from the coasts. So, warm climates predominate in the coastal plains, dry in the north, sub-humid to humid in the south of the country, and temperate climates predominate in the highlands, sub-humid and dry, depending on the distance from the coasts (INEGI, 2018). The rainfall regime is in summer, going from May/June to September/October

(INEGI, 2018). The altitude of maize sowings and mean annual precipitations in the edaphoclimatic regions are shown in Table 1 (SAGARPA *et al*., 2015; INEGI, 2018).

The N, P, and K rates of the experiments were determined according to an estimation of the expected yield, based on information obtained by the personnel who participated in the field experimentation. These ranged from 30 to 350 kg N ha^{-1}, 16 to 260 kg P_2O_5 ha^{-1}, and 30 to 230 kg K_2O ha^{-1}, in the form of urea (46 % N), triple Ca superphosphate (46 % P_2O_5) and K chloride (60 % K_2O), respectively. Nitrogen application time was determined according to the expected yield: for yields less than 4000 kg ha^{-1}, one-third was applied at sowing and the rest in the first tillage, and for yields greater than 4000 kg ha^{-1}, the whole N was applied in the first tillage. P and K were applied at sowing. Stocking density, weed, pest, and disease control were carried out according to the recommendations given by the National Institute of Forestry, Agricultural and Livestock Research of Mexico (INIFAP) for the states of the edaphoclimatic regions (SAGARPA, 2015). The experimental design was a randomized complete block, without replications. The experimental units were plots of 5.6 × 8.0 m, with six furrows of maize, separated by 0.80 m.

At each experimental site, soil sampling was carried out at a depth of 20 cm, taking 10 subsamples to obtain a composite sample. The determinations were OM, by wet combustion with a mixture of $K_2Cr_2O_7$ and H_2SO_4; P, by the Olsen method (assuming that the pH value in some soils was greater than 7.0), and colorimetry with molybdenum blue; and exchangeable K, with 1 N ammonium acetate at pH 7, and quantified by flame emission spectrometry. All chemical procedures were performed according to the Mexican Official Standard (SEMARNAT, 2002). The mean value and range of the determined properties were as follows OM, 2.05 %, 0.34-4.0 %; P Olsen, 28 mg kg^{-1}, 6-103 mg kg^{-1}; and, exchangeable K, 384 mg kg^{-1}, 57-1624 mg kg^{-1}.

Because the maximum maize yields observed (treatment with complete fertilization) varied between and within edaphoclimatic regions, yield classes were established as an estimate of attainable yields: in rainfed conditions, depending on the soil and climatic factors present, and under irrigation, depending on an assumed irrigation intensity, all of which have not been determined. These classes were: (1) rainfed, <1750,

Table 1. The altitude of maize sowings and mean annual precipitation in edaphoclimatic regions.

Region	Altitude (m)	Precipitation† (mm)
Pacifico	< 40	250-450, 300-500, 500-800
Bajio	<1600-2600	400-1000, 1000-1500
Valles Altos	1600-2600	400-1000
Tropico	< 2300	350-750, 600-1000, 1000-1500
Intermedia	< 2100	300-500, 550-700

†By subregion.

1750-3000, 3000-4250, 4250-5500, 5500-6750, 6750-8000, and 8000-9250 kg ha^{-1}; and (2) irrigated, 8000-10000, 10000-13000, and 13000-16000 kg ha^{-1}, in the Pacific region, and irrigated maize in the Bajio and Tropico regions.

The information was analysed by regression to obtain a production function of maize yield as a function of applied N and soil OM content as an estimator of soil N supply, and other factors considered, both for rainfed and irrigation. These factors were: (1) years, as an auxiliary variable; (2) Olsen P and exchangeable K content of the soil, as estimators of the contribution of P and K by the soil; (3) amounts of N, P and K applied as inorganic fertilizers; and (4) attainable yield classes, which were considered as a numerical variable, of 1, 2, 3, 4, 5, 6, and 7 for rainfed, and 2, 3 and 4 for irrigation. In rainfed, native and improved maizes were considered together, and under irrigation conditions, only the improved maize was considered. The regression procedure used to perform the analysis and obtain the production functions was that proposed by Volke (2008), which consisted of: (1) specifying an initial regression model for N, as indicated by the graphical relationship of crop response to N application, and for some other factor that had an observable effect on yield; (2) the model underwent the PROC REG procedure of SAS (Statistic Analysis System), and the R INFLUENCE option (Freund and Littell, 2000), in order to observe the presence of possible atypical observations (outliers), which in such case were eliminated ($p=0.01$) (Myers, 1990; Freund and Littell, 2000); (3) the R INFLUENCE option allows to graphically observe the fit to the model of the factors already included in it, as well as the model for factors not yet included, whose inclusion will be tested; (4) among the variables to be tested are the interactions between factors, depending on the phenomenon; and (5) the final model was the one with the lowest mean square of the error, and interpretable in terms of the phenomenon.

With the production function and the N/maize price ratio (calculated from the total cost of N and the net price of the product), the economic optimum N rates were calculated for the yield classes of rainfed and irrigation conditions, and the soil OM contents (1.0, 2.0 and 3.0 %). For this purpose, a SAS optimization program was used, which in addition to the economic optimum N rates, allows calculating the economic optimum yields, and if fixed costs are considered, the net income and benefit/cost ratios can also be estimated (Briones *et al*., 2009).

The total cost per N unit was 1.19 USD kg^{-1}, which includes the market price and transportation, application and interest on invested capital costs, and was an average of the ammonium sulphate and urea sources most frequently used by producers. The net price of maize was 0.167 USD kg^{-1}, which corresponds to the market price minus the costs of harvesting, transportation, and interest on invested capital. Based on the N and maize prices, the N/maize price ratio was 7.14 The fixed production costs considered in each production condition and attainable yield class are shown in the tables. The economic criterion used for the calculation of economic optimum N rates was "the maximization of net incomes per area (hectare)" (Chen *et al*., 2011; Morris *et al*., 2018: Velázquez-Xochimil and Portillo, 2018). Economic optimization was carried out with the current N/maize price ratio and increased by 25, 50, 75, and 100 %, to evaluate the effect of such an increase on the decrease of the economic optimum N rates, the cost of N, the economic optimum yields and net incomes, and on the decrease of N losses and environmental pollution.

RESULTS AND DISCUSSION

Production functions

The production functions generated for rainfed and irrigated maize are the following:

$$Y_{rainfed} = 65.458 + 7.063\ NT - 0.01257\ N^2T + 636.314\ M^{0.75}T^{0.75} - 0.8900\ NMT$$
$$(Pr.\ F = 0.01,\ CME = 962\ 852,\ R^2 = 0.839)$$

$$Y_{irrigation} = 4588.040 + 34.454\ N^{0.75}R - 0.00609\ N^2\ R + 578.424\ M^{0.75}\ R - 1.563\ N\ M$$
$$(Pr.\ F = 0.01,\ CME = 651\ 551,\ R^2 = 0.939)$$

where: Y = maize yield (kg ha^{-1}), N = nitrogen applied (kg N ha^{-1}), T = yield rainfed class (scale 1, 2, 3, 4, 5, 6 and 7), R = yield irrigation class (scale of 2, 3 and 4), M = soil OM content (%).

The production functions included the following factors: applied nitrogen rates, attainable yield class, and soil OM content, for which economic optimization will be carried out. However, the following factors were not included: year, Olsen P and soil exchangeable K, and treatments without P and K applied. In the case of years, this implies that the within-year variation was greater than the between-year variation, and for P and K it would mean that there were no significant effects, which is not in agreement with what was expected.

Economic optimum nitrogen rates for rainfed and irrigated maize

Economic optimum N rates (EONR) were determined for the mean yields of the attainable yield classes of the edaphoclimatic regions, with different soil and climatic conditions; therefore, in rainfed conditions, it is assumed that the same attainable yield is possible to obtain in different soil and climatic conditions, depending on how these are. On the other hand, it is also assumed that N concentration in the plant is relatively constant, and therefore, N extraction by the crop was based only on yield.
Attainable yield has been considered in countries such as the USA, in almost all subsystems of N recommendation generation, in the period from 1970 to 2005 (Morris *et al*., 2018), and in China, where it continues to be used (Wang *et al*., 2012; Ren *et al*., 2015), countries that are the largest maize producers in the world. However, in the USA, since 2005, the generation of N recommendations based on economic maximum return criteria is being promoted (Morris *et al*., 2018).
For the EONR on the function of soil OM contents, even when dealing with maize-maize production systems, it can be assumed that the different soil and climate

conditions observed in the edaphoclimatic regions could have caused differences in soil OM mineralization, and thus N soil supply (Tremblay *et al*., 2012). This means that the obtained EONR will correspond to mean values for such varying soil and climate conditions.

For the rainfed condition, native and improved maize crops were considered together. Improved maize has increased yields over time in relation to unimproved maize, and at the same time diminished plant N concentration; thus, their increased N requirements may not be of a significant magnitude (Woli *et al*., 2016). Accordingly, if the improved maize is placed in a higher attainable yield class, it may have a higher N recommendation than the correct one.

Soil OM contents varied between and within edaphoclimatic regions, according to the following mean value and range: Pacifico, 2.46 %, 1.2-4.0 %; Bajio, 2.60 %, 1.6-3.9 %; Valles Altos, 1.68 %, 0.34-2.7 %; Tropico, 1.97 %, 1.1-4.0 %; and Intermedia, 1.35, 1.2-1.5 %. The economic optimization was done for soil OM contents of 1.0, 2.0, and 3.0 %, valid as mean contents for the Pacifico, Bajio, and Tropico regions. For the Valles Altos and Intermedia regions, such economic optimization should be done for the contents of 0.5, 1.5, and 2.5 % in the former and 1.5 % in the latter, which was not done in this study.

The economic optimum yields (EOY), net income (NI), and N/MPR for attainable yield classes and soil OM contents of 1.0, 2.0, and 3.0 %, plus the amount of fixed costs, are presented in Tables 2 and 3; for native and improved rainfed maize in the Bajio, and Tropico regions (Table 2), and irrigated improved maize in the Pacifico region (Table 3).

In rainfed conditions, lower yields are associated with the presence of a limiting rainy season due to shortage and poor distribution of rainfall, and soil limitations (texture, depth, etc.); in irrigated conditions, it is assumed that yields would be mainly associated with irrigation intensity. On the other hand, in both moisture conditions, soil OM content increased yield only slightly with the attainable yield classes, on average between 325 and 450 kg ha^{-1} in rainfed conditions and between 200 and 825 kg ha^{-1} in irrigation conditions.

The EOY and EONR were higher in irrigated than in rainfed conditions, and EONR increased with higher yield and decreased with higher soil OM. This result is congruent with these considerations: (1) the higher the grain yield and therefore biomass, the higher the N demand (Wortmann *et al*., 2011; Wang *et al*., 2020); and (2) the higher the soil OM content, the higher the N supply to the crop (Morris *et al*., 2018). Therefore, EONR will increase and decrease, respectively.

When relating EOY to EONR, for a soil OM content of 2.0 % (Figure 1), different trends are observed in rainfed (positive curvilinear) and irrigated (practically positive linear) conditions. In rainfed conditions, the increase in EOY becomes relatively greater than that in EONR at values greater than 100 kg N ha^{-1} This situation could indicate that higher yields increase the efficiency of applied N utilization (Feng *et al*., 2016; Sifuentes *et al*., 2018).

Table 2. Economic optimum nitrogen rates for attainable yield classes of rainfed maize, soil organic matter contents, and associated variables.

Yield class (kg ha^{-1})	Soil organic matter (%)	Economic optimum N rate (kg ha^{-1})	Economic optimum yield (kg ha^{-1})	Net income (USD ha^{-1})	Benefit/ cost ratio	Fixed costs (USD ha^{-1})
<1750	1	0	701	0	0	166.7
	2	0	1135	22.6	0.14	
	3	0	1516	86.0	0.52	
1750-3000	1	105	2154	43.7	0.14	190.5
	2	70	2481	139.8	0.51	
	3	35	2781	231.4	1.00	
3000-4250	1	150	3445	181.4	0.46	214.3
	2	115	3828	286.9	0.82	
	3	80	4184	387.9	1.25	
4250-5500	1	175	4646	326.0	0.74	238.1
	2	140	5065	439.4	1.09	
	3	105	5488	546.7	1.51	
5500-6750	1	185	5752	476.5	0.99	261.9
	2	150	6191	591.5	1.34	
	3	115	6610	702.9	1.76	
6750-8000	1	200	6895	601.5	1.10	309.5
	2	165	7345	718.2	1.42	
	3	125	7742	832.0	1.81	
8000-9250	1	205	7964	726.1	1.21	357.0
	2	170	8414	842.8	1.51	
	3	135	8855	957.9	1.85	

Table 3. Economic optimum nitrogen rates for attainable yield classes of irrigated improved maize and soil organic matter contents, and associated variables.

Yield class (kg ha^{-1})	Soil organic matter (%)	Economic optimum N rate (kg ha^{-1})	Economic optimum yield (kg ha^{-1})	Net income (USD ha^{-1})	Benefit/ cost ratio	Fixed costs (USD ha^{-1})
8000-10000	1	210	8680	791.9	1.21	404.7
	2	170	8894	875.2	1.44	
	3	135	9099	951.0	1.68	
10000-13000	1	280	11528	1135.6	1.44	452.4
	2	250	12081	1263.5	1.68	
	3	225	12568	1374.4	1.91	
13000-16000	1	325	14369	1469.9	1.70	476.2
	2	300	15283	1666.2	2.00	
	3	275	16036	1821.6	2.27	

The decrease in EONR with increasing soil OM, from 1.0, 2.0 to 3.0%, in the different attainable yield classes was: (1) in rainfed conditions, 35 kg N ha^{-1}; and (2) under irrigated conditions, between 25 and 30 kg N ha^{-1} for the 10000-13000 and 13000-16000 kg ha^{-1}

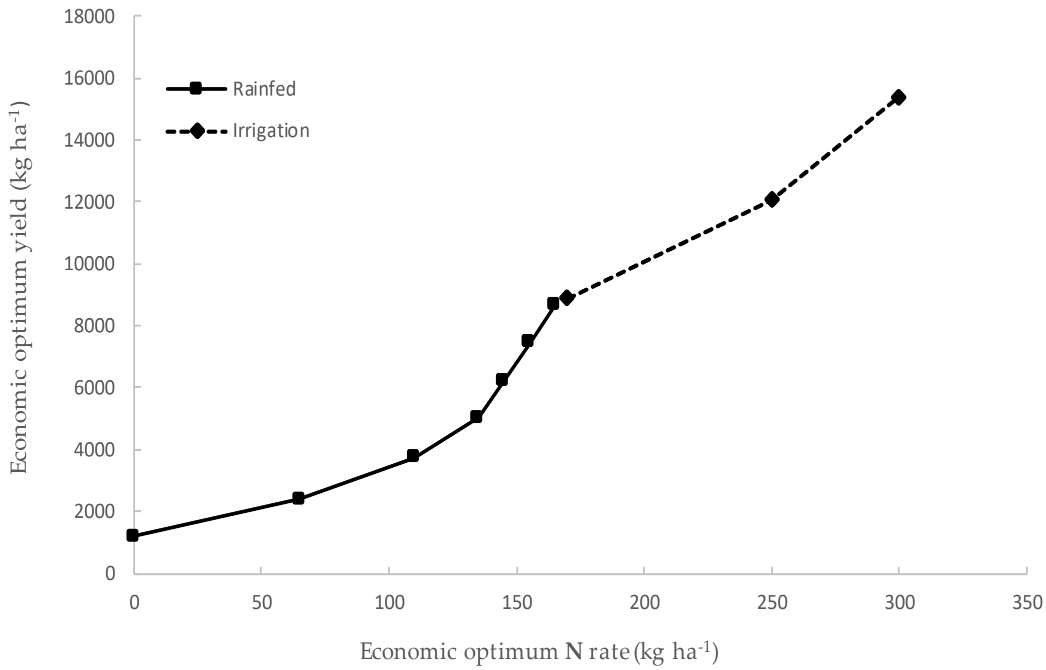

Figure 1. Relationship between economic optimum yield and economic optimum nitrogen rate, at 2.0 % soil organic matter content.

yield classes, and between 35 and 40 kg N ha^{-1} for the 8000-10000 kg ha^{-1} yield class. These values would correspond to the N supply made by soil OM; however, they are higher values compared to those indicated by some literature (Morris *et al*., 2018).

The NI and B/CR increased with the increment of maize yield and soil OM content, to a greater extent NI in the irrigated condition. In the case of OM, its greatest effect was due to the EONR decrease it caused. Although the B/CR may vary among farmers, due to their variable and fixed costs, from an economic point of view a ratio lower than 0.50 would not be profitable for commercial production, though it would be justified if the objective is self-consumption.

The use of soil OM as a tool to generate N recommendations for maize, for different attainable yields associated with climate and soil conditions, and production systems, may allow for greater accuracy in this task. However, it would be interesting to know the effect of not complying with the recommendations according to the OM content of the soil. In this sense, if we take as an example the attainable yield class of 5500-6750 kg ha^{-1} in rainfed conditions (Table 2), this effect is manifested in two ways. The first, for 1.0 % OM, if instead of 185 kg N ha^{-1}, 150 kg N ha^{-1} is applied, there would be a 6.0 % decline in yield (343 kg ha^{-1}) and only a 3.3 % decrease of NI (15.57 USD ha^{-1}), and at the same time a drop in N cost of 41.67 USD ha^{-1}; if only 115 kg N ha^{-1} is applied, the decline in yield would be 14.6 % (841 kg ha^{-1}) and 11.8 % of NI (56.33 USD ha^{-1}), but the decrease in N cost would be 83.33 USD ha^{-1}; thus, it would be more important and economical to reduce the cost of N acquisition than the impact on yield reduction and NI. The second, for 3.0 % OM, if instead of 115 kg N ha^{-1}, 150 kg N ha^{-1} is applied, the yield would increase by 2.8 % (186 kg ha^{-1}) and NI decreased by 1.5 % (10.71 USD ha^{-1}), with an increment in N cost of 41.67 USD ha^{-1}; if 185 kg N ha^{-1} are applied, maize yield would increase by 3.3 % (217 kg ha^{-1}), and NI decreased by 6.7 % (47.10 USD ha^{-1}), with an increase in N cost of 83.33 USD ha^{-1}; therefore, using higher rates according to what would correspond to the OM content of the soil implied that the N applied underwent a rise between 30 and 65 kg N ha^{-1}, respectively, which to a large extent will end up causing environmental pollution; this shows the importance of not using N rates higher than what the soil analysis suggests.

The practical use of EONR generated by the procedure followed in this study requires the farmer to specify the yield that can be obtained under his production conditions, either with native or improved maize, although this yield may be affected by the deficient use of management components, which will have to be considered; and, to determine the OM content of the soil there are two options: (1) if soil test is not available, propose a probable percentage based on soil colour; and (2) if soil test is available, consider the recommendation for the OM content present in the land of the farmer.

Economic optimization with increased N/maize price ratios

The economic criterion of maximizing net income per area (MNIA) used in this study generates the maximum EONR, as well as the greatest yields and associated costs. This economic criterion can be used with increased (in percent) N/maize price ratios (N/MPR) (Dobermann *et al*., 2011; Morris *et al*., 2018), to obtain EONR lower than the economic maximum. Then, for responses of decreasing marginal returns, calculated with a quadratic or similar model as in this study, it is important to establish the effect of decreasing EONR on yields, fertilization costs, and net incomes. As an example, this situation is presented for yield attainable classes 4250-5500 and 6750-8000 kg ha^{-1} in rainfed maize and 10000-13000 kg ha^{-1} in irrigated maize, in soil with 2.0 % OM (Table 4).

As the N/MPR increased, the EONR decreased, and consequently their cost, as well as EOY and NI. Considering as an example a N/MPR increased by 75 %, the effect of decreasing EONR, EOY, N cost and NI is on yield classes: (1) 4250-5500 kg ha^{-1} in rainfed, of 55 kg N ha^{-1}, 540 kg ha^{-1}, 65.48 USD ha^{-1}, and 24.52 USD ha^{-1}, respectively; (2) 6750-8000 kg ha^{-1} in rainfed, of 40 kg N ha^{-1}, 394 kg ha^{-1}, 47.61 USD ha^{-1}, and 18.10 USD ha^{-1}, respectively; and (3) 10000-13000 in irrigation, of 85 kg N ha^{-1}, 830 kg ha^{-1}, 101.19 USD ha^{-1}, and 36.70 USD ha^{-1}, respectively.

From an economic point of view, it would be justified to diminish the EONR in this case using the N/MPR, without significantly decreasing the EOY and NI, within certain limits. This is worth considering when N rates are being generated with the MNIA economic criterion; such is the case, for example, in the USA, the largest maize producer worldwide, where the use of this economic criterion is being promoted since 2005 (Morris *et al*., 2018).

Table 4. Economic optimization with increased N/maize price ratios, in attainable yield classes of rainfed and irrigated maize, and 2.0 % soil organic matter†.

Yield class (kg ha^{-1})	Increased N/MPR (%)	EONR (kg ha^{-1})	EOY (kg ha^{-1})	N cost (USD ha^{-1})	NI (USD ha^{-1})
Rainfed					
4250-5500	0	140	5065	166.7	439.4
	25	120	4904	142.8	436.4
	50	100	4702	119.0	426.6
	75	85	4525	101.2	414.9
	100	70	4325	83.3	399.4
6750-8000	0	165	7345	196.4	718.2
	25	150	7225	178.6	716.6
	50	140	7127	166.7	711.6
	75	125	6951	148.8	700.1
	100	115	6815	136.9	689.4
Irrigation					
10000-13000	0	250	12081	297.6	1263.5
	25	220	11838	261.9	1258.7
	50	190	11542	226.2	1245.1
	75	165	11251	196.4	1226.8
	100	140	10917	166.7	1200.4

†N/MPR = N/maize price ratio, EONR = economic optimum nitrogen rate, EOY = economic optimum yield, NI = net income.

The incorporation of N/MPR into the MNIA economic criteria, with the lower EONR it causes, reduces N losses associated with greater N applications and, consequently, environmental pollution. In this regard, Table 5 provides an estimate of what the decrease in applied N losses (EONR) would be with the use of N/MPR in the economic optimization with the MNIA economic criterion.

Final remarks

Nutrient extraction by crops at a given yield comes from soil supply, and when this is not sufficient, fertilizers provide what is needed. If the nutrients extracted are not adequately replenished in the soil, deficiencies will occur at some point, affecting the sustainability of the production system. One way to estimate soil nutrient reserves is through soil analysis, which in turn allows for more accurate fertilizer recommendations, as indicated by the abundant literature on the subject. However, its use by farmers is not widespread, even in the most developed or major grain-producing countries. On the other hand, in various countries, it is common to observe farmers applying excessive amounts of nitrogen fertilizers to crops, which will eventually cause an increase in groundwater pollution and the generation of greenhouse gases. The increased production of greenhouse gases has originated in

Table 5. Estimated nitrogen losses from the use of N/maize price ratios in economic optimization, in rainfed and irrigation attainable yield classes, and 2.0 % soil organic matter†.

Yield class (kg ha^{-1})	N/MPR (%)	EONR (kg ha^{-1})	N saving (kg ha^{-1})
Rainfed			
4250-5500	0	140	0
	25	120	20
	50	100	40
	75	85	55
	100	70	70
6750-8000	0	165	0
	25	150	15
	50	140	25
	75	125	40
	100	115	50
Irrigation			
10000-13000	0	250	0
	25	220	30
	50	190	60
	75	165	85
	100	140	110

†N/MPR = N/maize price ratio, EONR = economic optimum N rate.

the last decades a greater interest of researchers to generate more precise optimum N rates through different approaches, to diminish the high and excessive rates applied by many farmers (Chen *et al*.,2011; Huang *et al*., 2012; Millar *et al*., 2018; Flores-Sánchez *et al*., 2019).

With the same purpose, researchers such as Chen *et al*. (2011), have developed in parallel to the concept of economic optimum rates, the concept of ecological optimum rate, which is determined at the point where the marginal nutrient uptake is equal to the marginal nutrient loss. In this way, it was possible to reduce the amount of N to be applied and its loss by 22-53 kg N ha^{-1} in rice varieties, with a yield reduction of less than 10.0 %. Another way to decrease the EONR is the use of N/MPR in optimization with the economic criterion of maximizing net incomes per area, which is the one developed in this study. This approach requires working with yield production functions, as the function of crop response to nutrients, soil analysis, such as organic matter, and yields attainable by the producer, according to soil and climate conditions, and production system, considering non-limiting management. With this approach, it was possible to reduce optimal N rates and fertilization cost, and therefore N losses and environmental pollution, without significantly reducing yields and net incomes.

In Mexico, fertilizer application, particularly nitrogen fertilizer, differs between rainfed and irrigated conditions. In rainfed conditions, the adoption of fertilizer recommendations has depended on the edaphoclimatic and socioeconomic conditions of the farmers. The use of high and excessive rates of fertilizers is not frequently observed among farmers. In irrigation, the situation is different; for example, in the El Bajio area, up to 554 kg N ha^{-1} have been applied in maize, with an average of 309 kg N ha^{-1} (Flores-Sánchez *et al*., 2019), and in the Valle del Yaqui, the average N application in wheat has been 300 kg N ha^{-1}, which is around twice the economic optimum rates (Millar *et al*., 2018). Considering the results of this study, the next challenge is how to demonstrate and convince farmers that with lower N rates and the consequent lower costs, it is possible to obtain yields and incomes similar to those obtained with excessive rates, and thus reduce environmental pollution.

CONCLUSIONS

Economic optimum N recommendations were generated for rainfed and irrigated maize, for different attainable maize yields and soil organic matter content as an estimator of soil N supply to the crop. The organic matter content present in the first 20 cm of the soil can be an indicator of the average N availability of different soils and climatic conditions.

The use of N/maize price ratios in the economic optimization, with the economic criterion of maximizing net income per area, caused the economic optimum N rates and associated costs to decrease, without excessively reducing the economic optimum yields and net incomes. This shows that N/maize price ratios can be a way to reduce N use and the resulting environmental pollution.

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