Article

Economic optima of fertilizer in the production of white corn in High Valleys

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Abstract

Corn production is carried out in most agricultural areas in the country, Mexico has about 64 races of corn selected for thousands of years by indigenous and mestizo groups, in addition to hybrids and improved varieties. The production technologies used by producers are diverse, ranging from traditional through intermediate to the most modern that use advanced technological packages. The latter apply high doses of fertilizers and high planting densities, with mechanized processes to obtain high yields per hectare; while other producers who apply lower doses of fertilization, with lower yields achieve better profits. The present work aims to identify, in field experiments, the optimal economic dose of fertilizer (F) for producers to achieve the maximum profit. The experiment was carried out in the Experimental Agricultural Field of the Chapingo Autonomous University using a completely randomized experimental design with four repetitions, during the spring-summer cycle of 2019. The estimated quadratic production function of white corn allows calculating the optimal economic or maximum profit dose of F (848 kg ha^{-1}), taking into account the market prices of corn and fertilizer; also the maximum yield dose (1 893 kg ha^{-1}). The results obtained will serve as an economic criterion for making production decisions for both small producers with scarce resources and medium and large producers with more resources.

Keywords: maximum profit, maximum yield, production function.

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Introduction

The production of white corn is carried out in almost all geographical regions and rural areas of Mexico, in a great diversity of environments: wet, dry, cold and hot; it is also cultivated from sea level to about 3 400 masl, with a diversity of agricultural practices and uses of more than 80 indigenous ethnic groups and many mestizo peoples. In Mexico, there are about 64 races of corn (CONABIO, 2021) resulting from a process of domestication, selection and evolution under cultivation carried out mainly by indigenous groups for 8 000 years and more recently also by mestizo groups (Wellhausen *et al*., 1951; Kato *et al*., 2009, Biodiversidad, 2020, SAGARPA, 2012).

It is the grain par excellence, so it represented 88.3% of the national production of basic grains in the agricultural year 2020 (SADER-SIAP, 2020). Which is produced under different production systems and with different technologies used that involve from small production units (PUs) of family self-consumption that allocate more than 80 percent of their production to their food, medium semi-commercial PUs that sell more than 63% of the grain, medium PUs of livestock self-consumption that allocate more than 83 percent of the corn they grow to feed the animals they raise and the large commercial PUs that sell more than 96% of their production to the national tortilla industry and that one that produces food for animal consumption, starches, vegetable oil and starches, among other products (Yunes and López, 2021).

Despite the great wealth of biodiversity and the natural, cultural conditions and millenary experience of its production by ethnic groups, all the corn that Mexican society requires to meet its nutritional needs is not produced. In 2019, an amount equivalent to 38% of the apparent national consumption was imported and represented 59% of the national production (SEADER-SIAP, 2020), although most of it was yellow corn, a raw material necessary to make food for livestock consumption and for agro-industry, which reflects a strong dependence on foreign supply.

Derived from production systems, fertilizer doses can be very varied, while some white corn producers in Mexico apply high doses of fertilizers and high sowing densities, with very mechanized processes to obtain high yields per hectare, to obtain good profits, on the other hand, there are producers with fewer resources, who apply lower doses of fertilization and therefore, lower yields but achieve higher profits per hectare because they use this input more efficiently. The hypothesis is that the former are using overdoses of inputs that lead them to obtain lower economic benefits per hectare.

This constitutes an economic problem, especially for those who sell the grain and for whom an economic solution can be shown. Producers applying doses below the economic optimum could increase their profits if they used the optimal dose on a smaller area according to their resource availability. The objective pursued in this research is to identify the optimal economic doses of fertilizer in field experiments, which will allow corn producers to use their scarce resources more efficiently to achieve the maximum return on investment in fertilizers.

Methodology

To address this study, the use of mathematical functions that empirically represent the law of diminishing returns by using mathematical functions mainly of exponential type, third- and second-degree polynomials, among others, is first analyzed (Martínez, 1972; Beattie and Taylor, 1993, Nicholson, 2002). To demonstrate this, as a first point, the relationship between nutrients and yield is established (Martínez, 1972; Jauregui and Sain, 1992; Portillo, 2015), which is expressed mathematically as follows: Let be the dose of nutrients (inputs) N, P, K, …, applied to the soil per unit area, denoted by the letters *n*, *p*, *k*, …, and Y the yield of the crop per unit area. Y= f (n, p, k,) (1). Where f can be set by a cubic, quadratic, exponential function, etc. Relationship (1) will be denoted as 'production function'.

From the economic point of view, the application of N, P, K, …, has a cost that is determined by the relationship: TC= g (n, p, k, ...) (2). Where TC is the total cost of applying nutrients per unit area, which is a function of the doses of *n*, *p*, *k*, ..., relationship (2) will be denoted as 'total cost function'. One of the most used functions in practice is a function of the form: TC= FC + $P_N n$ + $P_P p$ + $P_K k$ +…, (3). Where: FC represents the fixed costs of application and the symbols P_N, P_P, P_K, …, the unit market prices of nutrients N, P, K, ..., respectively. The total income of the producer is given by $P_Y Y$. Donde: P_Y is the unit market price of the product.

Defining the economic optimum as the amount of nutrient that generates the yield or production of maximum profit or economic benefit, that amount of input is obtained, equalizing the value of the marginal product of the input (VMgPI= MgPI $*$ $P_Y Y$) to the price of the input P_I= P_N, P_P, P_K, …, which is equivalent to equalizing the marginal product of the input (resource), (MgPI= $\partial Y/\partial I$) to the price ratio of the nutrient to the price of the product (P_I / P_Y), as stated in equation (4). Mathematically, the problem is limited to finding the maximum of the product $P_Y Y$ subject to constraint (3), assuming a linear cost function. Forming the following Lagrange function: L= $P_Y Y$ + λ (TC – FC - $P_N n$ - $P_P p$ - $P_K k$ - …).

Deriving L successively with respect to *n*, *p*, *k*, ..., and equalizing the corresponding equalities to the input/product price ratio, one obtains: $\frac{\partial L}{\partial n} = \frac{P_N}{P_Y}$, $\frac{\partial L}{\partial p} = \frac{P_P}{P_Y}$ (4), $\frac{\partial L}{\partial k} = \frac{P_K}{P_Y}$. The system of equations (4) is solved simultaneously. The values of *n*, *p*, *k*, …, that are obtained must satisfy the system and are the optimal doses of resources. When considering the FC of the application of fertilizers, it may happen that the value of the increase in yield is not sufficient to cover the TC of the application. Low-dose applications may be insufficient to pay for FC, even if they cover the variable costs $P_N n$ + $P_P p$ + $P_K k$ +…, of equation (3).

From the above, it is deduced that there must be a minimum value of *n*, *p*, *k*, ..., whose applications below these minimum doses will produce losses instead of the desired profit. Based on Pesek and Heady (1958) cited in (Martínez, 1972), the quantities of inputs that make maximum net profits per monetary unit are considered as minimum doses of application. Considering that the total profit is the difference: $\pi = P_Y Y - TC$; from where the net profit per monetary unit spent is denoted as R and defined as follows: R = ($P_Y Y$ – TC) / TC. The doses of N, P, K, ..., for which R is a maximum are calculated by simultaneously solving the system: $\frac{\partial L}{\partial n} = 0$; $\frac{\partial L}{\partial p} = 0$ (5); $\frac{\partial L}{\partial k} = 0$.

Note that TC in the above system is not a constant, but that TC is a function of doses *n*, *p*, *k*, ... The quantities obtained when solving the system (5) establish the minimum quantities that are required to obtain the highest profits, that is, the producer must fertilize with the minimum recommended amounts the area covered by these conditions and the rest that the minimum level of fertilization cannot cover must be left unsown (Martínez, 1972; Portillo, 2015), since a different combination of dose and area will reduce the profits for a certain quantity of fertilizer.

This is explained because the classic response of crops to successive fertilizer additions follows the Law of diminishing 'marginal returns' '... at low doses of nutrients, increases in doses produce greater increases in yields, and conversely at high doses of nutrients, increases in doses produce minor increases in yields' (Martínez, 1972). So mathematical functions that empirically represent the law of diminishing returns are used.

However, second-degree polynomials allow for a very reasonable representation of a crop's responses to nutrient applications. This second-degree polynomial allows calculating the economic optimum and the technical optimum due to the linear and quadratic effects that are observed between the nutrients and the yield of a crop. For the case of 1 and 2 two inputs, there are the following equations: $\mathrm{N}: \mathrm{Y} = \beta_0 + \beta_{1n} + \beta_{2n^2}$ (6) . $\mathrm{N, P}: \mathrm{Y} = \beta_0 + \beta_{1n} + \beta_{2p} + \beta_{3n^2} + \beta_{4p^2} + \beta_{5np}$ (7).

The system of equations (4) simply reduces to the following equation, in the case of a nutrient or a balanced fertilizer formula, (F): $\beta_1 + 2\beta_{2n} = \frac{P_N}{P_Y}$. Where: $n^* = \frac{1}{2\beta_2}\left(\frac{P_N}{P_Y} - \beta_1\right)$ (8). Where: n* or f* is the optimal dose of N or F, respectively.

Establishment of the experiment

Location of the study area

The experiment was established on May 27, 2019. Two varieties of corn (Estrella and Celeste) were used to which different doses of fertilization were applied in order to subsequently evaluate the grain yield. The experiment was developed in the 'El Ranchito' Experimental Agricultural Field, in lot X-11, belonging to the Chapingo Autonomous University, Texcoco de Mora, State of Mexico. The lot is geographically located between the parallels 19° 24' and 19° 33' north latitude, the meridians 98° 38' and 99° 02' west longitude.

Soil analysis

Prior to the establishment of the crop, a soil sampling was carried out to determine its fertility, which was established from 15 subsample samples in a random and representative way of the terrain, and finally form a composite sample and send it to the Nutrelab chemical analysis laboratory, by the methods established in the Official Mexican Standard NOM-021-SEMARNAT-2000.

Treatment design

The crop was developed under rainfed conditions with supplemental irrigations at eighty-six days, ninety-eight and one hundred and nine days after sowing due to the drought that occurred during the crop cycle. The treatments were arranged in a completely randomized design (CRD) with four repetitions each. Each lot or experimental unit measured 8.8 m wide by 20 m long, giving an area of 176 m^2 and a sowing density of 1 056 plants, equivalent to 60 000 per ha^{-1}.

During the development of the crop, agricultural practices of fertilization, weeding, hoeing, hilling and supplemental irrigations were carried out until ripening. An average of 5 cobs in a linear meter, in complete competition, in each of the treatments, were harvested, having elapsed 163 days since sowing. The grain was dried until reaching an average moisture of 14%, the grains were removed from the cob and weighed on an analytical balance to estimate the average yield per hectare of corn. The data were captured, sorted and systematized to be analyzed in an analysis of variance (Anova) with the Statistical Analysis System (SAS) package version 9, to test the equality of treatments in order to accept or reject the null hypothesis. For each variable evaluated, an analysis of variance, comparison of means tests using Tukey’s test (α= 0.05) and the honest minimum significant difference (HMSD) were performed. Regression analysis was used to estimate production function and the results were interpreted and discussed.

Results and discussion

The results of the soil analysis found low content of organic matter and inorganic nitrogen (N), while excess amounts of phosphorus (P_2O_5) and potassium (K_2O). In micronutrient content, there was Cu deficiency, low Fe and Zn level, medium CaO, high Mn and excess Mg and B. CEC was also low and medium pH (Table 1). Taking into account this information and the requirements of the corn to produce an expected average yield of 10 t ha^{-1}, the balanced fertilizer formula (F) was made with the following contents: 23% of N, 0% of P_2O_5, 26.53% of K_2O, 17.73% of CaO plus the mixture of micronutrients mentioned above.

Table 1. Result of the soil analysis and fertilization formula.

Nutrients	Content (mg kg^{-1})	Nutrient classification	Fertilizer recommendations (kg ha^{-1})	Fertilization formula (kg ha^{-1})			
				400	600	1200	1800
Organic matter (%)	1.41	Low	14 516.7	-	-	-	-
Inorganic nitrogen	14	Low	161.8	92	138	276	414
Phosphorus (P_2O_5)	49.59	Excess	3.4	0	0	0	0
Potassium (K_2O)	293.74	Excess	186.7	106	159	318	476
Calcium (CaO)	1 410.96	Medium	125	71	106	213	319
Magnesium (Mg)	631.9	Excess	0	0	0	0	0

Nutrients	Content (mg kg^{-1})	Nutrient classification	Fertilizer recommendations (kg ha^{-1})	Fertilization formula (kg ha^{-1})			
				400	600	1200	1800
Iron (Fe)	10.26	Low	2.18	0.56	1.08	2.18	3.27
Manganese (Mn)	47.42	High	0	0	0	0	0
Zinc (Zn)	0.85	Low	5.3	1.59	2.65	5.3	7.95
Copper (Cu)	0.5	Deficient	3.4	1.02	1.7	3.4	5.1
Boron (B)	0.72	Excess	1.14	0.34	0.57	1.14	1.71
CEC (me 100 g^{-1})	12.00	Low	-	-	-	-	-
Sulfur (pH)	5.85	Medium	-	-	-	-	-

CEC= cation exchange capacity; Me= milliequivalents per 100 g. Soil analysis carried out by the Nutrelab laboratory.

Once the required fertilizer formula was determined, the experimental design was established, which was bifactorial treatments 2x5. The first factor consisted of two varieties of corn (Estrella and Celeste). The second factor in five fertilization doses (T0= absolute control; T1= producer's dose; T2=1/2 of the optimal dose; T3= optimal dose and T4:1+1/2 of the optimal dose). T0 consisted of not applying any type of fertilizer to the soil or the plant, T1 was that applied by the producers of the region (400 kg ha^{-1} of F) and the optimal dose was carried out based on the soil analysis, which was 1 200 kg ha^{-1} (with 276N-0P-318K-213CaO + micronutrients) and served as a reference point for the other treatments.

Analysis of variance

In Table 2, it was observed that the Estrella variety had the highest statistical yields. Similarly, T4 generated the highest values in this variable while in treatments T1, T2 and T3, there was no significant difference. On the other hand, the control, as expected, produced the lowest grain yields. These results are consistent with those presented by Martínez-Gutiérrez *et al*. (2018), they determined the agronomic characteristics of white hybrids in five different environments, the best response, also defined the effect of the genotype × environment interaction on yield and obtained an average yield of 12 t ha^{-1}.

On the other hand, Zamudio *et al*. (2015) evaluated six hybrids at three sites in the State of Mexico, fertilized with 250 kg ha^{-1} of N and four foliar fertilization treatments and they obtained an average yield of 12.07 t ha^{-1} of corn grain. Aguilar-Carpio *et al*. (2015) analyzed corn yield and profitability based on genotype, biofertilizer and nitrogen in Iguala, Guerrero, Mexico in 2011 and found that the highest dry matter (DM) and grain yield (GY) was achieved with the combination of H-562, biofertilizer and 160 kg N ha^{-1} (30 000 and 9 243 kg ha^{-1}, respectively) and the lowest corresponded to the treatment VS-535, with biofertilizer (Bio) and without nitrogen (17 030 and 3 760 kg ha^{-1}, respectively).

Table 2. Anova and comparison of yield means in t ha^{-1} of two varieties of corn under five doses of fertilization.

SV	-	F	-	Pr> F
		Yield		
Variety	-	26.01	-	<0.0001
Dose	-	18.02	-	<0.0001
CV (%)	-	-	5.9	
	-	E	-	12.77 a
Variety	-	C	-	11.61 b
HMSD	-		-	0.46
	-	T4	-	13.8 a
	-	T2	-	12.31 b
Dose	-	T1	-	12.15 b
	-	T3	-	11.89 b
	-	T0	-	10.79 c
HMSD	-		1.05	-

Values with the same letter in the same column are not statistically different (Tukey, α= 0.05), HMSD= honest minimum significant difference; CV= coefficient of variation; E= Estrella variety; C= Celeste variety; T0= control. T1= treatment one; T2= treatment two; T3= treatment three; T4= treatment four.

The highest net income was obtained with H-562 and 160 kg N ha^{-1} regardless of the use of Bio. In the work of Díaz *et al*. (2007), two doses of N (300 kg and 400 kg) were evaluated, and the researchers reported that the supply of 400 kg of N ha^{-1} promoted a greater effect on the variables leaf area index (FDI), biomass production and grain yield.

Selection of the function

With the results obtained in the experiment of white corn production and after testing different functional forms such as linear, quadratic, cubic, transcendental, logarithmic and Cobb-Douglas, the ones that showed the best fit were linear and quadratic. The latter shows that at a certain level of use of the variable input, positive increases in production begin to occur, but each time of lesser magnitude (decreasing marginal products).

A level of use of the variable input is reached in which the last unit of this resource does not increase production at all (zero marginal product). At this level of use of fertilizer input, the maximum production per hectare is reached. This second-degree polynomial allows calculating the economic optimum and the technical optimum, for this reason it is the one that was selected and is presented immediately: $Y= 9129.9023 + 4.1646\ F - 0.0011\ F^2 - 1520.2652\ C$, $R^2= 0.61$; Adjusted $R^2= 0.53$ (3.25)*** (-1.86)* (-2.28) **.

Where: Y is the corn yield in kg ha^{-1}, F is the fertilizer formula applied in kg ha^{-1} and C is a dummy (binary) variable for managing zeros and ones, where 0 represents the crop that was sown the previous year, which was corn and 1 refers to nothing being grown in the previous year (fallow).

The values of t in the parentheses: ***, ** and * denote statistical significance at 1%, 5% and 10%, respectively. Other variables that can influence corn yield, such as rainfall, soil type, soil degradation, seed and type of sowing, harvesting method, land, labor, machinery, herbicide use, among others, are assumed to be constant at a given level, during the crop cycle, the independent coefficient represents the yield attributable to factors other than the formula.

To obtain the level of fertilizer that generates the maximum profit or maximum benefit, equality is sought between the marginal product given by the derivative of the production function and the price ratio: price of the input/price of the product, considering the market prices, prevailing in the area, of the input and the product $11.50 and $5.00 per kg, respectively, the value of the factor where the marginal product is equal to 2.3= $11.50/$5.00 was sought. In such a way that obtaining the derivative of the function and equaling to 2.3, similarly as in equations (4 and 8), the following expression is reached: $\frac{\partial Y}{\partial f} = \frac{P_F}{P_Y} = 4.1646 - 0.0022\,F = \frac{11.5}{5} = 2.3\,;\ F = \frac{-1.8646}{-0.0022} = 848\ \text{kg ha}^{-1}$ is the optimal technical or maximum profit dose.

As for the value of F that generates the maximum yield per hectare, it is obtained by equalizing the derivative of the function to zero (marginal product= 0) and then clearing the value of F, one has: $\frac{\partial Y}{\partial f} = 0 = 4.1646 - 0.0022\,F = 0\ F = \frac{-4.1646}{-0.0022} = 1\,893\ \text{kg ha}^{-1}$ is the optimal technical or maximum yield dose.

Based on economic optimization, the optimal amount of fertilizer that corn producers must apply to obtain the maximum economic benefit or profit (25 226.02 $ ha^{-1}) is 848 kg ha^{-1}. Since the optimum is a random variable, it is possible to estimate a confidential region for it as shown in (Castellanos-Pérez *et al.*, 2006). From the point of view of marginal analysis, it is convenient for the corn producer to produce additional quantities of this grain, as long as the income obtained from this product is greater than or equal to the cost of one more unit of F necessary to produce these quantities.

That is, it will be convenient for them to produce a greater amount of corn, if the marginal income (MgI) they obtain from the sale of this grain is greater than or equal to the cost of an additional kg of F (marginal cost: MgC), with which they produce that amount of grain. Based on this economic criterion and that of maximum profit, as observed in (Table3), this is reached when the MgI ($11.50) is equal to the MgC ($11.50), which is consistent with the elasticity of production (ε_p= 0.19), which corresponds to the economic region of the production function (0< ε_p < 1).

Table 3. Variables analyzed: fertilizer, yield, total income, marginal income, variable cost, marginal cost and profit or benefit.

Fertilizer applied	Yield	Total income in $	Marginal income in	Variable cost of	Marginal cost in	Profit or benefit
(F: kg ha^{-1})	(Y: kg ha^{-1})	(TI = $ Pc∗Y)	(MI = F $ ΔTI/ΔY)	(VCF = $ Pf∗F)	(MgC = in $ ΔVCF/ΔY)	(π = TI C)
8 46	10 346	51 728.01	_	9 729	-	25 226.01
847	10 348	51 739.52	11.51	9 740.5	11.5	25 226.02
848	10 350	51 751.02	11.50	9 752	11.5	25 226.02

Fertilizer applied	Yield	Total income in $	Marginal income in	Variable cost of	Marginal cost in	Profit or benefit
(F: kg ha^{-1})	(Y: kg ha^{-1})	(TI = $ Pc∗Y)	(MI = F $ ΔTI/ΔY)	(VCF = $ Pf∗F)	(MgC = in $ ΔVCF/ΔY)	(π = TI C)
849	10 353	51 762.51	11.49	9 763.5	11.5	25 226.01
1 892	11 551	57 757.15	0	21 758	11.5	19 226.15
1 893	11 551	57 757.15	0.01	21 769.5	11.5	19 214.65
1 894	11 551	57 757.15	-0.01	21 781	11.5	19 203.15

∂Y/∂I is the partial derivative of Y with respect to F. $= peso; Pc= corn price= 5.00 $ kg^{-1}; Pf= price of the fertilizer formula= 11 50 $ kg^{-1}; VCF= variable cost of fertilizer; Δ= is the change or variation; C= VCF + FC. Where: FC= fixed cost= $16 773.00.

On the other hand, the technical optimal amount of F that generates the maximum yield is 1 893 kg ha^{-1}, this maximum amount of corn per hectare does not produce the maximum profit, so seeking the highest yield per hectare does not necessarily yield the maximum economic benefit that any rational producer who produces corn to sell in the its market would seek. In the case of small producers, who only have few resources to buy 424 kg of F, they must apply this nutrient in 1/2 ha and would obtain a profit per peso spent on F of $1.12. Which contrasts with the result of Aguilar-Carpio *et al*. (2015), who used Bio plus 80 kg N ha^{-1} with H-562 and obtained the greatest profit per peso invested, since for each peso they recovered $4.33.

Conclusions

Of the 4 treatments evaluated, the one that had the best response in the yield variable evaluated was T4 (the highest dose of fertilization), so in this aspect it was the best. While for this same variable, the control treatment had the lowest values. With the Celeste variety and the highest dose, the highest yield was obtained, which was 13.83 t ha^{-1}, while with the Estrella variety and this same fertilization dose, a yield very close to the previous one of 13.77 t ha^{-1} was recorded. The estimated quadratic production function of white corn allows obtaining the optimal economic dose or maximum profit of F (848 kg ha^{-1}) and the optimal technical dose or maximum yield (1893 kg ha^{-1}).

The results obtained can serve as an economic criterion for making production decisions by the small producers of white corn, who have fewer resources to buy fertilizers, so that, optimally using this resource, they could apply only 424 kg of F in half a hectare and thus obtain the maximum net profit per peso spent on F, as well as by medium and large producers, who have more resources to acquire the amount of F that allows them to achieve the maximum profit. It is recommended that in future research the region to be explored be expanded, in such a way that the size allows to observe the type of classic response. It is also convenient to explore an experimental design of random blocks.

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