



Soil Nitrogen as Nitrate (N-NO₃) and Fertilization Based on Soil Supply and Corn Demand in *rhodic Luvisols* of Campeche, Mexico

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Abstract

In Campeche Mexico, corn production is particularly very important due to its large area of medium and high-yield potential. For any plan production, soil fertility needs to be understood considering that all nutrients extracted from the soil and exported to the harvested crops need replenishment. The fertilizer should be exactly as required. Current fertilization practices are based only on local experiences without details. This is the case of Nitrogen (N), a highly demanding nutrient for corn in the *rhodic Luvisols* of Campeche. This study aimed to recommend the best amount of N (kg·ha⁻¹) for corn production keeping in mind the Soil N SUPPLY and the N-Corn-DEMAND in five locations with *rhodic Luvisols* in Campeche. Nine individual samples were taken in each location considering the first arable depth of the soil, which ranged from 16 to 24 cm. N-NO₃ was the form of N quantified in ppm taking 20 to 40 ppm as the optimum. The amount of N-NO₃, in the soil as ppm, was converted into kg·ha⁻¹ (Soil-Supply). With the Corn-Demand of 100 kg·ha⁻¹ of N for a target Yield of 5 t·ha⁻¹. The dose of N (kg·ha⁻¹) was calculated with the formula: **Demand-Supply/Ef**. The Efficiency Factor (**Ef**) related to the efficiency of fertilization were 0.8 and 0.4 for efficient irrigation and rainfed conditions respectively. The amount of UREA was calculated accordingly. The recommended N Dose (kg·ha⁻¹) for the locations were the next for a 0.8 **Ef**(irrigation): **DZ** (95.5), **VG** (91.55), **HE** (75.38), **EZ** (71.75) and **KA** (69.86). Under rainfed conditions, the above values doubled because the efficiency of fertilization diminished substantially due to uncontrolled external factors and the losses need to be compensated with extra fertilization. The amount of Urea (kg·ha⁻¹) recommended are the next: 207.7, 199.0, 163.9, 156.0, 151.9 for an **Ef** of 0.8 and the double for rainfed conditions with an **Ef** of 0.40. Technical and scientific knowledge needs

to be developed.

Subject Areas

Agricultural Engineering

Keywords

Soil Fertility, Efficiency Factor, Urea, Arable Depth

1. Introduction

Campeche is one of the three states in the Yucatán Peninsula (YP) of Mexico where corn production is particularly prevalent due to its large area of medium and high-yield potential.

74.41% of the area planted with cyclical crops in the state corresponds to corn (Uzcanga Pérez *et al.*, 2015) [1], with a total area planted of 166,545 ha, (97% rain-fed) (SAGARPA, 2024) [2].

This best area is confined in the northern and central part, which is a region of high and medium-yield potential. According to Ku *et al.*, 2005 [3], these regions have the best soil and climate conditions.

Both regions represent approximately 70% of the total planted area. The central zone comprises the municipalities of Champotón, Campeche, and Hopelchen, with more than 83,000 ha whilst the north zone with its municipalities of Calkiní, Hecelchakán, and Tenabo have more than 26,211 ha with predominant *rhodic Luvisols*.

For any area and soil type, it is important to consider the soil fertility before initiating any planting plan with the consideration that at first step, the dynamic of soil nutrients and plant nutrition must be properly understood. The premise is that all nutrients extracted from the soil and exported to the harvested crops (INPOFOS, 1997) [4] need replenishment to maintain productivity.

Since fertilization is the agronomic practice that most influences production costs, it is important to apply the strictly required amounts of nutrients. However, current fertilization doses are based only on the empirical and local experiences of farmers. Too much is needed under the support of a scientific and technological knowledge.

Among the essential nutrients, nitrogen (N) has been considered one of the most limiting factors for maize yield, causing severe reductions in crop growth (Torres Duggan, 2016) [5]. Therefore, it is important to consider the N balance criterion to determine fertilization needs, taking into account not only soil SUPPLY but also crop DEMAND.

It is estimated that maize requires approximately 20 to 25 kg·ha⁻¹ of N per ton of grain produced (Torres Duggan, 2016; Castellanos, 2000; Herrera and Rontondaro, 2014) [5]-[7]. However, local experience (Ramírez Silva *et al.*, 2016a;

Ramírez Silva *et al.*, 2016b) [8] [9] suggests that between 16 and 20 kg of N per ton of grain are needed for tropical hybrids.

Due to the need for updating basic information for the region, where corn is growing increasingly, the National Institute of Forestry, Agricultural and Livestock Research of Mexico (INIFAP) developed a strategic plan to understand the chemical characteristics of the main soils of Campeche, Mexico where N is the main component of the most used fertilizers by farmers.

This study aimed to recommend the best bet amount of N ($\text{kg}\cdot\text{ha}^{-1}$) for corn production keeping in mind the Soil N SUPPLY and the Corn-DEMAND in different locations with *rhodic Luvisols* in the state of Campeche, Mexico.

2. Materials

Sampled Sites, Regions and Municipalities

The study was conducted during the rainy season spring-summer in the northern and central regions of Campeche Mexico in the municipalities of Calkini, Tenabo, Hecelchacan and Hopelchen in ten hectares of each location: Calkini, Dzibalche, Emiliano Zapata, Hecelchakan and Vicente Guerrero (**Table 1**).

Table 1. Locations and geographic coordinates of *rhodic Luvisols* in the state of Campeche, Mexico.

Location	Municipality	Geographic Coordinates
Calkini (KA)	Calkini	20.34244 N. Lat. -89.91154 W. Long.
Dzibalche (DZ)	Calkini	20.33005 N. Lat. -90.00636 W. Long.
Emiliano Zapata (EZ)	Tenabo	19.83540 N. Lat. -90.15845 W. Long.
Hecelchakan (HE)	Hecelchakan	20.11912 N. Lat. -90.05228 W. Long.
Vicente Guerrero (VG)	Hopelchen	19.59670 N. Lat. -89.60252 W. Long.



Figure 1. Typical *rhodic Luvisol* in Campeche Mexico.

All locations have deep arable soils classified as *rhodic Luvisols* (*Kancab* in Maya) of intense red color (**Figure 1**) located in the lower part of the microrelief with high amounts of oxidized iron (Fe_2O_3) known as *Hematite* (Bautista *et al.*, 2005) [10] with a metallic gloss. Another important component is the *Halloysite* which is an aluminosilicate clay mineral with the empirical formula $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$, forming part of the *kaolinite* 1:1 *group* with 1 layer of silica tetrahedra and 1 of aluminum octahedral with good drainage.

3. Methods

3.1. Sampling Process by Using a Random Systematic Two-Dimensional Method (RSTDM)

Nine individual samples were taken in each 10-hectare location considering the first arable depth of the soil which ranged from 16 to 24 cm depending on the location. A Random Systematic Two-Dimensional Method (**RSTDM**) for soil sampling combines elements of both random and systematic sampling to ensure good spatial coverage while maintaining a degree of randomness. This approach is often used in grid-based sampling designs, providing a more representative sample than simple random sampling alone. **Figure 2** shows a plot under field conditions where nine individual samples were taken randomly and previously marked on a spreadsheet.

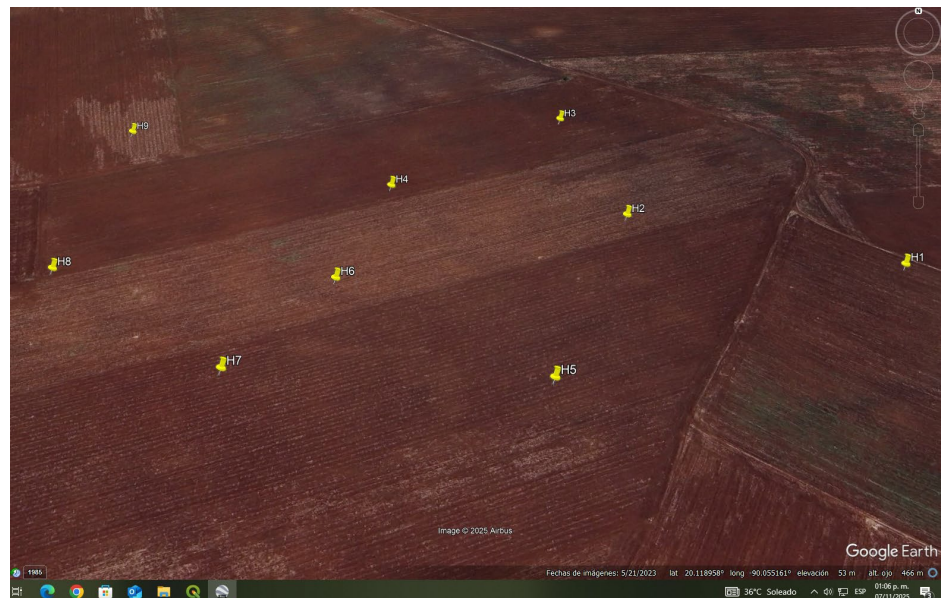


Figure 2. Individual samples taken on a *rhodic Luvisol* of Campeche, Mexico.

Plots were divided into 9 strips, and each strip subdivided into 12 small grids. One grid of each strip was randomly selected in order to take the individual sample which was previously georeferenced with geographic coordinates with degrees and decimals. 20 to 40 ppm was considered as the Critical Range of Soil-N- NO_3 below which there are deficiencies and above there are excesses [11].

3.2. Statistical Analysis of soil N-NO₃ in Different Plots

In the Analysis of Variance (ANOVA) the five locations were considered as treatments in addition, the nine individual samples as replications, distributed in a Completely Random Design ($p = 0.05$) using Stat-graphic Advisor Software.

3.3. Soil N-NO₃ Content, Soil Supply and Corn Demand

3.3.1. Soil Supply

To know the *Soil Supply* the nitrogen content in ppm ($\text{mg}\cdot\text{kg}^{-1}$) as nitrate (N-NO₃), determined by the Brucina-Colorimetric Method, was converted into kilograms per hectare ($\text{Kg}\cdot\text{ha}^{-1}$) by using the average effective Depth (cm) of the arable soil, the Bulk Density ($\text{gr}\cdot\text{cm}^{-3}$) and the area ($10,000 \text{ m}^2$) to calculate the weight of one hectare of each plot.

The formula used was the next:

$$\text{Weight of 1 ha (Kg)} = (\text{Volume}) (\text{Bulk Density})$$

$$\text{Volume} = (\text{Area}) (\text{Depth})$$

$$\text{Kg}\cdot\text{ha}^{-1} \text{ of } N\text{-NO}_3 = (\text{ppm of } N\text{-NO}_3) (\text{Weight of 1 ha of } N\text{-NO}_3)$$

$$\text{ppm } (\text{mg}\cdot\text{kg}^{-1}) \text{ of } N\text{-NO}_3 = 1 \text{ Kg of } N\text{-NO}_3 \text{ in 1 Million Kg of soil}$$

Using the *Clod Method*, the Bulk Density in $\text{g}\cdot(\text{cm}^3)^{-1}$ was determined with the formula: *Weight of Clod (gr)/Volume of Clod (cm³)* [11] using the *Paraffin Method* by Selecting and weighing the dry soil clod. The clod was immersed in melted *paraffin* which was remove it, and allow it to cool. This creates a water-repellent layer that seals the clod and prevents it from absorbing water. The clod with paraffin was weighed.

The paraffin-coated clod submerged in water and the volume of water displaced was recorded and considered it as the volume of the clod, since paraffin does not absorb water. The bulk density was calculated by dividing the mass of the dry soil by the total volume of the clod.

The amount of *N-NO₃* in $\text{Kg}\cdot\text{ha}^{-1}$ was referred as the *Soil Supply*.

3.3.2. Corn Demand

The most important piece of data in calculating N demand is the unit extraction rate. That is, the amount of N required for producing one ton of grain. This is not a fixed value and can vary from 20 to 25 $\text{kg}\cdot\text{ton}^{-1}$ [6]. Other authors suggest variations of 14-18 $\text{kg}\cdot\text{ton}^{-1}$ and 21 $\text{kg}\cdot\text{ton}^{-1}$.

In this work, the N *Crop Demand*, was determined considering 20 kilograms of N to produce 1 ton of corn grain per hectare in 62,000 plants $\cdot\text{ha}^{-1}$ already suggested [8] [9] for local conditions. Therefore, for a target yield of 5 $\text{t}\cdot\text{ha}^{-1}$, the extraction of 100 kilos of N per hectare will be necessary. The target yield of 5 $\text{t}\cdot\text{ha}^{-1}$ is based on the fact that it is an achievable yield by most producers, but only 14.0% of them are successful because they make more efficient use of fertilizers. 40.0% of total farmers reach yields between 2.0 and 3.7 $\text{t}\cdot\text{ha}^{-1}$ [12].

3.3.3. Nitrogen Fertilization Dose ($\text{Kg}\cdot\text{ha}^{-1}$) for Corn

The next formula is suggested to calculate the N dose per hectare of corn:

$N\text{Dose (kg}\cdot\text{ha}^{-1}\text{): } [(TY \times Ne) / Ef] - (IN) = \text{Demand-Supply} / \text{Efficiency Factor}$

TY = Target Yield (5.0 t·ha⁻¹)

Ne = N extracted per ton of corn (20 kg·t⁻¹)

Ef = Efficiency Factor (0.40 - 0.8)

IN = Inorganic N (kg·ha⁻¹ of N-NO₃)

A factor of greater relevance in calculating the N dose per hectare is the Ef , since it ultimately determines the proportion by which the calculated N dose needs to be increased. This is an additional amount to counteract the soil N losses and unable it to be exported to the crop. An Ef of 0.4 was taking into account in this work for rainfed conditions. However, under efficient irrigation the Ef can increase to 0.8.

The dynamics of N in the soil-plant system include losses of available N through leaching, denitrification, and volatilization. Given the difficulty of quantifying these losses, an Ef between 0.4 and 0.8 suggested by Garcia (2005) [13] was considered as a reference value for the purpose of this work. Silva *et al.*, 2017 [14] mentioned N losses as ammoniac (NH₃) of 31%.

In this work, the N Doses, under rainfed conditions ($Ef = 0.4$), was doubled as compared to efficient irrigation ($Ef = 0.8$) because rainfed involves many factors (drought, excess water, leaching, volatilization, etc.) that are more difficult to control.

4. Results

4.1. Contents (ppm) of N-NO₃ in Soils and Statistical Analysis

Table 2 shows the different contents of N-NO₃ in the nine individual samples taken on each location. Taking into account the Critical level of 20 - 40 ppm (mg·kg⁻¹) and considering the next qualifications: **Very Low**: 0 - 10 ppm; **Low**: 10 - 20 ppm; **Medium**: 20 - 40 ppm; **High**: 40 - 60 ppm; **Very High**: >60 ppm all plots showed N deficiencies with an average above 65% of the 9 individual samples taken.

Being more specific, *Dzibalche* was the location with the higher percentage (89%) of sampled points with **Very Low** amounts of N-NO₃ followed by *Vicente Guerrero*, *Calkini*, *Hopelchen* and *Emiliano Zapata* with 55.5%, 44.4%, 33.3% and 22.2% respectively. In the same order of location but for the **Low** level of 10 - 20 ppm the percentage for each location was 0.00%, 22.2%, 33.3%, 55.5% and 44.4% whereas for the **Medium** Level (20 - 40 ppm), and following the same order of locations, the percentages were: 11.11%, 22.22%, 22.22%, 11.11% and 33.33%. In that way *Dzibalche* was the location with the higher number of samples in the range of **Very Low**.

On the other hand, the ANOVA (**Table 3**) of concentrations of N-NO₃, considering the five locations with their corresponding nine replications, shows No statistical differences between locations.

The ANOVA table decomposes the *Variance* into two components: between-groups (Locations) and within-groups component (Replications). The **F-ratio**,

which in this case is equal to 0.9026, is the ratio between the *Mean Square* of Locations and the Mean Square within-groups or replications. Since the *p-value* of the *F-ratio* is greater than or equal to 0.05, there is no statistically significant difference between the mean of Locations with a 95.0% confidence.

Table 2. Concentration of N-NO₃ (ppm) in different locations with *rhodic Luvisols* in the state of Campeche, Mexico.

Location (Treatments)	1	2	3	4	5	6	7	8	9	Average	Sampled Points with N Deficiencies (%)
Calkini	16.51	4.21	4.45	25.15	18.65	4.78	26.92	8.63	14.00	13.7	77.7
Dzibalche	6.84	8.95	8.35	26.22	9.48	9.8	9.12	7.42	4.4	10.1	89.0
Emiliano Zapata	21.74	9.19	17.46	10.85	8.99	31.5	17.66	14.71	23.36	17.3	66.6
Hecelchakan	7.44	1.7	19.7	10.76	12.47	13.82	1.71	14.58	30.02	12.5	89.0
Vicente Guerrero	13.02	32.56	10.98	9.48	4.1	6.92	8.94	24.39	5.5	12.9	77.7

Medium level: 20 - 40 ppm (mg·kg⁻¹); **Very Low:** 0 - 10 ppm; **Low:** 10 - 20 ppm; **High:** 40 - 60 ppm; **Very High:** >60 ppm.

Table 3. Analysis of Variance (ANOVA) of N-NO₃ (ppm) in different locations with *rhodic Luvisols* in the state of Campeche, Mexico.

Source of Variation	Square sum	Degree of Freedom	Mean Square	F	P(0.05)
Locations	245.58	4	61.3958	0.9026	0.4716
Replications	2720.70	403	68.0174		
Total	2966.28	44			

4.2. Soil N-NO₃ Supplied by the Soil

Table 4 is showing the amount of N-NO₃ in kg·ha⁻¹ for the five locations. Kalkini had the highest amount with 44.1 kg·ha⁻¹ followed in, descending order, by Emiliano Zapata, Hecelchakan, Vicente Guerrero and Dzibalche with 42.6, 39.7, 26.8 and 23.6 kg·ha⁻¹ respectively. Considering the value of Kalkini as a relative percentage of 100%, just Emiliano Zapata and Hecelchakan reached, relatively, 96% and 90% as compared to the 100% whilst Vicente Guerrero and Dzibalche had 60.7% and 53.5% respectively. Consequently, the amount of N for recommendation to each location must be inversely proportional to the values obtained; the higher the amount of N the lower the amount of fertilizer for recommendation.

Table 4. N-NO₃ in ppm of five locations, with *rhodic Luvisols*, converted into (kg·ha⁻¹) taking into consideration the Bulk Density, the effective Soil Arable depth and Weight of one ha.

Location	N-NO ₃ (ppm)	Bulk Density [gr·(cm ³) ⁻¹]	Soil arable depth (cm)	Factor depending of 1 ha weight	N-NO ₃ (kg·ha ⁻¹)
Calkini	13.70	1.32	24.33	3.2	44.1
Dzibalche	10.06	1.22	19.22	2.3	23.6
Emiliano Zapata	17.27	1.31	18.78	2.5	42.6
Hecelchakan	12.47	1.39	22.89	3.2	39.7
Vicente Guerrero	12.88	1.30	16.00	2.1	26.8

4.3. Dose of N (kg·ha⁻¹) Recommended for Locations

Before issuing a balanced fertilizer recommendation, it is important to know the soil nutrient *Supply* and the crop *Demand*. The inorganic N, as N-NO_3 , qualified as the soil *Supply* was determined in the laboratory, converted into kg ha⁻¹ and compared with the *Crop Demand*. **Table 5** shows the amount of N needed for each location with a target yield of 5.0 t·ha⁻¹ of grain. This demand refers to 100 kg·ha⁻¹ as the amount of N that the plant needs to absorb to achieve the desired yield. The fertilization Efficiency was 0.4 for rainfed and 0.8 for irrigation conditions.

Table 5. Dose of N (kg·ha⁻¹) for five locations, with *rhodic Luvisols*, for future recommendations.

Location	N Soil Supply (S) (kg·ha ⁻¹)	N Corn Demand (D) (kg·ha ⁻¹)	D-S (kg·ha ⁻¹)	D-S/0.8 (kg·ha ⁻¹)	D-S/0.4 (kg·ha ⁻¹)
Calkini	44.1	100.00	55.9	69.86	139.71
Dzibalche	23.6	100.00	76.4	95.55	191.10
Emiliano Zapata	42.6	100.00	57.4	71.75	143.50
Hecelchakan	39.7	100.00	60.3	75.38	150.76
Vicente Guerrero	26.8	100.00	73.2	91.55	183.10

In descendent order, the recommendation N Dose (kg·ha⁻¹) for the locations would be the next for 0.8 vs. 0.4 Efficiency Factor (*Ef*). Dzibalche (95.5 vs. 191.10), Vicente Guerrero (91.55 vs. 183.10), Hecelchakan (75.38 vs. 150.76), Emiliano Zzapata (71.75 vs. 143.5) and Kalkini (69.86 vs. 139.71).

On the other hand, the amount of Urea (kg·ha⁻¹), as fertilizer (**Table 6**) with 46% N, would be the next: 207.7, 199.0, 163.9, 156.0, 151.9 for an *Ef* of 0.8 and 415.0, 398.0, 327.7, 312.0, 303.7 for an *Ef* of 0.4 for **DZ**, **VG**, **HE**, **EZ** and **KA** respectively.

Table 6. Dose of N-Urea fertilizer for five *rhodic Luvisols* locations in Campeche, Mexico.

Location	Urea (0.8 Ef) (kg·ha ⁻¹)	Number Bags of Urea (0.8 Ef) (50 kilos per bag)	Urea (0.4 Ef) (kg·ha ⁻¹)	Number Bags of Urea (0.4 Ef) (50 kilos per bag)
Calkini	151.9	3.0	303.7	6.1
Dzibalche	207.7	4.2	415.4	8.3
Emiliano Zapata	156.0	3.1	312.0	6.2
Hecelchakan	163.9	3.3	327.7	6.6
Vicente Guerrero	199.0	4.0	398.0	8.0

5. Discussion

Beside the *Ef* as a basic factor to determine the ultimately dose of nutrients to be recommended, the inorganic N released by the *OM* during its decomposition is also important

In this work, the contribution of the *OM* was discarded because of the lack of

detailed information. However, the amount of Carbon (C) in the *OM* and its relationship with the N needs to be known.

Even though, 55% of the *OM* is C the N content may vary; however, a 10:1 (C:N) ratio is considered adequate for rapid mineralization and a prompt release of available N.

On the other hand, when recommending fertilization doses the *Ef* is so important that its value depends on different factors such as: the physical properties of the soil (texture, compaction), land leveling, incorporation and characteristics of crop residues, application system and irrigation management, type of fertilizer and application time, rainfall, and depth of the root system.

The method described in this work provides a rational approach to the nitrogen fertilizer dose to be applied. However, there is a lack of detailed information regarding the *Ef*. Nevertheless, it is a fundamental tool for establishing a first approximation of nitrogen requirements.

Beside the works of García (2005) [12] suggesting *Efs* from 0.4 to 0.8, other authors [15] suggest important variations on N utilization efficiencies depending on the locations. The range suggested were 32% to 37% at site T1, 4% to 7% at site T2, and 0% at site M. The low efficiency was associated to high N-NO₃ concentration, low yields due to late planting, low rainfall, micronutrient deficiency, and white grub (*Phyllophaga* spp.) infestation.

Another important issue for recommendations is the way of how to transmit the knowledge to producers. For this reason, **Table 6** shows the number of *Urea bags* as the most common way producers request it in the market.

Even the most prominent farmers in the area, where this work was launched, apply an average of just two bags of Urea and their yields range from 2.6 to 3.9 t·ha⁻¹ [16]; depending on the soil chemical and biological heterogeneity.

From a sample of 511 maize producers, surveyed in mechanized *rhodic luvisols*, 96% apply just a first dose of fertilizer: 29 kg (Nitrogen) + 70 kg (Di-ammonium Phosphate); this is 43 kg·ha⁻¹ equivalent to two bags of Urea (46%), which is 72% less N than the recommended in this work (6 - 8 bags). Less than 14% made a second application [16].

It is noteworthy that corn producers do not carry out an adequate fertilization practice, which could explain a large part of the low yields. This is an excellent opportunity for the transfer of technology generated by the National Research System as INIFAP.

6. Conclusions

Campeche is one of the three states in the Yucatán Peninsula (YP) of Mexico where corn production is particularly prevalent. 74.41% of the area planted with several crops corresponds to corn.

The central and northern part of the state represent approximately 70% of the total planted area with *rhodic Luvisols* as prevalent soils.

It is clear that nutrients extracted from the soil, by the harvested crops, need to

be replenished to maintain soil productivity.

Since fertilization is the agronomic practice that most influences production costs, it is important to apply the strictly required amounts. However, the application of current fertilization doses is applied based only on empirical decisions without any detailed technical knowledge.

This study aimed to recommend the best bet amount of N ($\text{kg}\cdot\text{ha}^{-1}$) for corn production keeping in mind the Soil N SUPPLY and the Corn-DEMAND.

The main conclusions are the next:

- 1) No statistical differences were found between locations.
- 2) Based on Soil N SUPPLY and the N DEMAND of the maize crop, the recommendation N Dose ($\text{kg}\cdot\text{ha}^{-1}$) for the locations were the next for an *Ef* of 0.8 vs. 0.4: **DZ** (95.5 vs. 191.10), **VG** (91.55 vs. 183.10), **HE** (75.38 vs. 150.76), **EZ** (71.75 vs. 143.5) and **KA** (69.86 vs. 139.71).
- 3) The amount of Urea ($\text{kg}\cdot\text{ha}^{-1}$) recommended are the next: 207.7, 199.0, 163.9, 156.0, 151.9 for an *Ef* of 0.8 and 415.0, 398.0, 327.7, 312.0, 303.7 for an *Ef* of 0.4 for **DZ**, **VG**, **HE**, **EZ** and **KA** respectively.
- 4) Even the most prominent corn producers apply the equivalent to two bags of Urea per hectare, which is 72% less N than that recommended in this work (6 - 8 bags).
- 5) Even though the corn producers have the potential to obtain $5.0 \text{ t}\cdot\text{ha}^{-1}$ they do not carry out an adequate fertilization practice to reach it. This is an excellent opportunity for the transfer of technology generated by the National Research System as INIFAP.
- 6) It is important to continue generating technical and scientific knowledge related to *Nutrient Supply* and *Demand* for different soils and maize varieties in the tropical regions.

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Conflicts of Interest

The authors declare no conflicts of interest.

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