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Article

Fertilization analysis in the corn agroecosystem in the Papaloapan basin

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Abstract

Corn is the main crop of the basic basket in Mexico and one of the products of greatest commercial and economic importance nationwide. Among the main factors of agronomic management that determine its level of productivity is fertilization. Currently, as a result of the armed conflicts between Russia and Ukraine, there is a shortage and, consequently, a rise in the price of fertilizers. Therefore, this work studied the fertilization factor in the Papaloapan basin to analyze the effect of chemical nutrition on the corn crop based on its productivity in t ha^{-1} of grain. Three fertilization scenarios were simulated with the use of the SWAT model, and the results of the factors were mapped by statistically analyzing the difference in means of the treatments through an Anova, which yielded a value of P= 2e-16, showing a significant difference in the effects of the factors analyzed on the yield of the crop. In conclusion, the fertilization factor was higher than the non-fertilization factor, with a difference between means of 7.8 t ha^{-1} of grain, which indicates that the absence of fertilization work of the crop negatively impacts the productivity of corn grain. Nonetheless, the efficiency between half and full doses of nitrogen fertilization in terms of yield was found to be similar, with the half-dose factor being more efficient than the previous one.

Keywords:

corn grain, fertilization, study, SWAT.

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Introduction

According to SIAP (2022), corn production in Mexico has increased since 2006, reaching 27.5 million tonnes between 2020 and 2021. This crop represents more than 60% of the calories of the poorest sectors of the population (Bourges, 2013). Although Mexico is one of the largest producers (ASERCA, 2018), it also imports 34.12% of the corn it consumes, the second highest in the ranking of importers (FIRA, 2016).

Corn is Mexico's staple food, and its production is vital to the nation's food security (Ureta *et al*., 2020). Mexico is also one of the largest reservoirs of corn genetic diversity, hosting approximately 50% of the known genetic diversity in the Americas (Vigouroux *et al*., 2008). Any imbalance in the development and production of corn agroecosystems could put this genetic diversity at risk.

One of the relevant factors in the agronomic management of the corn crop is fertilization. Soil fertilization with nitrogen (N) is a priority for profitable crop production, followed by the use of phosphorus (P) and potassium (K). A balanced dose of NPK greatly influences crop growth and yield (Garbanzo *et al*., 2021).

According to CEPAL (2022), transnational armed conflicts, such as the current one between Ukraine and Russia, are affecting the world economy and trade, including Latin America. Among the repercussions on input trade, fertilizers are one of the most affected products, as Mexico and other Latin American nations import 88% of agricultural fertilizers from Russia.

Although nitrogen fertilizer prices are already declining, they still remain at historically high levels, and their use is expected to decrease in the field due to issues of affordability and availability, which would negatively affect grain production at the national level and food security (CEPAL, 2022). In Mexico, according to Bada-Carbajal *et al*. (2021), the Papaloapan basin is one of the main corn-growing regions, with municipalities such as San Andrés Tuxtla or José Azueta with high grain yields per hectare, and a negative impact on the crop fertilization process would greatly affect certain socioeconomic areas of the basin. Therefore, this work studied the fertilization factor in the Papaloapan basin to analyze the effect of chemical nutrition on the corn crop based on its productivity in t ha^{-1} of grain.

Materials and methods

Study area

The Papaloapan basin is located on the southern slope of the Gulf of Mexico (Figure 1). It covers territories of the states of Puebla, Oaxaca, and Veracruz, with an area of 46 263 km^2, represents 2.36% of the national territory and is the second most important region in the country for its volume of runoff, estimated at 46 billion m^3 per year (Murillo and López, 2005).

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Figure 1. Geographic location of the Papaloapan basin.

Analysis of fertilizer use in the corn crop

The SWAT (Soil and Water Assessment Tool) model (Neitsch *et al*., 2009) was implemented to calculate the productive potential of corn in the Papaloapan basin. Three scenarios were compared: a) one with recommended fertilization agronomic management (Tinoco, 2019); b) half fertilization dose; and c) lack of fertilization under rainfed conditions. The simulation covered the period 2016-2021 and considered three variables of analysis: optimal fertilization, half dose of fertilization, and no fertilizer applications.

Delimitation of the sub-basins within the Papaloapan basin

SWAT works at the basin and sub-basin levels. The model subdivides the basin into sub-basins based on the topography of the study area (Akhavan *et al*., 2010; Garg *et al*., 2011). For the present work, the total area of the Papaloapan basin was taken. The sub-basins were generated using a digital elevation model (DEM) with 90 x 90 pixels acquired from (INEGI). The generation of accumulated flows and the runoff network was formed based on the DEM and a river map. The sub-basins were delimited by selecting all the outlets of the flow network generated by the model. For this process, 168 sub-basins were generated for the total study area.

Generation of hydrological response units (HRUs)

The sub-basins were subdivided into hydrological response units (HRUs) based on soil type, land use, and slope (Akhavan *et al*., 2010; Garg *et al*., 2011). The HRUs within the basin were generated using a soil map from INEGI (2015) in vector format (scale 1:250 000). The database used in the study consisted of 4 418 soil profiles classified according to the WRB system (INEGI, 2015). These data provided information on the environmental characteristics, physical and chemical analyses of 14 349 soil horizons, as well as morphological details and limitations for land use and management (Paz-Pellat, 2018).

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From the soil vector layer and its attribute table, 340 soil types were unified according to the WRB classification for the study area, considering the first subdivision and its horizons. To assess land use, a mask was created in raster format, which simulated the potential yield of the corn crop over the entire surface, assuming that the area of the basin was allocated to agricultural use in this study.

For the generation of the slope ranges, five categories were generated (0-3, 3-8, 8-15, 15-30, and

>30%) based on the digital elevation model. At the end of the process, the model generated 4 852 HRUs. Table 1 shows, by way of example, the typical profile of the skeletic-mazic-Vertisol (skmzVR) soil with the parameters required by the model, as well as the source of their obtaining.

Table 1. haracteristics of the typical skeletic-mazic-Vertisol soil profile.

Horizon	Dep (mm)	Text (%)	BD (g cm^{-3})	AM (mm mm^{-1})	OC (%)	SHC (mm hr^{-1})	RC (%)	Alb	USLE K	EC (dS m^{-1})
A	130	14-14-72	1.48	0.15	1.5	0.08	0	0.21	0.5	2
B1	440	32-14-54	1.56	0.15	0.3	0.1	0	0.21	0.25	2
B2	830	36-14-50	1.54	0.15	0.2	0.11	0	0.21	0.25	2

Dep= depth (INEGI, 2015); Text= texture in the following order: clay, silt, sand (INEGI, 2015); BD= bulk density (Saxton *et al*., 1986); AM= available moisture (Saxton *et al*., 1986), OC= organic carbon (Neitsch *et al*., 2009); SHC= saturated hydraulic conductivity (Saxton *et al*., 1986); RC= rock content (INEGI, 2015); Alb= dimensionless albedo (Harris equation, CurveExpert 2.0 software); USLE K= factor 'K' of the universal soil loss equation (Neitsch *et al*., 2009); EC= electrical conductivity (INEGI, 2015).

Climate generation and allocation

Historical data from 1 074 weather stations of the National Meteorological Service (SMN, for its acronym in Spanish) located in the humid tropics were used. These data cover at least 100 years of records of precipitation and maximum and minimum temperature in the period 1912-2020. Using the EPIC climate generator (Sharpley and Williams, 1990), the climate statistics required by the model and daily temperature and precipitation data were generated for the entire period from 1950 to 2020.

The climatic variables considered are the following: a) maximum temperature; b) minimum temperature; c) standard deviation of the maximum temperature; d) standard deviation of the minimum temperature; e) average monthly rainfall, f) standard deviation of average monthly rainfall; g) asymmetry coefficient of average monthly rainfall; h) probability of a wet day after a dry day; i) probability of a wet day after a wet day; j) average number of days with rainfall per month; k) maximum rainfall in half an hour; and l) solar radiation. For the total area of the Papaloapan basin, the model selected 128 weather stations based on the proximity to the centroid of the sub-basins generated.

Entering physiological parameters and management

To calculate the productive potential of crops, the model requires the physiological parameters of the species to be simulated. SWAT contains a database with physiological parameters of various crops, within which, according to Neitsch *et al*. (2011), those corresponding to the corn crop were entered. Table 2 shows, by way of example, the physiological parameters entered into the model.

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Table 2. Physiological parameters of corn enter into SWAT.

Specie	RUE (kg ha^{-1}/Mj m^{-2})	2^{a} point RUE	LAI	HI	Canopy height (m)	Root depth (m)	Optimal temperature (°C)	Base temperature (°C)
Corn	39	45	6	0.5	2.5	2	25	8

RUE= radiation-use efficiency; LAI= leaf area index; HI= harvest index.

To calculate crop yield, management was entered into the model, including sowing and harvest dates, fertilization doses, and cultural tasks (Table 3).

Table 3. Optimal management of the corn crop entered into the model under rainfed conditions.

Activity	Year	Task	Input or activity	Date
Soil preparation	1	Chapeo (cutting with a machete)	Blade	May 14
	1	Subsoiling	Disk Plow	May 24
	1	Harrowing	Finishing Harrow	May 29
	1	Harrowing	Finishing Harrow	May 30
	1	Furrowing	Furrow Diker	May 31
Crop establishment	1	Sowing	Corn	June 1
Fertilization	1	1^{a} Fertilization	60-00-00 NPK (kg ha^{-1})	June 1
	1	2^{a} Fertilization	00-60-00 NPK (kg ha^{-1})	June 1
	1	3^{a} Fertilization	60-00-60 NPK (kg ha^{-1})	June 27
Harvest	1	Harvest	Harvest and kill operation	September 28

NPK= nitrogen, phosphorus, potassium (Tinoco, 2019).

Analysis of results

Using geographic information systems, the potential yield of corn in the basin was mapped for three scenarios: complete fertilization, half dose of fertilization, and no fertilization. Statistical analysis of the difference in means in R® (R Core Team, 2021) was used with Fischer's Anova method (Cayuela, 2010) to assess the significance and accept or reject the null hypothesis of equal corn yield in the three simulated scenarios.

Results and discussion

By means of a box plot, Figure 2 shows the difference in means between the factors analyzed for the simulated yield of the corn crop in the Papaloapan basin. Fischer's method of analysis of variance (Anova) (Cayuela, 2010) was used to find the significance value and determine if there was a significant difference between the factors analyzed. The *P*-value obtained was 2e-16, which indicates that the null hypothesis is rejected, and it is demonstrated that there is a large significant difference between the factors analyzed based on the simulated yield of the corn crop in the Papaloapan basin.

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Figure 2. Difference in yield means of the corn crop under various fertilization effects.

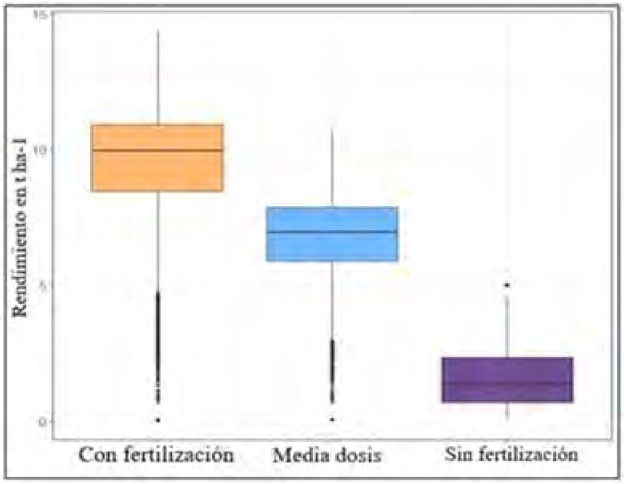

Table 4 presents the basic comparative statistics of the simulated scenarios (with fertilization, half dose of fertilization, and without fertilization) where the significant differences of the three factors analyzed are observed.

Table 4. Basic statistics of analysis of the effect of fertilization on the corn crop in the Papaloapan basin.

Factor	Mean (t ha^{-1})	Minimum (t ha^{-1})	Maximum (t ha^{-1})
With fertilization	9.4	0.04	14.37
Half dose of fertilization	6.75	0.05	10.7
No fertilization	1.6	0.05	5.2

The spatially explicit distribution of the effects of the factors analyzed on the corn crop in the basin are shown in Figure 3, of the corn crop with fertilization (Figure 4), corn crop under the effect of half dose of fertilization, and Figure 5 corn crop without fertilizer application.

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Figure 3. Corn crop yield under a complete fertilization regime in the Papaloapan basin.

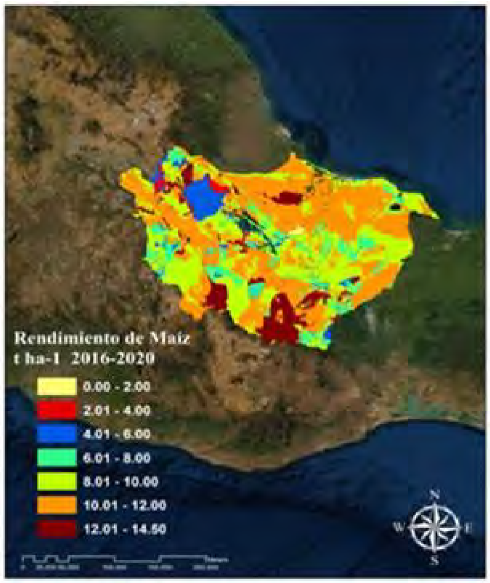

Figure 4. Corn crop yield under half fertilization regime in the Papaloapan basin.

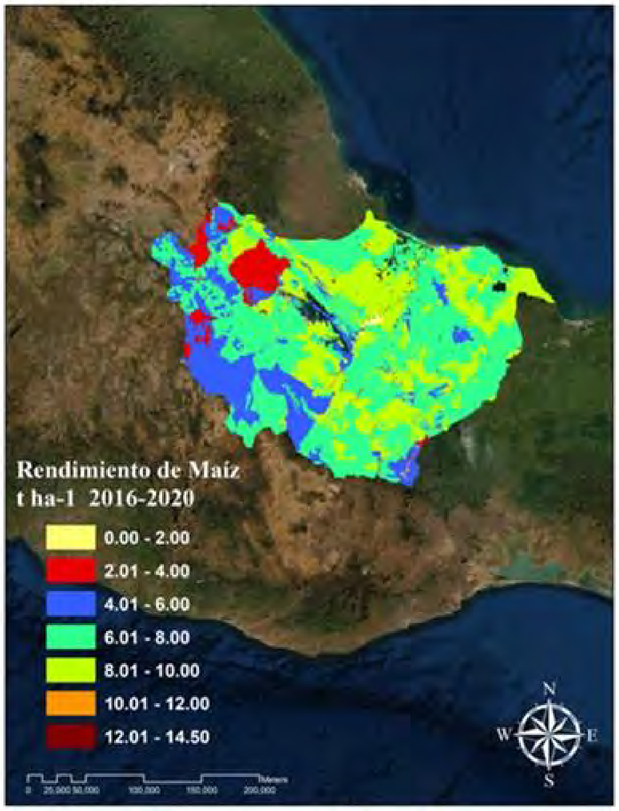

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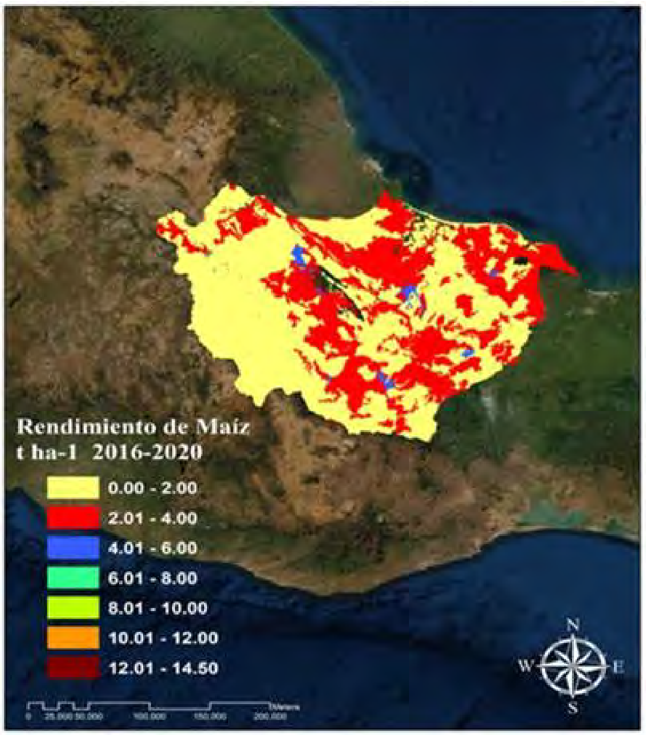
Figure 5. Corn crop yield without fertilizer application in the Papaloapan basin.



Using Pearson's correlation method (Lalinde *et al*., 2018), data measured in the field were validated based on those obtained through the simulation process. The analyzed values are shown in Table 5.

Table 5. Correlation analysis of data measured in the field based on data simulated by the model.

Locality	HRU	Simulated yield (t ha^{-1})	Measured yield (t ha^{-1})
[+]Ignacio de la Llave	1 219	8	6.65
[+]San Andres Tuxtla	2 457	7.96	6.69
[*]Loma Bonita	3 702	6.79	5.99
[+]Tlalixcoyan	1 730	6.01	5.18
[+]Cotaxtla	1 285	8.5	7.74
[+]Mata de Agua	2 175	7.28	5.82
[+]Rodriguez Clara	3 819	4.05	3.3
[+]Sampedro Quilitongo	6 140	4.01	1.28
[*]San Juan Bautista Coixtlahuaca	6 153	4.02	1.48
[*]Tepelmeme de Morelos	4 310	4.01	1.27

[*] = Sánchez *et al*. (2019); [+]= Sierra *et al*. (2008).

Figure 6 shows the behavior of the correlation analysis of data taken in the field compared to the values obtained through the simulation process. The R^2 value obtained shows a high correlation and, therefore, demonstrates that the SWAT model (Neitsch *et al*., 2009) simulates with remarkable precision the behavior of the corn crop in the Papaloapan basin.

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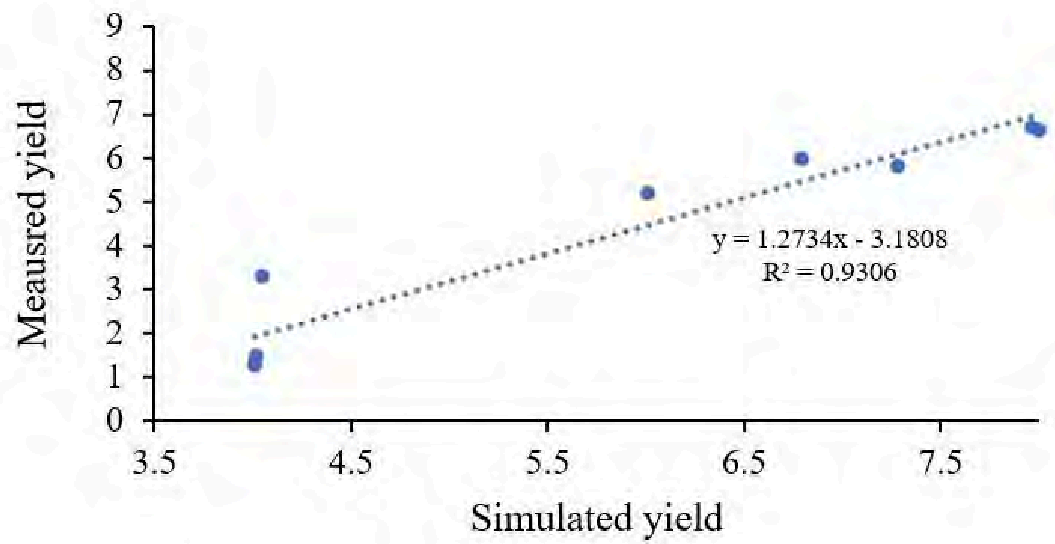
Figure 6. Behavior of the correlation of the data analyzed in Table 5.



Based on the results obtained, it can be seen that the application of fertilizer in the corn crop of the Papaloapan basin is crucial for grain production; in turn, it was observed that the difference between a half dose of nitrogen (60 kg ha^{-1}) and an optimal dose (120 kg ha^{-1}) is only 3.67 t ha^{-1}. Based on this, the efficiency of nitrogen use in both scenarios was analyzed. The efficiency in the use of nitrogen was calculated according to (Dobermann, 2005), with the following formula: PFPN = YN/FN. Where: PFPN= nitrogen-use efficiency; YN= crop yield under the application of N (t ha^{-1}); FN= amount of N applied (kg ha^{-1}). The nitrogen-use efficiency of the scenario with a half dose of fertilization was found to be higher than that of the full dose. Table 6 shows the results obtained in proportion to the statistical value of the mean and maximum value of the effects evaluated.

Table 6. Nitrogen-use efficiency under the application of half and optimal doses of nitrogen in the Papaloapan basin.

Factor FN	Mean YN	Maximum YN	Value of PFPN
Optimal fertilization (120 kg N ha^{-1})	9.4 t ha^{-1} of corn	14.37 t ha^{-1} of corn	PFPN (mean)= 0.08 PFPN (maximum)= 0.12
Half dose of fertilization (60 kg N ha^{-1})	6.75 t ha^{-1} of corn	10.7 t ha^{-1} of corn	PFPN (mean)= 0.11 PFPN (maximum)= 0.18

The optimal dose of fertilizer for the corn crop in the Papaloapan basin turns out to be excessive, as indicated by Capetillo *et al*. (2021). Applying half the dose of nitrogen fertilizer is sufficient to obtain yields greater than 10.7 t ha^{-1}, as shown in Figures 7 and 8. This practice not only has implications for the benefit-cost ratio but also contributes to the sustainability of the agroecosystem by avoiding degradative processes associated with the inefficient use of nitrogen fertilizers, as mentioned by Saynes-Santillán *et al*. (2019).

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Figure 7. Nitrogen-use efficiency (PFPN) value in the corn crop under an effect of half the fertilization dose.

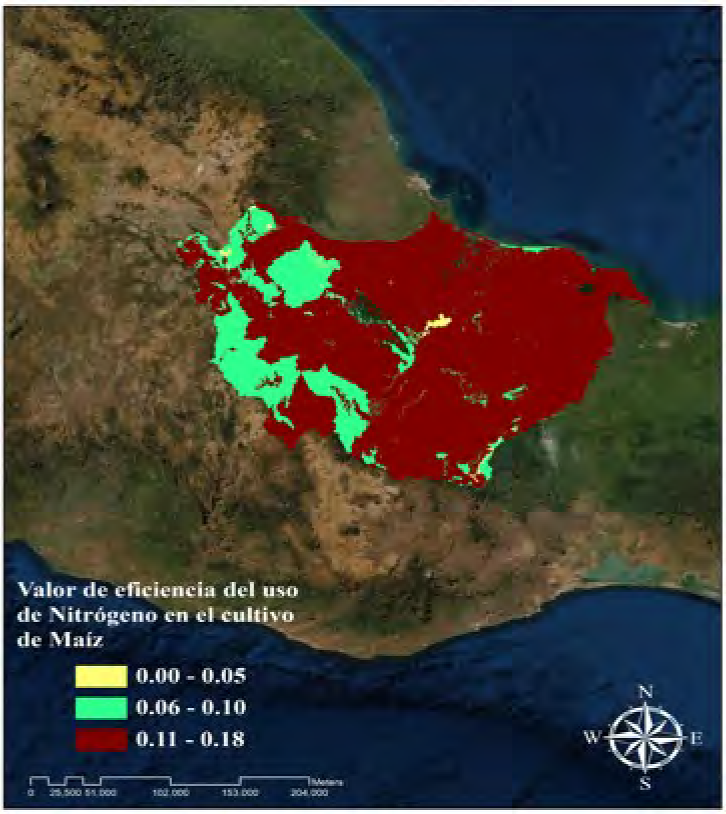

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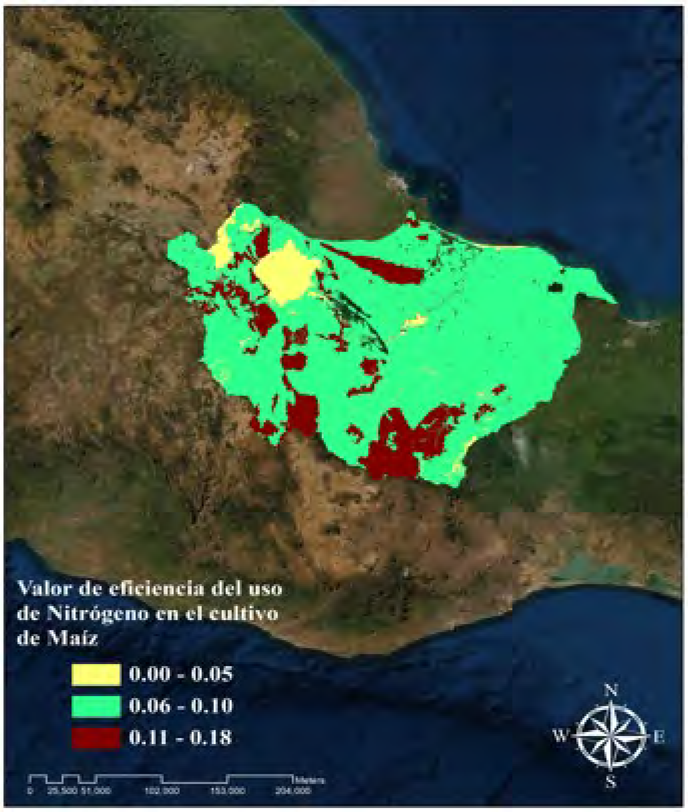
Figure 8. Nitrogen-use efficiency (PFPN) value in the corn crop under an effect of optimal fertilization dose.



Conclusions

Fertilization is crucial for corn crops since a significant difference in yield is observed between fertilization and non-fertilization, with an average of 7.8 t ha^{-1}. Nevertheless, waste in the use of nitrogen fertilizers has been found since the yield does not vary so much between the full dose and the reduced dose. This suggests that a moderate application of fertilizer could be sufficient to obtain good yields, above 10.7 t ha^{-1}, and be more sustainable for the corn agroecosystem. Further research is required to improve the use of nitrogen fertilizers through new technologies and agronomic practices.

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