

CLIMATE CHANGE AND ITS EFFECTS ON AGRICULTURE IN MEXICO

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ABSTRACT

Climate change is a major concern around the world, particularly in developing countries like Mexico, where agriculture is the primary rural activity. As a hypothesis, it was proposed that high concentrations of CO₂ in the atmosphere increase crop yields in Mexico, while the increase in temperatures and precipitation variations decrease them. The effect of climate change on agriculture in Mexico was examined using CO₂ concentrations in the atmosphere, temperature, and precipitation. The climatic factor that has the greatest influence on agricultural productivity at the national level was identified. The ordinary least squares (MCO) method was used to estimate a Cobb-Douglas econometric model with statistical significance ($p \leq 0.05$). CO₂ concentration in the atmosphere was the climatic factor that had the greatest influence on agricultural production at the national level, with a direct relationship: if CO₂ increased by 1 %, agricultural yield increased by 0.46 %. Corn and sugarcane, two of the three most important crops in terms of productive value in Mexico, are plants with a C₄ photosynthetic pathway that benefit from the CO₂ fertilization effect and mitigate the negative impact of climate change. However, in the last thirty years, global CO₂ emissions have increased by an average of 0.5 % per year. If its growth continues to follow the same pattern in the short term, temperatures will rise, rainfall patterns will change, and agricultural production will be negatively affected.

Keywords: CO₂, agricultural production index, temperature, precipitation, C₄ crops.

INTRODUCTION

Climate change (CC) is one of the greatest concerns worldwide. Climate change has had an impact on ecosystems, society, and economic sectors in recent decades (SEMARNAT, 2016). This concern is intensified in developing countries, which rely more on agriculture and have less capital to implement adaptation measures. (López-Feldman and Hernández-Cortés, 2016). CC is caused by an increase in the concentration of greenhouse gases (GEI) in the atmosphere, which cause a rise in the planet's temperature and a change in rainfall patterns (Medina-García *et al.*, 2016). According to the Ministry of Environment and Natural Resources in Mexico, climate change has reduced wheat and corn crop yields in many regions around the world. At

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the national level, an increase in temperatures, regional variations in precipitation, sea level rise, increased cyclones, tornadoes, and droughts, and less productive soils have been observed, with serious economic and social consequences (SEMARNAT, 2019). According to INEGI (2022), agriculture is the main component of the primary sector. In 2021, it contributed 62 % of this sector's GDP and was the primary activity of the rural environment, where 21 % of the national population lived. In addition, agriculture serves multiple functions (FAO, 2009). According to the Economic Commission for Latin America and the Caribbean (López-Feldman, 2015), agricultural development is critical to the country's long-term economic growth and poverty reduction. According to the National Institute of Ecology and Climate Change (INECC), a decrease in maize productivity is expected in Mexico by the 2050s based on future scenarios; therefore, studying the effect of climate change on agriculture is of the utmost importance.

There are currently several methods for estimating the relationship between crop yield and climatic variables. Fernandez (2013) classifies these approaches into structural and spatial; stating that the former uses models to simulate the effects, adaptations, and economic consequences of climate change, while the latter simulates the outcome of climate change on agriculture based on differences in land values, agricultural production, and other climate-related costs.

Adams (1989), a pioneer in the study of the effects of climate change on agriculture, used the spatial approach in counties across the United States, doubling the CO₂ content through simulation. He found that when the fertilizer effects of increased CO₂ are projected alongside with climate change, yield reductions are mitigated and, in some cases, increase above the baseline. Following the same methodology, Stöckle *et al.* (2010) found that the impact of climate change will be slight in the short term, but increasingly damaging over time. However, they anticipate that the increased CO₂ levels will mitigate crop yield losses while increasing yields for others.

The Ricardian approach was developed by Mendelsohn, Nordhaus, and Shaw in 1994 to estimate the effect of climate variables on agricultural land prices. They concluded that global warming could have a positive economic impact on agriculture. Nonetheless, using a methodology that corrects for the bias of the production function approach and incorporates the value of land, Gonzalez-Velandia and Galera-Gelvez (2014) found that the estimated impact of global warming on agriculture was lower than that obtained with the production function approach. Thus, this study analyzed the behavior of climate variables at the global and national levels during the study period.

The goal was to investigate the impact of CC on agriculture in Mexico through three variables: atmospheric CO₂ concentration, temperature, and precipitation, by using the production function approach to determine the climatic factor that most influences agricultural productivity at the national level. It was hypothesized that the increase in the concentration of carbon dioxide in the atmosphere contributes to an improved productivity of agriculture in Mexico, whereas an increase in temperature and precipitation changes reduce crop yields.

MATERIALS AND METHODS

To estimate the econometric model, data were collected for 35 years. According to the World Meteorological Organization, the effects of climate change become evident in the long term over a time horizon of 30 years or more. Mexico keeps a national inventory of greenhouse gases and compounds for the 1990–2019 period.

For the dependent variable, the FAO gross production index (base 2014–2016) for agriculture in Mexico was used. This includes 106 crops and shows the relative level of the overall agricultural production for each year compared to the base period. The production harvested in the fields and orchards is analyzed in the irrigated and rainfed modality as a whole, since there is no index for each type of agriculture.

The country's contribution to global emissions in 2016 was only 1.4 %. In that same year, according to the International Energy Agency, five countries were responsible for 57.6 % of the CO₂ emitted worldwide due to the consumption and burning of fossil fuels: China, the United States, Russia, Japan, and India (SEMARNAT, 2019). Therefore, global CO₂ emissions were used as the independent variable, accounting for more than 70 % of total GEIs and providing more reliable and homogeneous data globally (SEMARNAT, 2016).

The data used were collected from CO₂ observations taken at the Mauna Loa observatory, Hawaii, USA. Mauna Loa is regarded as one of the best locations for atmospheric measurements. The possible contribution of vegetation or human activities on CO₂ concentration are minimal; the influence of volcanoes can be excluded from the records. Because CO₂ is a gas that is easily dispersed in the atmosphere, measurements made anywhere in the world are considered representative (Keeling *et al.*, 2021).

The maximum, mean, and minimum averages in °C for each year were used for temperature variables, and the accumulated measurement in mm was used for precipitation variables. Both correspond to national data from the SMN (Servicio Meteorológico Nacional), which is part of the CONAGUA (Comisión Nacional del Agua). Statistical analyses of unit root and stationarity were performed for the explanatory variables using the Dickey-Fuller, Phillips-Perron and KPSS tests. CO₂, temperature, and precipitation were found to be non-stationary time series. The trend was eliminated using the equations $\nabla\text{CO}_2 = \text{CO}_2_{(t)} - \text{CO}_2_{(t-1)}$, $\nabla T = T_{(t)} - T_{(t-1)}$ and the absolute value of $\nabla P = P_{(t)} - P_{(t-1)}$.

Using the production function approach, we examined the effect of annual changes in atmospheric CO₂ concentration, temperature, and precipitation on agricultural productivity in Mexico. An econometric model was estimated using the ordinary least squares (MCO) method using the SAS[®] statistical package. The starting point was a Cobb-Douglas function that transformed into a linear function by a double-logarithmic function. The dependent variable is agricultural yield (Y) and the explanatory variables are CO₂, temperature (T), and precipitation (P); β_1 , β_2 , and β_3 are the estimators of each variable; α is the estimated coefficient of the constant, i.e., the response to other factors such as technological and policy changes; ε represents the error term (unobservable effects).

The linear model evaluated for agricultural yield in Mexico with the explanatory climatic variables is presented in Equation 1:

$$\ln Y = \alpha + \beta_1 \ln CO_2 + \beta_2 \ln T + \beta_3 \ln P + \varepsilon \quad (1)$$

The goodness of fit of the econometric model was determined by using the coefficient of determination (R^2) to determine how much of the variation in the dependent variable is explained by the independent variables. The *p-value* associated with the *t*-statistic value was ≤ 0.05 , indicating that the econometric model's parameters have statistical significance. The estimated coefficients were interpreted as elasticities; for example, if CO_2 varies by 1 %, agricultural production changes by β_1 %, and the same is true for temperature and precipitation, with their respective estimators.

The present study may have underestimated the effects of climate change on agriculture, since it did not take into account the response of farmers to this phenomenon, such as, for example, the modification of crop patterns, the use of improved seeds or other agricultural inputs, as well as variations in planting dates and other actions to counteract the negative effects of this phenomenon. Another limitation was the generalization of the results, considering that the FAO agricultural production index was used at the national level, which includes 106 crops. The results do not explain the impact of climate change on agriculture by region, nor do they include indicators of sensitivity and exposure to extreme weather events.

Data analysis

Based on data from the United States National Aeronautics and Space Administration (NASA, 2021), the warmest years worldwide were 2016 and 2020. The temperature variation in 2020 was 1.02 °C compared to the base period (1951–1980), with a rise close to 1 °C in 2016. From 1940 to 1976, the global temperature fluctuated in relation to the average, indicating that there was no global warming. However, from 1977 to the present, the variations have only been temperature increases relative to the baseline period.

The warmest recent years in Mexico were 2017 and 2020, with temperature variations of 1.6 and 1.5 °C above the average (1951–1980), respectively (FAO, 2021). According to CONAGUA (2021), temperatures (maximum, mean, and minimum) in Mexico increased during the study period (Figure 1A, 1B, 1C). The maximum, mean, and minimum average temperatures were 28.8, 21.3, and 13.7 °C, respectively. The highest extremes occurred in 2015, with a minimum temperature of 15.1 °C, and in 2017, with a maximum temperature of 30.1 °C (Table 1).

During the study period, the average precipitation in Mexico was 925 mm (CONAGUA, 2021). Its behavior does not show a change in pattern, although there are variations throughout the years. The wettest year during the period was 2010, with an average precipitation of 1100 mm, while the year with the least rainfall was 2019, with an average of 718 mm (Figure 1D).

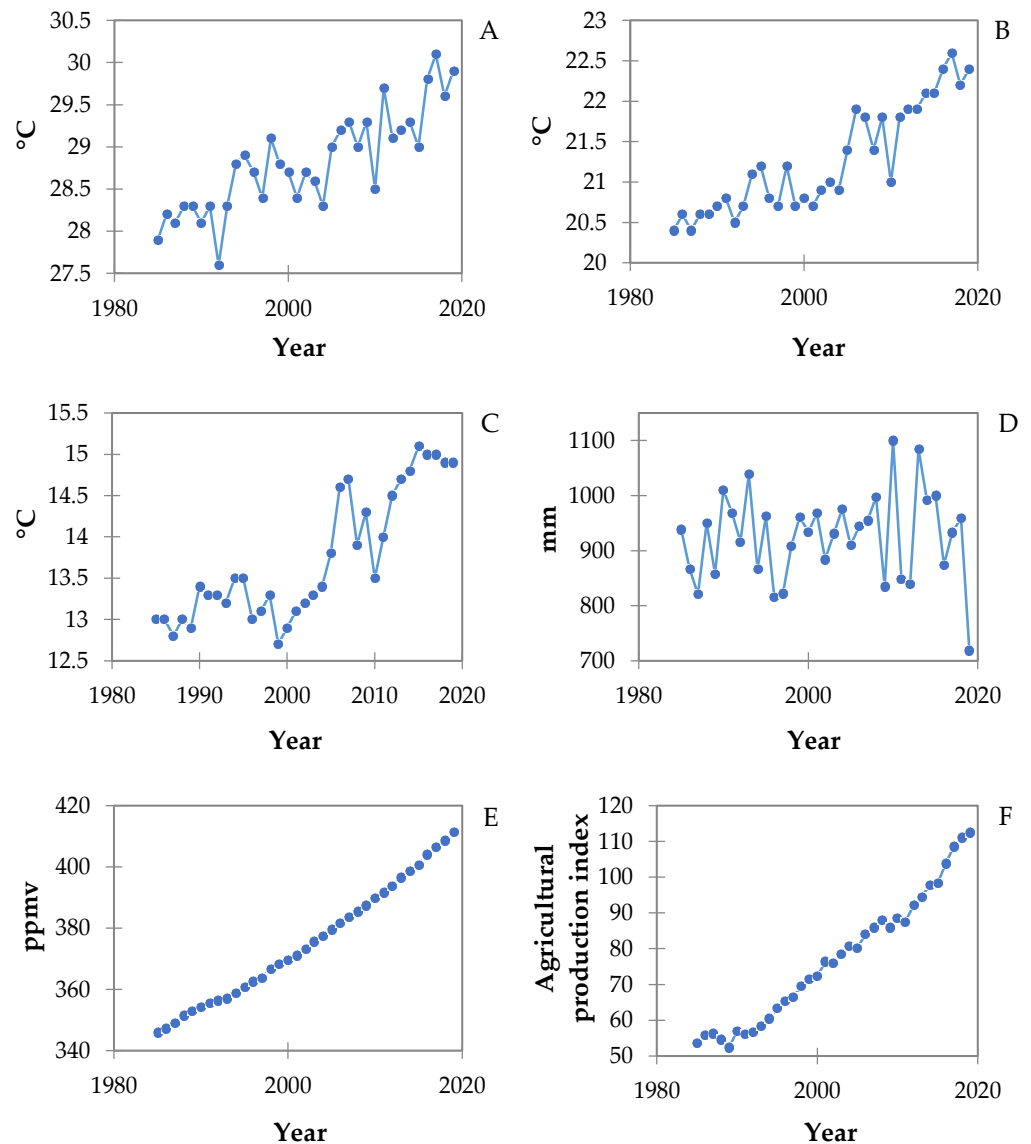


Figure 1. Behavior of the climatic variables analyzed and agricultural production in Mexico. A: maximum temperature; B: mean temperature; C: minimum temperature; D: precipitation; E: global CO₂; F: agricultural production index.

The existing historical series of carbon dioxide concentration in the atmosphere is divided into two periods. The information from 1010 to 1955 comes from ice core samples, and from 1959 to 2019 correspond to direct measurements of the atmosphere. According to records from the National Environmental and Natural Resources Information System, in 1010 the concentration of carbon dioxide was 279.5 ppmv, during the pre-industrial era it remained around 280 ppmv, and in 2018 it was 408.6

Table 1. Descriptive statistics of the climatic variables analyzed.

Variable	Minimum	Maximum	Mean	Standard deviation
Agricultural production index	52.360	112.520	77.175	18.067
Mean temperature (°C)	20.400	22.600	21.257	0.660
Maximum temperature (°C)	27.600	30.100	28.814	0.595
Minimum temperature (°C)	12.700	15.100	13.731	0.778
Precipitation (mm)	718.300	1100.418	925.321	80.050
Global CO ₂ (ppmv)	345.903	411.400	375.339	19.521

ppmv (SNIARN, 2021). In 2018, 33 513 million Mg CO₂ were emitted globally from fuel combustion (Figure 1E). The main emitting countries were China, the United States, India, Russia, Japan, and Germany, with 28.43, 14.68, 6.89, 4.74, 3.22, and 2 %, respectively. Together, they accounted for 60 % of total global emissions; other nations individually emit less than 2%. Mexico emitted 448.5 million Mg CO₂ (1.34 %) (IEA, 2021).

Mexico keeps a National Inventory of Greenhouse Gas and Compound Emissions; the most updated one has information for the 1990–2015 period and includes carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (hfc), and sulfur hexafluoride (SF₆). In 2015, CO₂ was the gas with the highest contribution to national emissions with 71.97 %, followed by CH₄ with 20.32 %, and N₂O with 5.9 %. These three gases account for 98.1 % of total GEIs. The remaining 1.8 % is attributed to hfc and SF₆. In the same year, the energy sector generated 71 % of total emissions, livestock 10 %, and 19 % were attributed to industrial processes, product use, waste, aggregate sources, and others besides CO₂ from land (INECC, 2018).

CO₂ emissions from fuel combustion in Mexico during the period 1989–2012 showed an increasing trend. It decreased slightly in 2013 and 2014. From 2015 to 2018 it increased, although at a slower rate. The agricultural production index in Mexico has shown an increasing trend, with a minimum of 52.36 in 1989, and a maximum of 112.52 in 2019 (Figure 1F).

RESULTS AND DISCUSSION

Estimation of the econometric model for the index of agricultural production in Mexico.

To determine the individual effect of annual changes in temperature, precipitation, and CO₂ on agricultural yields in Mexico, econometric models 1, 2, 3, 4, and 5 were estimated (Table 2). Carbon dioxide is the climate variable that best explains the country's agricultural production, with an R² of 0.36 that is higher in models 2, 3, 4, and 5. Carbon dioxide accounts for 36 % of agricultural production. CO₂ and maximum temperature both had a *p-value* ≤ 0.05.

Table 2. Estimates for determining the most influential climatic factor on agricultural production in Mexico.

Variables	Estimate 1	Estimate 2	Estimate 3	Estimate 4	Estimate 5
Intercept	4.083	4.398	4.356	4.352	4.434
Ln CO ₂	0.399 (4.315)* [†]				
Ln T max		0.061 (2.359)*			
Ln T mean			0.018 (0.810)		
Ln T Min				0.013 (0.720)	
Ln P					-0.027 (-0.662)
R ²	0.360	0.144	0.019	0.015	0.013
R ² adjusted	0.341	0.118	0	0	0
Critical value of F	0.0001	0.024	0.423	0.476	0.512

[†](statistical *t*); * *p*-value ≤ 0.05 %.

Globally, according to the results of the estimation to determine the agricultural production function, which included carbon dioxide, maximum temperature, and precipitation as dependent variables and explained approximately 58 % of the variance in the agricultural production index in Mexico, the adjusted R² was 0.5782. The critical value of F was < 0.0001, indicating that there is a significant linear relationship between agricultural productivity and the set of independent variables.

The statistical analysis provided the data required to create the double-logarithmic function corresponding to the agricultural production index. It is observed that the *t*-statistics of the independent variables are greater than 2 in absolute value and have a probability of less than 0.05 (Table 3).

According to the estimation parameters, the agricultural production function was obtained (Equation 2).

$$\ln Y = 4.40 + 0.46 \ln CO_2 + 0.07 \ln T - 0.06 \ln P \quad (2)$$

Table 3. Estimation of the agricultural production function.

Variable	Parameter estimator	Standard error	Value t	Pr > t
Intercept	4.397	0.118	37.077	< 0.0001
ln T	0.072	0.018	3.998	0.0004
ln CO ₂	0.459	0.075	6.065	< 0.0001
ln P	-0.062	0.027	-2.279	0.0297

The calculated value of α represents the response to other factors such as technological and political matter changes, which in this case is 4.40. The calculated value for β_1 is 0.46, which indicates that if temperature and precipitation remain constant, a 1 % increase in the global carbon dioxide concentration corresponds to a 0.46 % increase in the agricultural production rate in Mexico. The CO_2 variable has a direct relationship with crop productivity. The trend is as expected: the higher the CO_2 emissions, the higher the agricultural production. The results are consistent with studies conducted elsewhere. Plants use CO_2 and sunlight to carry out photosynthesis and transform carbon dioxide into sucrose, starch or cellulose, as stated by Taiz and Zeiger (2006). Plants are classified as C_3 , C_4 , or CAM, based on the type of photosynthetic metabolism they perform (Carcia de Carvalho *et al.*, 2014). According to Wahid (2004), C_3 plants with optimal humidity and temperature benefit from increased atmospheric CO_2 ; Taiz and Zeiger (2006) reported that C_4 and CAM show less transpiration and more efficient use of water and nutrients under adverse conditions (high temperature and low humidity). However, although carbon dioxide is beneficial to plants, increasing its concentration could be detrimental to crop yields, with the degree of vulnerability depending on the type of crop.

Streck and Alberto (2006) found that increasing air temperature by 2, 3, and 6 °C may cancel out the beneficial effects of increased CO_2 levels on wheat, soybean, and corn yields in Brazil. Bravo-Ortega and Lederman (2005) argued that agriculture in Latin America is neutral in terms of carbon dioxide emissions, while Rabbinge *et al.* (2007) stated that CO_2 enrichment and increased temperatures have positive consequences on crop yields only when growing conditions are optimal. Therefore, the rise of carbon dioxide levels in the atmosphere is of concern because most crops are not growing in optimal conditions.

The calculated value of β_2 was 0.07, indicating that if global carbon dioxide concentration and precipitation remain constant, a 1 % increase in maximum temperature in Mexico would correspond on average to a 0.07 % increase in the agricultural production index. The temperature variable has a direct relationship with agricultural productivity. Caicedo-Aldaz *et al.* (2021) stated that increased temperatures would lengthen the growing season of plants in areas where crop potential is today limited by cold, and climate change in these regions could be seen as advantageous. Similarly, Iglesias *et al.* (2011) stated that changes in productivity in Spanish agriculture will depend on the agroclimatic region and crop type. Negative impacts are expected for the Mediterranean region, while not so severe effects (even positive effects) are expected in the rest of Spain.

Feder *et al.* (2010) highlighted the negative effects on most crops, especially where water scarcity is severe. Tubiello and Rosenzweig (2008) stated that, if global warming continues beyond mid-century, production in all regions of the world will be negatively affected. The vulnerability of countries will depend, among other things, on their geographical conditions and the type of crops they produce or can produce (López-Feldman and Hernández-Cortés, 2016). Carrasco-Choque (2016) found that

quinoa yields in Peru will be affected when temperature exceeds the optimal threshold required for that crop.

According to the Sistema de Información Agroalimentaria y Pesquera (SIAP, 2021), the most important crops in Mexico in terms of production value in 2019 were grain corn, avocado, and sugarcane, which together accounted for about 30 % of the total national production value. Maize and sugarcane are crops with a C_4 photosynthetic cycle. Kuwahara *et al.* (2016) noted that these grasses have high production potential due to higher water use efficiency in tropical regions with low latitudes, high insolation, and high temperatures. Orozco-Bolaños *et al.* (2019) outlined strategies farmers have adopted in the face of climate variations, including changing planting dates, selecting drought-resistant native seed, and using organic fertilizers. Therefore, it can be affirmed that crop yields in Mexico, as a whole, have not yet been adversely affected by the increase in temperature.

The calculated value of β_3 is -0.06. If atmospheric CO_2 and maximum temperature in Mexico remain constant, a 1 % change in cumulative national precipitation will correspond to a 0.06 % decrease in the agricultural production index on average. This result agrees with Guajardo-Panes *et al.* (2018) who stated that excessive precipitation can reduce soil oxygenation and the rate of water and nutrient uptake by the crop. Climate change may alter the variation in the frequency and intensity of extreme hydrometeorological phenomena, such as cyclones and drought. Mexico, due to its geographical location, climatic conditions, and socioeconomic characteristics of the population, is vulnerable to these phenomena (SEMARNAT, 2016). Bahena-Delgado *et al.* (2017) confirmed that changes in rainfall patterns increase the probability of short-term crop failure and reduce long-term production. Thus, rainfall is a determinant of agricultural production that can have positive or negative effects on agriculture; when rainfall is higher or lower than the parameters required by each crop, agricultural yields decrease.

According to the estimated model, the carbon dioxide concentration in the atmosphere has the greatest influence on agricultural production at the national level, with an elasticity of 0.46. It is followed by temperature (0.07) and precipitation (0.06). All three variables are inelastic. There is a direct relationship between the agricultural production index and CO_2 concentrations in the atmosphere, as well as with temperature; and an inverse relationship with changes in precipitation patterns.

According to the estimated double-logarithmic model, a Cobb-Douglas type production function was obtained (Equation 3).

$$Y = 81.45 CO_2^{0.46} T^{0.07} P^{-0.06} \quad (3)$$

Since $\beta_1 + \beta_2 + \beta_3 < 1$ ($0.46 + 0.07 - 0.06 = 0.47$), it is stated that such a production function has decreasing returns to scale. This indicates that as one of the variables (CO_2 , temperature, or precipitation) increases while the others remain constant, productivity decreases. The marginal product is then both positive and decreasing. Based on

Equation 3, the univariate production function was obtained, keeping temperature and precipitation constant (Equation 4).

$$Y = 67.95 CO_2^{0.46} \quad (4)$$

The graph corresponding to this function shows that the marginal yields are positive and decreasing (Figure 2).

The univariate model revealed that rising atmospheric CO₂ levels are a factor influencing agricultural productivity growth in Mexico. Marginal yields are declining, and the marginal product of this productive factor is also declining. As CO₂ levels grow, temperatures rise, causing changes in precipitation patterns that affect agricultural productivity.

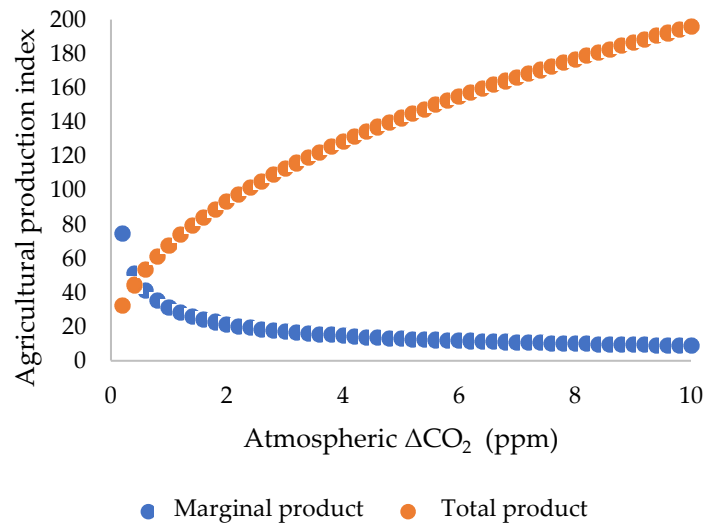


Figure 2. Marginal product and agricultural production function with respect to CO₂

Holding CO₂ and precipitation constant, a univariate production function was obtained to observe the behavior of agricultural production in terms of temperature (Equation 5). The variables were kept constant by using the averages of global emissions and annual variations for the study period.

$$Y = 81.71 T^{0.07} \quad (5)$$

From equation 3 the agricultural productivity of Mexico was obtained as a function of maximum temperature. Marginal yields are positive and decreasing (Figure 3). Temperature is a variable that influences agricultural production. However, in order to show an increase, carbon dioxide emissions must rise and a change in rainfall patterns must also occur.

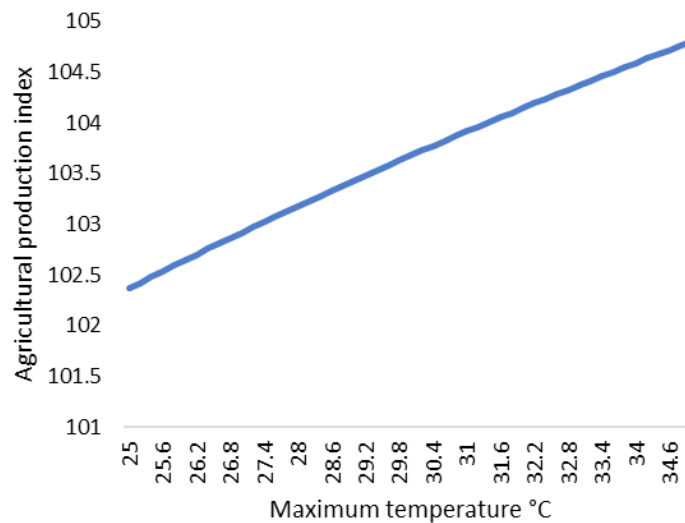


Figure 3. Agricultural production function with respect to temperature.

From Equation 3 we obtain the agricultural production function with respect to precipitation; global CO₂ emissions and temperature remain constant (Equation 6).

$$Y = 135.2 P^{-0.06} \tag{6}$$

According to the estimated production function, the increase in precipitation has an inverse relationship with the agricultural production index (Figure 4). As a result, changes in precipitation patterns caused by climate change have a negative impact on agricultural production in Mexico.

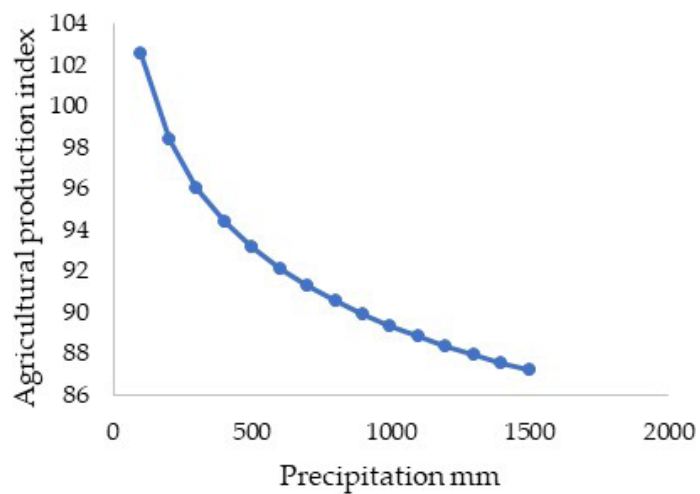


Figure 4. Agricultural production function with respect to precipitation.

CONCLUSIONS

Global and national statistics showed that carbon dioxide emissions increased in the atmosphere during the study period, which has led to a rise in temperature and changes in precipitation patterns. Agriculture in Mexico has so far benefited from high carbon dioxide levels. This is due to the effect of fertilization, since two of the three most important crops in terms of production value are C₄ plants (corn and sugar cane). Rising temperatures have not harmed agriculture; however, changes in precipitation patterns reduced agricultural yields.

Carbon dioxide emissions from global fuel combustion have increased year after year from 1985 to 2019. If greenhouse gas emissions continue to rise, temperatures will rise further, precipitation patterns will change, and agricultural production will be negatively affected.

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