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Research Paper

Change in the productive potential of rainfed maize under climate change scenarios in the Lerma–Toluca Sub-basin, Mexico

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ABSTRACT

Climate change represents a challenge for agricultural production in Mexico for it, this research was undertaken to determine the productive potential of rainfed maize crop in the Lerma-Toluca Basin under historical (1991-2020) and future (2050 and 2070) with Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios. For the scenarios, temperature and precipitation images were generated using the spline interpolation method of the ANUSPLIN program. The productive potential was estimated based on agroecological requirements of maize crop. The results show that, in the historical scenario, medium potential predominates (51.8%) and high potential (17.3%); in future scenarios with RCP 4.5 in 2050, the medium potential increases 0.69% and high potential 0.43%; in 2070, the medium potential decreases 0.68% and high potential increases 1.79%. Under RCP 8.5 in 2050, the medium potential decreases by 1.4%, and high potential increases by 2.16%; in 2070, the medium decreases by 14.96%, and high potential increases 13.15%, compared to the historical scenario. These results provide key information for future agricultural planning in the study area, allowing the design of climate change adaptation strategies that contribute to food security and sustainable resource management.

Keywords: Greenhouse gases, General circulation models, Representative concentration pathways, Global agroecological zones.

Climate change (CC) and climate variability (CV) pose a critical threat to global food security, directly affecting agricultural systems (Gowtham *et al.,* 2020). These phenomena, driven by the increase in greenhouse gases (IPCC, 2023), alter temperature and precipitation patterns (Pendergrass and Hartmann, 2014). The dynamic nature of these processes creates uncertainty regarding the magnitude, timing, and spatial distribution of their future impacts (Getnet *et al.,* 2023; Patidar *et al.,* 2020). These changes are already having tangible repercussions, such as changes in rainfall distribution (Haris *et al.,* 2010) and an increase in temperature that can reduce corn yields by up to 10% (Patidar *et al.,* 2020). Alterations such as these have already been documented in several regions, making it urgent to identify the areas where crops will be able to express their maximum productive potential in the future (Soria-Ruíz and Medina-García, 2022a). To address this challenge, the scientific community has developed various tools. On the one hand, climate models allow us to project future changes. Temperature increases can be predicted with confidence, while changes in precipitation patterns are more uncertain (Gowtham *et al.,* 2020). On the other hand, the assessment of potential through agroecological zoning has established itself as an essential tool for agricultural adaptation, as it allows the identification of areas suitable for cultivation under specific climatic conditions (Manorama *et al.,* 2014)

In Mexico, maize (*Zea mays* L.) is fundamental to food security, the economy, and the social structure, with the country being the world's seventh largest producer of this cereal (SECAMPO, 2023). Within Mexico, the Lerma-Toluca River Sub-Basin located in the State of Mexico is of critical importance, as it concentrates nine of the ten municipalities with the highest corn production, contributing 42% of the state's volume (INEGI, 2019; SECAMPO, 2023). This region is characterized by a predominance of rainfed agriculture—with traditional practices, low technification, and high intensity—where maize is the main crop. The objective of this research was to determine the productive potential of rainfed maize cultivation in Lerma-Toluca sub-basin, considering historical climatic conditions (1991-2020) and future conditions projected for

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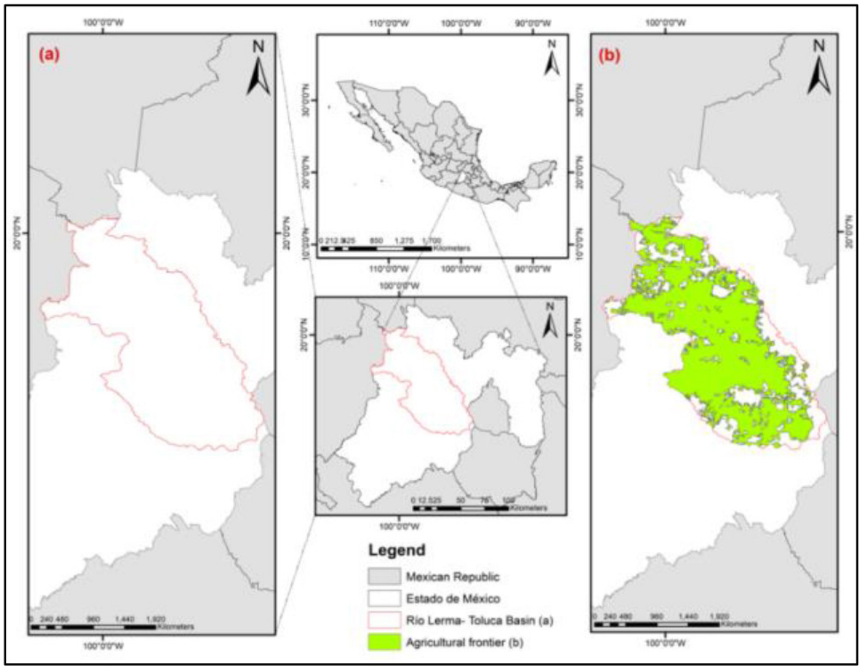

Fig. 1: (a) Location of the study area, (b) Agricultural frontier (SoriaRuiz and Medina-García, 2022a).

2050 and 2070 with Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios.

MATERIALS AND METHODS

Study area

The Lerma-Toluca River sub-basin is located within the State of Mexico, with an area of 5,354 km^2, and includes 30 municipalities in the State of Mexico (Fig. 1a) (INEGI, 2019). This paper calculated maize production potential exclusively within the agricultural frontier defined by Soria-Ruiz and Medina-García (2022a). The agricultural areas updated to 2022 in the Lerma-Toluca River Sub-basin cover 531,842.8 hectares, representing 70% of the study area (Fig.1b).

Climatic data

The climatological databases for the period 1991-2020 were obtained from the National Meteorological Service for 121 stations located in the State of Mexico and its surroundings (CONAGUA, 2023), for the spring-summer agricultural cycle, which includes the months of May to October. Interpolation was carried out using the spline algorithm of the ANUSPLIN package (Zhang and Zhou, 2021), considering latitude, longitude (Guo *et al.,* 2020), and elevation as a covariate, which allows a better representation of the climatic factors (Yener, 2023).

Generation of future climate data

To estimate of future climate scenarios for the spring-summer (P-S) growing season (May to October) of maize, we used models that were considered for Mexico and cited in the Fifth IPCC Report: (BCC-CSM1-1, CCSM4, GISS-E2-R, HadGEM2-AO, HadGEM2-ES, IPSLCM5A-LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MRI-CGCM3 and NorESM1-M) (IPCC, 2014; Salinas *et al.,* 2014) were obtained from the World Clim portal, with a resolution of 30 arc seconds. Each of these models was analyzed with two climate change scenarios: RCP 4.5, representing intermediate emissions with moderate reductions and RCP 8.5, characterized by high emissions without mitigation measures (IPCC, 2014; INECC, 2022).

Estimation of maize production potential

For the estimation of productive potential of the maize crop, it was based on the methodology proposed by Medina-García *et al.,* (2020) and Soria-Ruíz and Medina-García, (2022a), which classifies the areas into three categories: high, medium, and unsuitable productive potential, considering climatic and soil conditions. The INEGI soil map at a scale of 1:250,000 was used for soil characterization, applying the World Reference Base (WRB, 2015) classification (Table 1). Data integration and analysis were done using ArcGIS 10.5 geographic information systems.

RESULTS AND DISCUSSION

Climate modelling

The results show, based on the interpolation, that currently the temperature varies between 5.2°C and 16.5°C and according to the agroecological requirements of the crop, it allows the study area to have a medium productive potential. Future scenarios project more favorable temperatures since with the increase in greenhouse gases (GHGs) the temperature also increases, this allows more zones in the study area to have the conditions for a high productive potential which according to Table 1 this range goes from 18°C to 24°C, as observed with the RCP 4.5 that reaches 18.5°C in 2050 and 18.9°C in 2070, while RCP 8.5 predicts 19.3°C and 20.5°C, respectively. Although this increase improves the crop, it is crucial to consider factors such as extreme weather events, water availability, and soil

Table 1: Agroecological requirements used to determine maize production potential in the study area

Category	Temperature range (°C)	Precipitation range (mm)	Soil group (WRB)
Unsuitable	< 12 or > 30	< 320 or > 1,900	Leptosol, Cryosol, Solonchak, Technosol, Arenosol, Cambisol, Podzol, Planosol, Stagnosol, Acrisol, Histosol, Ferralsol, Phaeozem, Durisol, Gypsisol, Regosol, Gleysol, Solonetz
Medium	12–18 or 24–30	320–630 or 1,500–1,900	Anthrosol, Technosol, Arenosol, Cambisol, Podzol, Planosol, Stagnosol, Acrisol, Histosol, Ferralsol, Phaeozem, Durisol, Gypsisol, Regosol, Gleysol, Solonetz
High	18–24	630–1,500	Chernozem, Kastanozem, Phaeozem, Luvisol, Nitisol, Calcisol, Umbrisol, Fluvisol, Lixisol, Alisol, Andosol

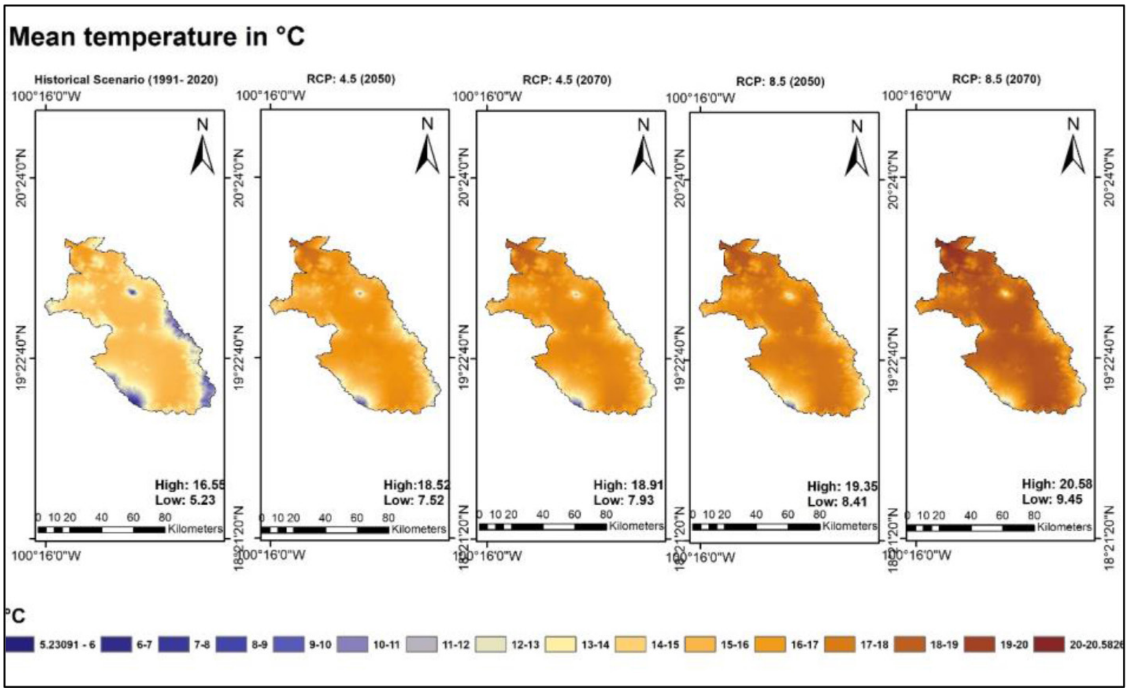

Fig. 2: Mean temperature behavior (May-October) with historical and future (2050 and 2070) climate under RCP 4.5 and 8.5 scenarios

conditions (Fig. 2).

On the other hand, current rainfall varies between 592 and 1,330 mm. This is favorable in most of the study area, since the availability of water allows the development of this crop with a medium to high potential. The highest values are found in high areas due to orographic factors. Although future scenarios indicate a reduction in precipitation this study predicts that rainfall will still be within the ranges to solve a medium 320 to 630 mm and high 630 to 1500 mm productive potential in the study area according to Table 1, as observed with RCP 4. 5 ranging from 585 to 1,219 mm in 2050 and 582 to 1,217 mm in 2070; while RCP 8.5 shows a greater decrease, with 533 to 1,169 mm and 486 to 1,106 mm, respectively. Although the amount of rainfall could meet crop requirements, the distribution of rainfall over the year is unknown, i.e., long periods of drought and torrential rains, which could compromise crop viability in certain areas (Fig. 3).

In both scenarios, the highest precipitation values are observed in the south of the study area, which corresponds to higher altitudes. The decrease in precipitation is greater in the northwestern part of the Basin, which could be a consequence of lower elevations, which reduces the effect of orography in this area and leaves it more exposed to the decrease in rainfall in CC scenarios, with a greater effect being found towards the years 2050 and 2070. A decrease in precipitation would increase water stress in the plant, limit nutrient availability, cause early leaf senescence (Shao *et al.,* 2024), and decrease the photosynthetic capacity of plants (Lobell *et al.,* 2011).

The study area shows an increase in temperature of up to 4 °C and a decrease in precipitation of more than 200 mm in the most extreme scenario (RCP 8.5) and in the longest time span (2070). Increased temperatures and decreased precipitation could increase evapotranspiration levels, generating water stress in the crop due to lack of moisture in its water balance and would bring with it several significant effects on maize production (Medina-García *et al.,* 2017). In addition, the increase in temperature could accelerate the phenological cycle of the crop, reducing grain filling time, and thus affecting grain quality (Hatfield and Prueger, 2015). In addition, high temperatures favor the development of pests and diseases, increasing crop vulnerability and reducing productivity (Garrett *et al.,* 2006).

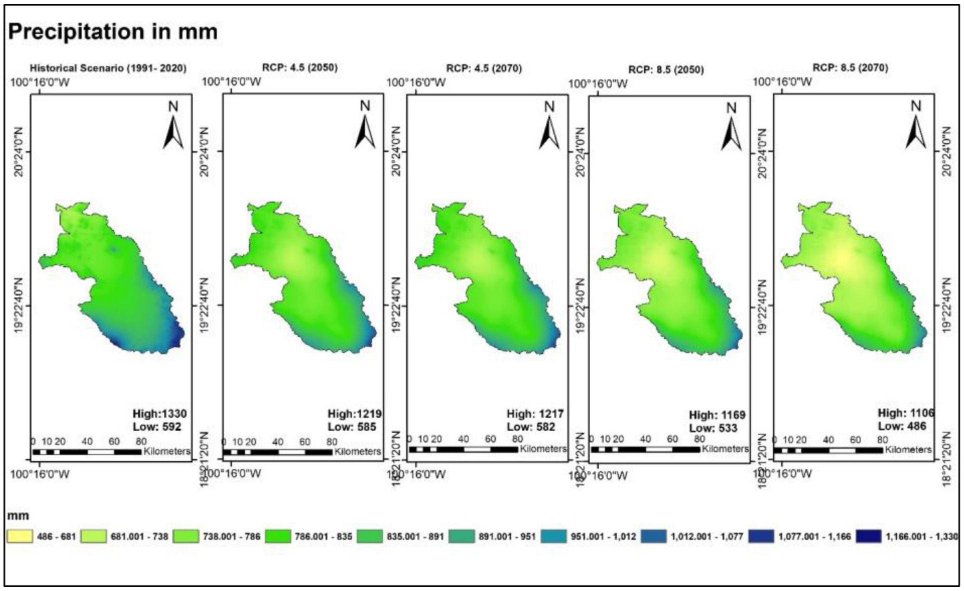

Fig. 3: Cumulative precipitation behavior (May-October) with historical and future (2050 and 2070) under RCP 4.5 and 8.5 scenarios

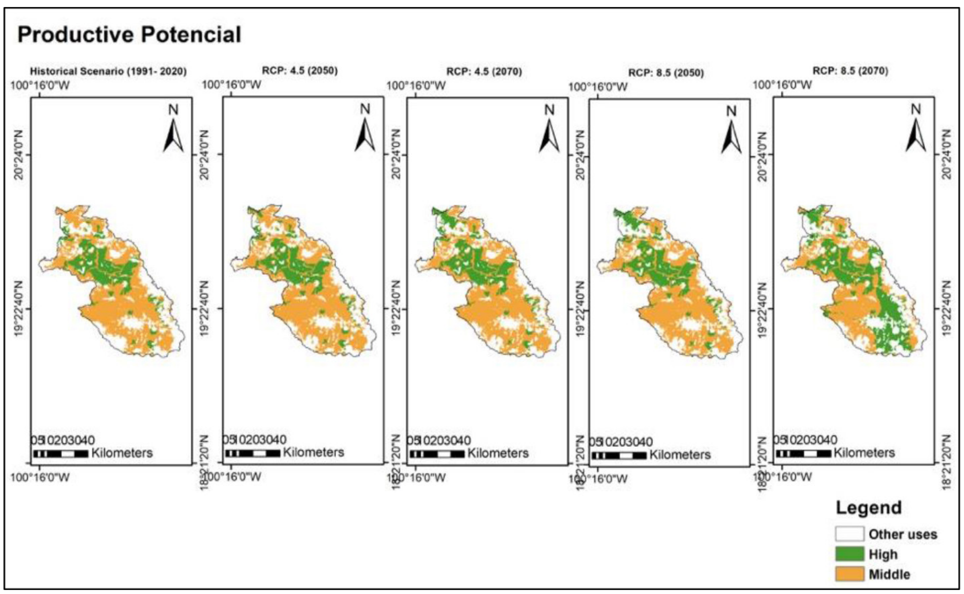

Fig. 4: Mapping the potential rainfed maize area in the study area (excluding non-agricultural areas) under the current and future climate change scenarios under RCP 4.5 and 8.5

Production potential under current and future CC scenarios

In the current scenario, the agricultural area presents a medium and high potential in the spring-summer crop cycle; this is due to favorable soil and climatic conditions, although low temperatures limit the development of corn in the early phenological stages of the crop, since low temperatures inhibit the development of crops, coinciding with what was reported by Jasso-Miranda *et al.,* (2022), who report that low temperatures limit the productive potential of maize (Fig. 4).

The results of this study, which indicate greater current productive potential compared to previous studies (Díaz-Padilla *et al.,* 2012; Soria-Ruíz and Medina-García, 2022a, 2022b), are attributed to the use of a more detailed soil classification and the increase in temperature in recent decades. However, recurrent frosts (Cruz-González *et al.,* 2024) remain a key limiting factor.

Under climate change scenarios, an expansion of areas with high potential is projected, especially in high valleys by 2070 under RCP 8.5, due to more favorable thermal conditions (Hatfield and Prueger, 2015), coinciding with Ruiz-Corral *et al.,* (2011) and Cruz-González *et al.,* (2025). However, although an expansion of areas with high potential is projected due to the increase in temperature, this benefit could be offset by the negative impacts of the temperature increase. Research such as that by Patidar *et al.,* (2020) and Gowtham *et al.,* (2020) shows that increases above 1°C reduce corn yields by up to 10% by drastically shortening the phenological cycle and affecting grain filling. Therefore, converting areas will not translate into higher yields without management

Table 2: Potential rainfed maize areas in the study region under current and future climate change scenarios

Scenarios	Period	Productive potential					
		High		Medium		Unsuitable	
		Area (ha)	(%)	Area (ha)	(%)	Areas (ha)	(%)
Historical	1990-2020	91,710.70	17.27	275,673.12	51.85	0	0
RCP 4.5	2050	94,145.25	17.70	279,401.03	52.54	0	0
	2070	101,350.74	19.06	272,037.65	51.17	0	0
RCP 8.5	2050	103,335.42	19.43	268,269.32	50.45	0	0
	2070	161,713.59	30.42	196,174.37	36.89	0	0

strategies that mitigate heat stress.

Although total precipitation would remain at adequate levels, its temporal distribution is crucial. While moderate reductions (10-20%) could be beneficial in humid areas (Patidar *et al*., 2020), in regions with stochastic rainfall patterns such as the Lerma-Toluca sub-basin, any decrease or greater variability in distribution will exacerbate water stress, limiting the productive potential estimated solely on the basis of total annual rainfall.

Table 2 presents the distribution of potential areas for corn production in the spring-summer cycle under historical and future scenarios (2050 and 2070) with RCP 4.5 and 8.5. In the historical scenario, the medium potential covers 51.85% of the study area and the high potential 17.27%. Under RCP 4.5, for the year 2050, the area of medium potential represents 52.54% (increase of 0.69% with respect to the present) and high potential represents 17.70% (increase of 0.43% with respect to the present). For the year 2070, the area of medium potential represents 51.17% (decrease of 0.68% with respect to the present) and high potential represents 19.06% (increase of 1.79% with respect to the present). In RCP 8.5, by the year 2050, the area of medium potential represents 50.45% (decrease of 1.4% with respect to today) and high potential 19.43% (increase of 2.16% with respect to today). For the year 2070, the area of medium potential represents 36.89% (decrease of 14.96% with respect to the present) and the high potential represents 30.42% (increase of 13.15% with respect to the present).

CONCLUSIONS

With the historical scenario, the surface with maize crop has medium to high potential; this is due to favorable soil and climatic conditions for good crop growth and development. With climate projections under RCP 4.5 scenario in 2050 and 2070, although medium potential predominates, some areas will evolve toward high potential. Under RCP 8.5, changes are moderate in 2050, but in 2070, a significant increase in high potential is observed, specifically in high valley areas, which are considered the most important for corn production. With RCP 8.5 scenario, the study area will experience a significant increase in temperature and reduced precipitation by 2070. Areas were identified with an increase in corn production potential, attributable to more favorable thermal conditions. However, this will be conditioned by water availability, soil quality, and the occurrence of extreme events such as drought and flooding.

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