Original Research Article

THE AGRICULTURAL SECTOR AND CLIMATE CHANGE IN MEXICO

ABSTRACT

The agricultural sector is extremely vulnerable to climate change. Rising temperatures and changes in precipitation patterns would reduce crop production and lead to the proliferation of weeds, diseases and pests on crops. Changes in rainfall patterns increase the likelihood of short-term crop failure and long-term production reduction. Although some crops in certain regions of the world may benefit, the impacts of climate change are generally expected to be negative for agriculture. Likewise, the low availability of feed for livestock use and the decrease in the availability of water will affect the productivity of milk and meat of the different breeds of cattle. Both low agricultural and livestock productivity threaten global food security. The objective of this study is to present a set of regional projections of humidity, temperature, rainfall and SPEI drought index for Mexico under the IPCC AR6 climate change scenarios, improving the projections of the Ocean-Atmospheric General Circulation Models and estimating the possible impacts of climate change on the agricultural sector of Mexico. Regional models for Mexico show temperature increases ranging from 0.5 to 5 °C, while the % change in rainfall will range from -20.3% to 13.5% depending on the scenario and analysis period. The low soil moisture (mm), the negative changes of NDVI and SPEI 12 show that the North, West and Bajío areas presented reductions in precipitation and increase in temperature that caused a severe deficit of soil moisture and water stress in the plants, considering these areas with scarce vegetation and presence of semi-permanent meteorological drought. Under these scenarios it is expected that practically the entire country will be subjected to moderate droughts (Center and South) to extremely strong (North) that will continue and sharpen between now and the end of the century. In Mexico, climate change will have various effects on crop yields, livestock reproduction and production of meat and its derivatives in all regions of the country in a differentiated way according to soil and climatic conditions. This will lead to additional price increases for major crops for both human and animal consumption. It will also cause not enough land suitable for cultivation and grazing; and availability of surface and groundwater demanded by the agricultural sector by the end of the XXI century. Finally, climate change will put Mexico's food security at risk during the present century.

Keywords: Agriculture, livestock, climate change, food security.

1. INTRODUCTION

Rising greenhouse gas emissions are increasing the planet's temperature and causing climate change. The consequences include melting glaciers, rising sea levels by dilation, increasing/decreasing rainfall depending on the area of the planet and high frequency of extreme weather events with modifications in climate seasons. The accelerated pace of climate change, coupled with population growth, threatens the climate, agricultural and livestock productivity; and as a consequence, the world's food security.

The agricultural sector is extremely vulnerable to climate change. Rising temperatures and changes in precipitation patterns would reduce crop production and lead to the proliferation of weeds, diseases and pests on crops. Changes in rainfall patterns increase the likelihood of short-term crop failure and long-term production reduction. Although some crops in certain regions of the world may benefit, the impacts of climate change are generally expected to be negative for agriculture.

Likewise, the low availability of feed for livestock use and the decrease in land and water availability will affect the productivity of milk and meat of the different breeds of cattle. Both low agricultural and livestock productivity threaten global food security.

Probably the most affected regions are those of developing countries, already vulnerable and prey to food insecurity. It is estimated that half of the economically active population of developing countries (2500 million people) depend on agriculture and livestock to secure their livelihoods. To date, 75% of the world's poor live in rural areas (World Bank, 2008).

This research aims to highlight the impacts of climate change on the agricultural sector in Mexico, evaluating the consequences on food security. The present analysis uses regional modeling of climate variables under climate change conditions that impact crop growth and livestock development, using two scenarios to simulate future climate.

BACKGROUND

The effects of climate change on the agricultural sector are considerable, as it is highly dependent on the climate and therefore vulnerable to climate change. The increase in temperature has negative effects on the vegetative development of crops and causes the proliferation of weeds and insects harmful to production, as well as the appearance of diseases that could affect livestock systems. Also, as a result of climate change, extreme events such as droughts, floods, heat waves and frosts are recorded, which negatively affect agricultural production, so, in the current context of food price volatility, these events play an important role (CEDRSSA 2020).

Various organizations such as the Food and Agriculture Organization of the United Nations (FAO), the Economic Commission for Latin America and the Caribbean (CEPAL) and the International Monetary Fund (FMI), have expressed their concern regarding the food issue, in particular for its effects on the population under conditions of poverty, although there is also uncertainty about the impacts by countries and regions (CEDRSSA 2020).

GHG emissions from the agricultural sector

The Inventory of México Greenhouse Gas Emissions (INEGEI) 1990-2015 estimates that Mexico emitted 683 million tons of greenhouse gas (GHG) carbon dioxide equivalent ($MtCO_2e$) in 2015. Of the total emissions, 64% corresponded to the consumption of fossil fuels; 10% for livestock production systems; 8% of industrial processes; 7% for waste management; 6% for fugitive emissions from oil, gas and mining extraction and 5% from agricultural activities (Figure 1). The inventory also accounted for 148 $MtCO_2e$ absorbed by vegetation, mainly in forests and jungles. The net balance between emissions and removals for 2015 was 535 $MtCO_2e$. The agricultural sector as a whole generated approximately 15% (102.5 $MtCO_2e$) of GHGs in Mexico (INECC, 2018).

The INEGEI includes emissions from, in the case of livestock activities, enteric fermentation and manure management for 8 types of different animals. Enteric fermentation is part of the breakdown of food that occurs mainly in ruminants during the digestive process in which methane (CH_4) is released. The manure generated in livestock systems can be a source of emission of methane (CH_4) and nitrous oxide (N_2O) into the atmosphere, particularly if there is no control in the storage, transport and final disposal of that excrement (INECC 2018).

In the case of agricultural activities, the INEGEI includes methane (CH_4) emissions from the anaerobic decomposition of organic matter in crops; nitrous oxide (N_2O) emissions from soil management for plant cultivation, which includes a series of inputs and activities that modify nutrient dynamics, in particular the nitrogen cycle, CH_4 and N_2O emissions from burning agricultural residues caused by crops (INECC 2018).

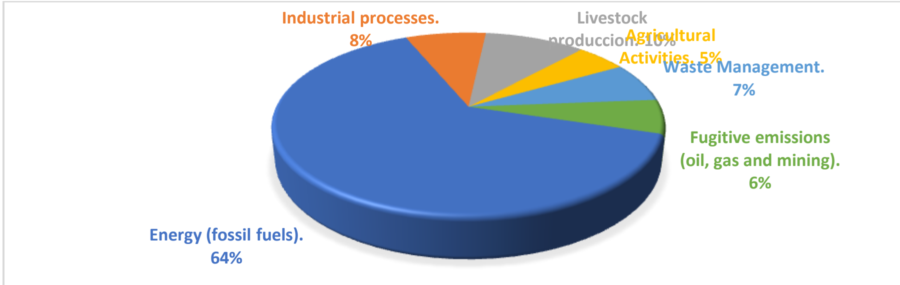


Figure 1 GHG emissions by sector 2015. Own elaboration: information from INEGEI 1990–2015.

According to INEGEI, emissions in 2015 estimated in units of carbon dioxide equivalent (CO_2e) totaled 682.9 million tons, of which the category of the agricultural sector released 15% (102.5 million tons CO_2e) (Figure 2). The energy category was the source with the highest number of emissions (503 million tons CO_2e), 67.3% of the total (INECC 2018).

With regard to GHG emissions from the agricultural sector, FAO presents international information, which includes data for Mexico. The data shows that GHG emissions from the agricultural sector in Mexico grew between 1990 and 2016, at an average annual rate (AAR) of 0.38%. On the other hand, enteric fermentation (process associated with the livestock sector) and manure deposited in pastures represented in 2016 53.9% and 24.3% respectively (Figura 3),GHG emissions (CEDRSSA 2020).

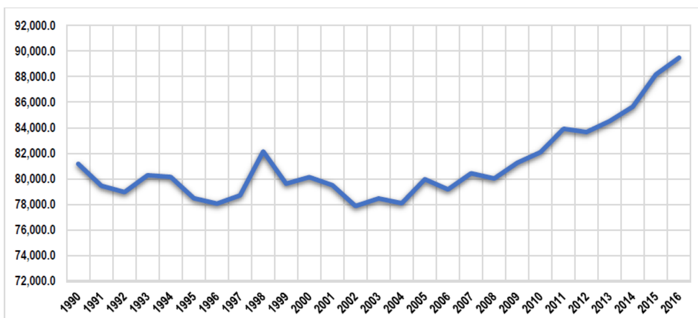


Figure 2 Emissions (CO_2e) from Agriculture. Source: FAO.

Figure 3 Emissions by subsector (CO_2e). Source: FAO.

The impact of climate change on Mexico's agricultural sector

Throughout this century, the effects of climate change and its impact on the agricultural sector will reduce economic growth, affect food security and complicate efforts to reduce poverty (Field et al., 2014). The effects shall not be uniform between or within countries; depending on local conditions and how they modify the response time to climate change and other phenomena such as economic growth (Mendelsohn and Dinar, 1999). In economic terms, the agricultural and livestock sectors are likely to be the most affected by the negative effects of climate change (Fischer et al., 2005; Mendelsohn, 2009).

The agricultural sector is diverse and full of contrasts; representing a small proportion of the global economy, it remains central to the lives of millions of people. In 2010, approximately 2600 million people in the world were economically dependent on this sector (Alston and Pardey, 2014). It is estimated that 40% of the planet's land area is occupied by agriculture and livestock; approximately 1500 million hectares of land are used for planting crops while 3500 million are used for grazing (Howden, et al., 2007; Alston and Pardey, 2014).

There is an empirical regularity that as a country's economy grows, the relative importance of the agricultural sector decreases (Johnston and Mellor, 1961; Anríquez and Stamoulis, 2007; Timmer, 2002). In 2010, agriculture accounted for 29% of total gross domestic product (PIB) in low-income countries (per capita income below $1005); while for middle- and upper-income countries it represented 10.5 and 1.5% (Alston and Pardey, 2014). Figure 4a shows, for Mexico, that as PIB per capita increases, the relative importance of the agricultural sector decreases. Although the causal relationship between PIB and agricultural development is difficult to identify, its correlation is more than evident, for the period from 1965 to 2020 it shows that an increase of 942 dollars of PIB per capita is associated with a 1% drop in the importance of agriculture in PIB (Figure 4b).

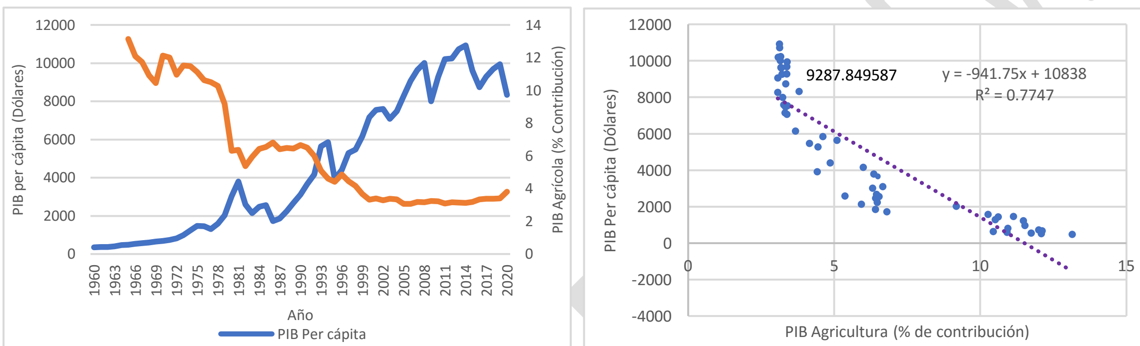


Figure 4 a) Inverse relationship between PIB per capita and percentage of contribution agricultural sector for Mexico, b) Negative correlation between % of contribution of Agriculture in PIB and PIB per capita. Source: Own elaboration with data from the World Bank.

The agricultural sector is a determinant of food security. No country has managed to sustain a process of rapid economic growth without first solving the problem of food security. This is necessary for growth as inadequate and irregular access to food limits productivity and reduces investment in human capital (Bliss and Stern, 1978; Strauss, 1986). At the macroeconomic level, recurrent food crises affect political and economic stability and reduce investment (Alesina and Perotti, 1996).

Under certain conditions, increases in agricultural productivity are reflected in reductions in poverty. These effects go beyond the landowners and are not necessarily limited to rural areas. Because when the poorest in rural areas usually have little or no land; a significant part of their income comes from working as agricultural employees. In addition, like the urban poor, they use a significant portion of their income to buy food (Thirtle, Lin and Piesse, 2003). The mechanisms by agricultural growth can contribute to poverty alleviation are: increasing the income and consumption of small farmers, reducing food prices, increasing the income generated by the rural non-agricultural economy, and increasing employment/salary of unskilled workers (Anríquez and Stamoulis, 2007). Generally speaking, growth in agricultural productivity has an effect on poverty reduction, the which is not the case with increases in productivity in the industrial and service sectors. It is necessary to increase growth agricultural to foster economic growth and improve opportunities for rural families to obtain income no agricultural (Valdés and Foster, 2010).

Various investigations have explored the magnitude of the impact of climate change on the agricultural sector in Mexico. According to the INECC, agriculture in Mexico can be affected by the presence of pests, insects and extreme weather events due to climate change (CEDRSSA 2020). It has been shown that the increase in temperature will affect the growth of some crops and livestock development, especially if water consumption and the proliferation of pests and diseases increase. Thus, agriculture in Mexico represents 22 million hectares of the country, that is, 11 percent of the national territory. Of which 5.7 million are irrigation and 16.3 million are temporary (CEDRSSA 2020).

The agricultural sector is the main user of water and soil, as irrigation crops use 78% of the liquid. This reflects the impact of food availability on food production. In addition, seasonal agriculture and the primary sector are vulnerable to the effects of climate change; with the decrease in areas suitable for crops and grazing and the deterioration of yield for a wide range of them (CEDRSSA 2020).

2. MATERIAL AND METHODS

Climate change scenarios at the regional level provide the information needed to estimate the potential impacts of extreme weather on the environment and human activities (IPCC AR6, 2021). Scenarios should not be tacitly considered as predictions or forecasts, but as consistent visualizations of possible future climates, responding to increased radiative forcing. This is very important since climate at the regional level can be affected by other variables that are not included in global models and climate projections such as the effects of land-use change, tropical cyclones, among others.

The Ocean-Atmosphere Global Circulation Models (AOGCM) do not have sufficient spatial resolution to represent some atmospheric processes of relevance to the regional climate of tropical zones (e.g., tropical cyclones) or land surface processes that determine the unique regional heterogeneity of Mexico's climate. Thus, biases in the simulations and the limited number of high spatial and temporal resolution experiments, either with nested models or statistical techniques, affected confidence regarding regional and local precipitation scenarios and, to a lesser extent, temperature scenarios. Therefore, the approach of obtaining regional scenarios focuses on reducing systematic errors in AOGCM to reach an adequate estimate of the expected ranges of change due to increased GHG concentrations.

Due to the coarse scale at which AOGMCs operate, the geographical locations of coasts or mountain ranges may be distorted, inducing systematic discrepancies in regional climate simulations. These discrepancies can spread in regional climate change scenarios if simple linear interpolation is used as a downscaling tool. Therefore, it is necessary to adjust the AOGGM so that their production can be interpolated at the regional level. CMIP6 (CCKP, 2022) was developed by the World Bank to statistically reduce discrepancies in climate model production from seasonal and regional climate predictions to perform regional model validation. The spatial resolution fields of the thick climate model of temperature and precipitation are approximately 300 × 300 km and can be reduced to finer spatial scales of the order of 100 × 100 km, comparable to observed analyses of regional climate.

Downscaling techniques (global to regional) calibrate statistical transfer functions through historical relationships between modeled and observed fields so that systematic errors in model output are reduced. The identification of such errors is best achieved when not only grid points but also patterns and modes of variability are correlated (Ebert & McBride 2000). The CMIP6 scenarios form the database of the IPCC Assessment Reports, so they were used to produce regional projections.

The integrations for climate change studies of the IPCC range from 1900 to 2100, allowing transfer functions to be constructed using the high spatial resolution of the temperature and precipitation fields observed for the period 1900-2020. In the present analysis, the stability and ability of the transfer function are evaluated using data from 1995-2014 as the reference period. As in any bias correction method, the quality of observational datasets limits the quality of bias correction. In addition, it is assumed that the bias behavior of the model does not change over time; therefore, in the downscaling, the relationships are assumed to be stable in a changing climate (for the period 2001-2100). Esto is important in scaling down climate change scenarios (Hagemann et al. 2011).

Various statistical approaches have been proposed to reduce the scale of the climate change scenarios of the AOGCM for Mexico to project the activity of medium, and even extreme events

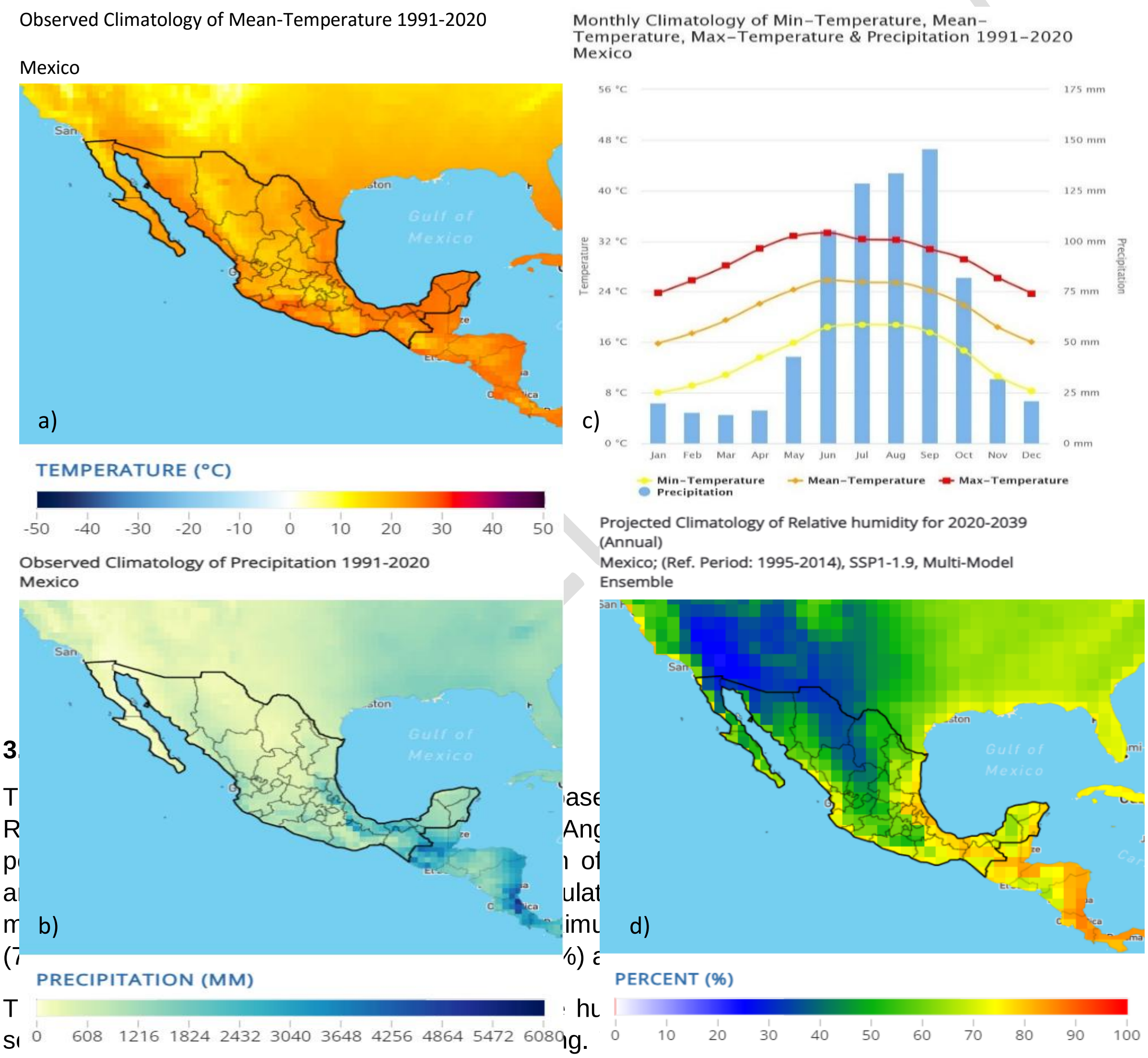
(Magaña et al. 1997, Cueto et al. 2010). However, most of these are based on a few models and lack the benefit of a multi-model set perspective, such as that presented at the IPCC AR6. The AOGCM climate change scenarios used in the IPCC AR6 model projections of temperature and precipitation are available at the IPCC Data Distribution Centre. The multi-assembly model output fields for the SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 radiative forcing scenarios have been reduced with the CMIP6 scenarios. The CMIP6 reference scenarios for each AOGCM were used to construct the projected changes in the regional climate.

In the process of downscaling, the monthly observed fields of temperature and precipitation of the Climate Research Unit (CRU) of the University of East Anglia were used, with a spatial resolution of 50 x 50 km for the period 1901-2020 (Mitchell et al. 2004). CMIP6 data capture Mexico's low-frequency variability and temporal temperature and precipitation trends.

For the present study, climate projection data is modeled data from global climate model compilations of the Coupled Model Intercomparison Projects (CMIP), overseen by the World Climate Research Programme. The data presented are CMIP6, derived from the Sixth Phase of the CMIP form the database of the IPCC Assessment Reports. This climate predictability tool, used as a statistical method of scale-down, allows the preparation of regional climate change projections to estimate the spread between models as a measure of uncertainty in projected changes in climatological variables. In this way, the changes in temperature, precipitation, relative humidity and annual drought index for the present century are obtained and together with vulnerability projections, the potential impacts on the agricultural sector in Mexico are estimated. The projection data is presented with a resolution of 1.0º x 1.0º (100 km x 100 km).

The ability to generate scenarios over a long period makes it possible to reproduce climate parameters and the response of the regional climate to large-scale forcing, such as increased radiative forcing, resulting from increased GHG concentrations. Thus, the estimated trend of temperatures, relative humidity, precipitation and annual drought index SPEI was obtained on a regional scale for Mexico between 2020 and 2099.

Other analyses were used to determine impacts on the agricultural sector such as the Normalized Difference Vegetation Index (NDVI), which was taken from the NASA data archive (Tucker et al. 2005). The NDVI is used to assess the impact of abnormal weather conditions on vegetation and is a measure of the amount and vigor of vegetation on the soil surface. The index ranges from −1.0 to 1.0, with negative values indicating clouds and water and positive values close to zero, indicating bare soil, and higher ranging from sparse vegetation (0.1−0.5) to dense green vegetation (0.6 and above). Because NDVI is an indicator of the amount and vigor of vegetation greenery, positive anomalies correspond to healthy vegetation conditions and negative NDVI anomalies to stressed vegetation. We also used Standardized Precipitation Evapotranspiration Indices (SPEI), which is an indicator of drought derived from precipitation, which calculates drought based on the standard deviation of accumulated precipitation from the long-term mean, including evapotranspiration. Positive values indicate positive water balance (or wet conditions) and negative values indicate negative water balance (or dry conditions). This indicator shows the frequency and intensity of droughts observed lasting 6 and 12 months. Longer periods can be used to indicate the risks associated with prolonged hydrological drought, such as reduced reservoir recharge and water availability. Temperature increases generally increase moisture and precipitation losses and therefore increase the risk of drought. This indicator should be used carefully in typically arid regions and dry seasons. The reference period for calculating the SPEI indicator is 1981-2010. Likewise, soil moisture ($meter^3/meter^3$) was estimated, which shows the average water content of the topsoil layer (0 to 5 cm deep) and is used as an indicator of the extent and duration of drought. There is a strong interrelationship between soil moisture, vegetation and climate in the short and long term. Soil moisture influences the type and condition of vegetation and in turn, evapotranspiration. Change in soil moisture can have considerable impacts on agricultural productivity, ecosystem health, livestock development and food security. Soil moisture data can be used to anticipate and manage drought-related risks and secondary hazards (e.g., wildfires), support crop insurance models, and guide long-term agricultural and livestock resilience programming. Finally, this information will be complemented by maps of drought episodes in Mexico in recent decades.



forcing a warmer climate (IPCC, AR6 2021). The regional linear trend over Mexico for the 1991-2020 is captured by CMIP6 regional set of climate change scenarios.

Figure 5. High spatial resolution climatology with CRU data (50 × 50 km) (base period 1991-2020) observed of a) average annual surface temperature (°C), (b) average annual precipitation (mm), (c) minimum, maximum, average and monthly precipitation temperatures; and (d) relative humidity (CCKP, 2022).

Regional climate change scenarios

Most studies agree that temperature will increase in the coming decades and that this will affect the hydrological cycle on a global and regional scale (IPCC, 2007, 2021, Alcamo et al. 2007). The impacts of permanent changes on the climate are expected to have a large number of socio-economic consequences, particularly in the agricultural sector in regions of developing countries where natural climate disasters have also occurred in recent decades. The IPCC (2007, 2021) has concluded that Mexico will be among the regions where the water deficit will be exacerbated due to increases in temperature, reduced relative humidity and rainfall, increasing drought. The regional climate change scenarios obtained through CMIP6 are able to show the contrasts in the projected climate changes between the regions of Mexico.

Regional models for Mexico show that the average annual surface temperature can experience a variety of increases ranging from 0.5 to 5 °C depending on the scenario and period selected and that can reach values above 40°C, while the percentages of change in rainfall from -20.3% to 13.5% depending on the scenario and analysis period with decreases of up to -180 mm/year. It is estimated that it is unlikely to limit GHGs and radiative forcing to the scenarios SSP1-1.9, SSP1-2.6, on the other hand it is expected that the actions that are taken to mitigate GHG emissions will allow the worst-case scenario not to be reached (SSP5-8.5), based on this it is estimated that the two most likely scenarios are the intermediate scenario SSP2-4.5 and the high scenario SSP3-7.0, which will be described and discussed. For changes in average, maximum and minimum temperatures, annual and monthly precipitation, relative humidity and SPEI, the period 1995-2014 will be taken as a reference. Likewise, they will be the scenarios with which the impacts on the agricultural sector will be evaluated.

For the SP2-4.5 scenario, the average annual temperature for Mexico in the period 2020-2039 is estimated at 22.09±4.13 °C, while for 2040-2059 with a value of 22.73±4.13 °C, the period 2060-2069 of 23.23±4.15 °C and at the end of the century (2080-2099) will reach a value of 23.61±4.18 °C (Table 1 and Figure 6). It should be remembered that the values are differentiated according to the region, state and municipality. In the SSP3-7.0 scenario the average annual temperature between 2020-2039 is estimated at 22.02±4.12 °C, between 2040-2059 with a value of 22.86±4.15 °C, the period 2060-2069 of 23.76±4.20 °C and in 2080-2099 it will reach 24.76±4.21 °C (Table 1 and Figure 7).

However, it must be remembered that crops are developed not with the average temperature but taking into account the minimum temperatures when the crops are in the dry season and the maximum when the crops develop with the wet season. Thus, for the SP2-4.5 scenario, the minimum annual temperature for Mexico in the period 2020-2039 is estimated at 14.41±4.06 °C, while for 2040-2059 a value of 15.00±4.08 °C, between 2060-2069 of 15.46±4.12°C and at the end of the century (2080-2099) will reach a value of 15.82±4.13 °C (Table 1). In the SSP3-7.0 scenario the minimum annual temperature in 2020-2039 is estimated at 14.37±4.05 °C, between 2040-2059 of 15.15±4.10 °C, between 2060-2069 of 16.01±4.14 °C and in 2080-2099 it will reach 16.98±4.15 °C (Table 1).

It is very likely that the maximum temperature is one of the variables that most impacts agricultural production. Thus, for the maximum annual temperature, it is estimated at 29.81±4.02 °C for the 2020-2039 scenario, while for 2040-2059 with a value of 30.48±4.03 °C, the period 2060-2069 of 31.02±4.06°C and at the end of the century (2080-2099) it will reach a value of 31.34±4.07 °C (Table 1 and Figure 8). In the SSP3-7.0 scenario the maximum annual temperature in 2020-2039 is estimated at 29.70±4.00 °C, between 2040-2059 with a value of 30.58±4.02 °C, the period 2060-2069 of 31.55±4.08 °C and in 2080-2099 it will reach 32.57±4.11°C (Table 1 and Figure 9).

The relative humidity projections at the regional scale of Mexico estimate that for the SSP2-4.5 scenario in the period 2020-2039 it is estimated at 57.18±6.50%, while for 2040-2059 of 56.61±6.75%, the period 2060-2069 of 56.05±6.86% and at the end of the century (2080-2099) it will reach 55.65±7.03% (Table 1). In the SSP3-7.0 scenario the relative humidity in 2020-2039 is estimated at 57±39.6.61%, in 2040-2059 of 56.56±6.65%, the period 2060-2069 of 55.40±6.97 and in 2080-2099 it will reach 54.66±7.27% (Table 1).

Table 1. Average, minimum, maximum temperatures, relative humidity, precipitation and SPEI drought index for Mexico according to the different scenarios of the IPCC (2021) SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5 during the present century, obtained from regional models (Own elaboration with data from CCKP, 2022).

Average temperatures in °C				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	21.95±4.18	22.08±4.17	21.97±4.18	21.88±4.18
SSP1-2.6	22.09±4.14	22.45±4.14	22.58±4.15	22.51±4.16
SSP2-4.5	22.09±4.13	22.73±4.13	23.23±4.15	23.61±4.18
SSP3-7.0	22.02±4.12	22.86±4.15	23.76±4.20	24.76±4.21
SSP5-8.5	22.20±4.12	23.20±4.13	24.40±4.14	25.80±4.14
Minimum temperatures in °C				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	4.41±4.13	14.54±4.14	14.47±4.11	14.34±4.13
SSP1-2.6	14.36±4.07	14.69±4.06	14.78±4.07	14.73±4.07
SSP2-4.5	14.41±4.06	15.00±4.08	15.46±4.12	15.82±4.13
SSP3-7.0	14.37±4.05	15.15±4.10	16.01±4.14	16.98±4.15
SSP5-8.5	14.56±4.06	15.50±4.09	16.69±4.12	18.03±4.18
Maximum temperatures in °C				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	29.61±4.05	29.72±4.07	29.60±4.09	29.95±4.09
SSP1-2.6	29.78±4.02	30.18±4.04	30.31±4.05	30.25±4.08
SSP2-4.5	29.81±4.02	48.30±4.03	31.02±4.06	31.34±4.07
SSP3-7.0	29.70±4.00	30.58±4.02	31.55±4.08	32.57±4.11
SSP5-8.5	29.84±4.02	30.89±4.02	32.12±4.03	33.57±4.13
Relative Humidity in %				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	57.32±6.91	57.96±6.94	57.23±6.85	57.66±6.64
SSP1-2.6	56.92±6.60	56.93±6.49	56.34±6.59	56.64±6.60
SSP2-4.5	57.18±6.50	56.61±6.75	56.05±6.86	55.65±7.03
SSP3-7.0	57.39±6.61	56.56±6.65	55.40±6.97	54.66±7.27
SSP5-8.5	57.28±6.63	56.18±6.82	55.20±7.12	53.59±7.48
Precipitation in mm				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	917.43±45.89	929.51±46.17	925.79±45.30	917.49±45.24
SSP1-2.6	911.97±43.62	901.93±42.82	890.75±41.93	899.51±42.62
SSP2-4.5	900.03±43.11	887.34±43.16	873.13±42.79	857.83±42.27
SSP3-7.0	886.88±41.61	856.44±40.75	827.52±39.54	805.27±39.13
SSP5-8.5	877.25±42.28	858.70±41.36	831.01±40.81	786.00±40.20
ANNUAL DROUGHT INDEX SPEI				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	-0.06±0.03	-0.05±0.06	-0.06±0.05	-0.05±0.04
SSP1-2.6	-0.02±0.01	-0.03±0.01	-0.05±0.02	-0.05±0.02
SSP2-4.5	-0.03±0.02	-0.07±0.02	-0.14±0.05	-0.17±0.07
SSP3-7.0	-0.02±0.01	-0.09±0.04	-0.25±0.07	-0.40±0.13
SSP5-8.5	-0.04±0.03	-0.22±0.13	-0.45±0.11	-0.82±0.14

The regional precipitation projections showed negative and positive changes depending on the period analyzed and/or the region of the country. The most important changes are in the North, Central and South of Mexico with a decrease in rainfall in almost the entire country. For scenario SP2-4.5, the average annual rainfall (mm) in the period 2020-2039 is estimated at 900.03±43.11, the period 2040-2059 with a value of 887.34±43.16, between 2060-2069 of 873.13±42.79 and at the end of the 2080-2099 century of 857.83±42.27 (Table 1 and Figure 10). In the SSP3-7.0 scenario, the average annual rainfall (mm) in the period 2020-2039 is estimated at 886.88±41.61, between 2040-2059 with a value of 856±44.40.75, between 2060-2069 of 827.52±39.54 and in 2080-2099 it will reach 805.27±39.13 (Table 1 and Figure 11).

The annual drought index SPEI presented for the scenario SP2-4.5, in the period 2020-2039 a value of -0.03±0.02, the period 2040-2059 with a value of -0.07±0.02, the period 2060-2069 of -0.14±0.05 and at the end of the century 2080-2099 will reach -0.17±0.07 (Table 1 and Figure 12). In the SSP3-7.0 scenario, the SPEI in the period 2020-2039 is estimated at -0±02.01, the period 2040-

2059 with a value of -0.09±0.04, between 2060-2069 of -0.25±0.07 and in 2080-2099 it will reach -0.40±0.13% (Table 1 and Figure 13).

Mexico is one of the regions of the world where rainfall is most likely to decrease under climate change (IPCC 2007). These reductions in rainfall combined with large increases in temperature imply a large increase in potential evapotranspiration and a substantial reduction in the availability of water and soil moisture, affecting Mexico's seasonal and irrigated agriculture and with them agricultural and livestock productivity that could put food security at risk. Thus, in general, it is expected by the end of the century the expected magnitude in temperatures ranges between 0.6 to 4.5 °C and that changes in rainfall will be between -45 and -115 mm, decrease in relative humidity by almost 5% and increases in drought as a result of these changes. Natural climate variability in some cases produces larger changes in annual precipitation than those estimated by climate change. However, if a large negative anomaly in precipitation resulting from natural variability is combined with the negative trend in precipitation due to the effect of climate change, then the effect would be magnified.

The temporal evolution of the projections indicates that increases in temperatures and decreases in relative humidity and rainfall are more likely to be more significant during the second half of the XXI century, showing a clear negative trend in any of the CIMP6 scenarios. If we add to this the observations of soil moisture (mm), Standard Precipitation Index of 12 months SPEI12, the index of vegetation of normalized difference (NDVI) and drought events (Figure 14) gives us a more robust picture of how temperature and precipitation changes will affect the water resources of Mexico and therefore agricultural activities, putting food security at risk. Thus, the soil moisture map (mm) allows us to show that the North, West and Bajío areas have the lowest values of soil moisture with values below 0.1, which will be intensified with higher temperatures that will cause greater evaporation and with less rainfall that will not allow the soil to recover its moisture; hence the importance of rains during the boreal winter months that although they are scarce, can be important to maintain soil moisture levels and reduce water stress on vegetation, crops and the supply of water for livestock during the spring (Magaña & Conde 2003). The South, Gulf and Southeast areas, although they have a higher level of soil moisture (between 0.2 and 0.4 mm), will also be affected as a result of climate change (Figure 14 a).

The SPEI is a standardized version of precipitation anomalies and has been used to characterize the severity of meteorological drought (Méndez & Magaña 2010). SPEI 12 makes it possible to evidence the effects of persistent precipitation anomalies and to estimate the potential trend towards more meteorological droughts. The map of SPEI 12 shows prolonged drought such as those that occurred in the 1910, 1930, 1950, 1970 and those of the late 1990 to date throughout the country, with more intensity in the North zone (Figure 14 b). The magnitude of SPEI 12 during the 20th century ranged from -1 to −2 when prolonged droughts occurred, which corresponds to the category of extremely dry conditions. The corresponding precipitation projections of the multimodel set at the regional scale for 2000−2099 do not include the magnitude of the observed natural variability. However, a more definite trend towards negative values of SPEI 12 is observed under the SSP3-7.0 scenario than under the SSP2-4.5 scenario, with average values of around -1, conditions considered as semi-permanent moderate meteorological drought over Mexico.

The NDVI (Figure 14 c) is closely related to soil temperature and moisture (Ichii et al. 2002). Thus, the changes of NDVI over Mexico are related to reductions in rainfall and increased temperatures. In the second half of the 21st century, projected patterns correspond to a severe deficit of soil moisture and water stress with terrible consequences for the agricultural sector. NDVI values are considered sparse vegetation. For example, projected changes in soil moisture and NDVI in SSP scenarios resemble observed in conditions of intense ENSO events (1982-1983, 1986-1993, 1997-1998, 2014-2016). Most of the affected regions are semi-arid areas. Very low frequency climate variability over Mexico with temperature anomalies of 5 °C and decreased rainfall resulted in increased forest fires without considering the effect of climate change. If climate change anomalies are attached to these conditions, it is possible that it will exacerbate the increase in fires in forests and jungles during the present century.

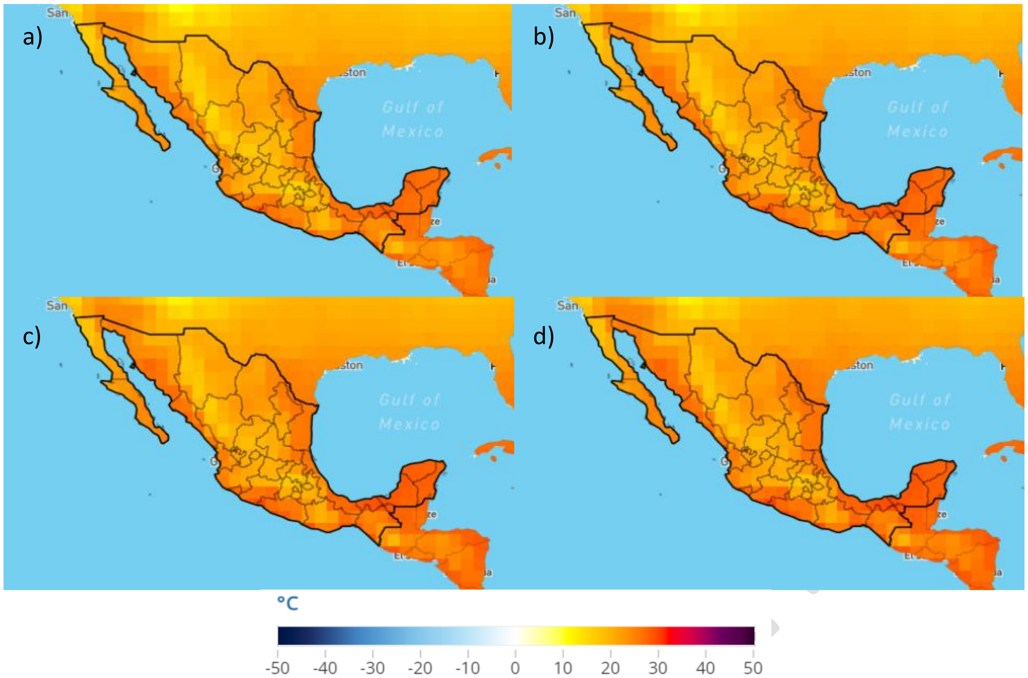


Figure 6. Average temperature (Annual) projected for Mexico under scenario SSP2-4.5 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).

Figure 7. Average temperature (Annual) projected for Mexico under scenario SSP3-7.0 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).

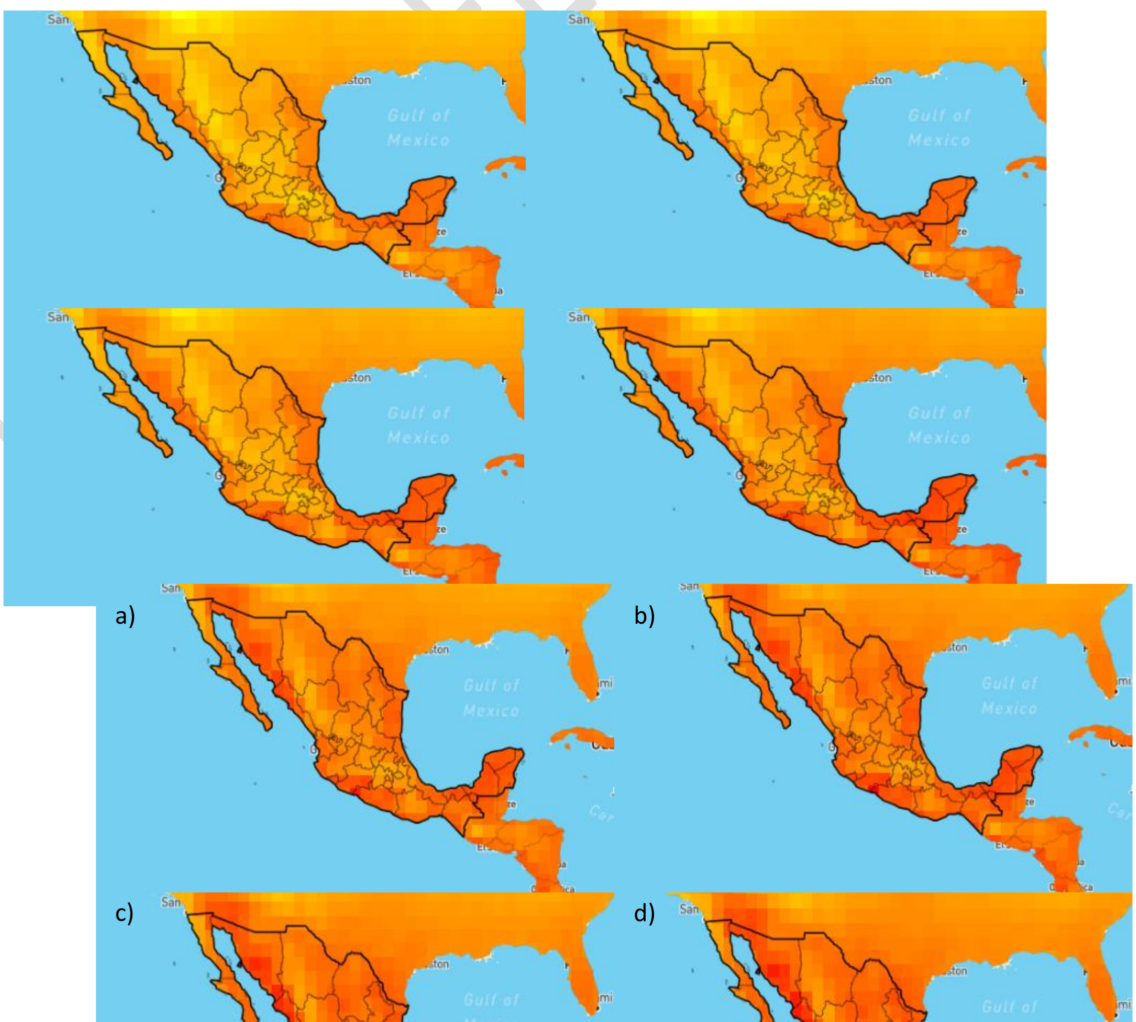


Figure 8. Maximum (Annual) temperature projected for Mexico under scenario SSP2-4.5 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).

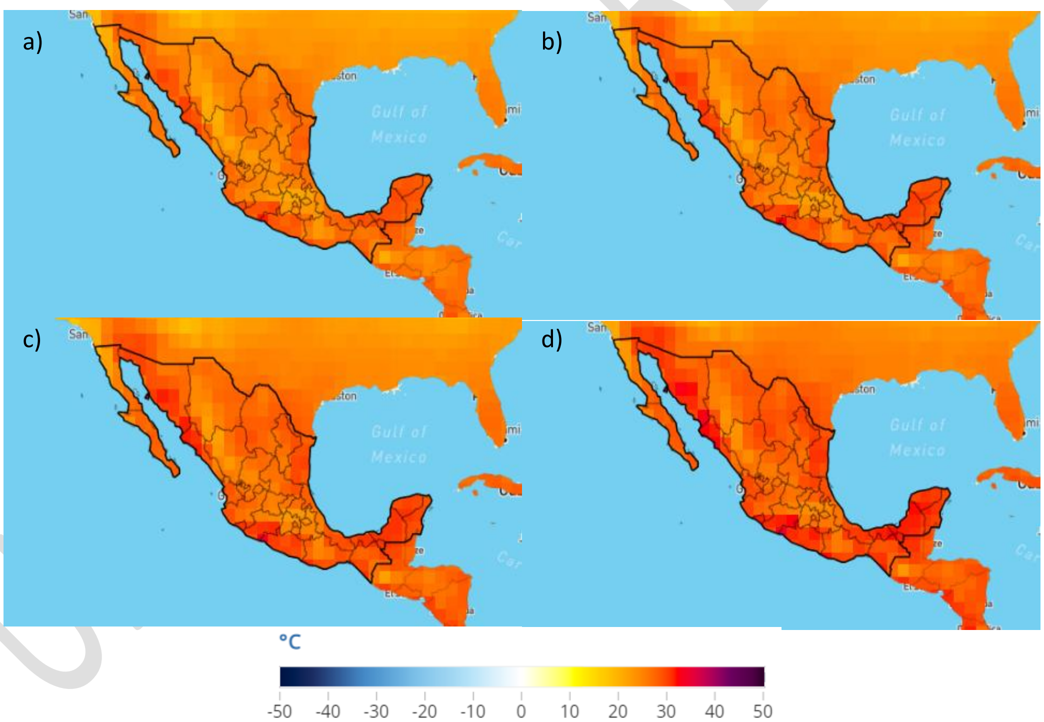
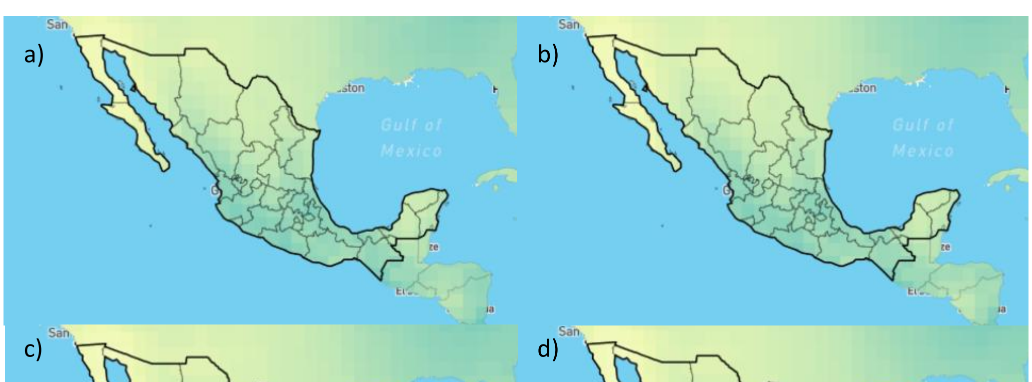


Figure 9. Average temperature (Annual) projected for Mexico under scenario SSP3-7.0 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).

Figure 10. Precipitation (Annual) projected for Mexico under scenario SSP2-4.5 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).



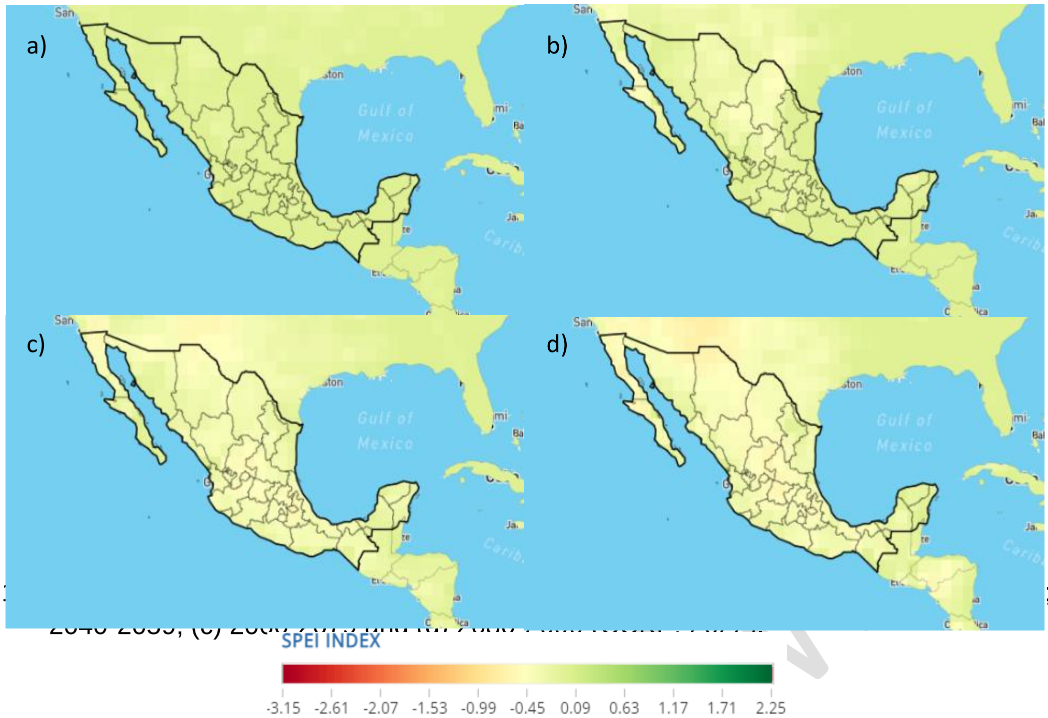


Figure 1 ; (b)

Figure 12. Annual SPEI drought index of the climatology projected for Mexico under the scenario SSP2-4.5 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).

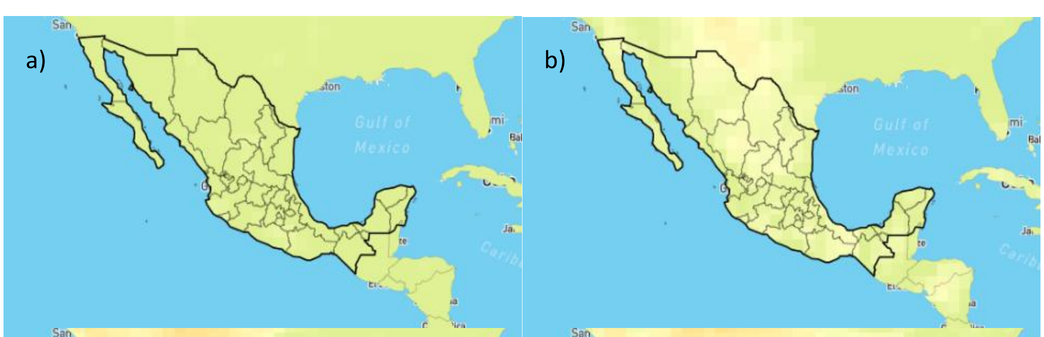


Figure 13. Annual SPEI drought index of the climatology projected for Mexico under the scenario SSP3-7.0 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).

Regional climate change scenarios suggest that by the end of the century, water availability in northern Mexico may be reduced by up to 30% due to global warming, a consequence of reductions in rainfall and temperature increases. Historically, droughts have had serious consequences on primary activities (agriculture, livestock, forestry and ecology). Anomalous high temperatures in northern Mexico persisted in the summers of 1998-2002 (around +2 °C) with below-normal rainfall (-20 to -30%), leading to a prolonged drought. Such climatic anomalies resulted in a severe deficit of soil moisture and water stress in which the potential for forest fires increased. The spring of 1998 turned out to be one of the seasons with the highest number of forest fires in recent decades, not only due to hydrological stress, but also due to agricultural slash and burn practices (Magaña 1999). Vulnerability in northern Mexico has not been reduced since then (Liverman 2001) and the risk of a major environmental disaster is still present (Wilder et al. 2010) and the effects of climate change will be greatly complicated before.

The drought map (Figure 14 d) shows that virtually the entire country has suffered from moderate (Central and Southern) to extremely strong (North of the country) droughts. Under the climate change scenarios SSP2-4.5 and SSP3-7.0 with conditions of strong increase in temperatures, decrease in humidity and rainfall, the panorama of droughts in Mexico will last and worsen until the end of the century, with the implications in the water sector, agriculture and will put food security at risk.

Impacts of climate change on water resources

On a global scale, it is expected that the effects of climate change on water and agricultural resources will be extensive, but of different signs from one region to another, according to latitude, altitude, biomes, orographic conditions, hydrography among others. In some regions of the planet, the first symptoms of affectation in water and agricultural resources are already recorded. The impact assessment on water resources was first carried out, and then with this information the vulnerability of the agricultural sector was evaluated.

With the climatology of Mexico, an increase in the surface temperature of Mexico of approximately 1.8 °C was already evidenced for the year 2020 but with respect to 1900, remaining above the global values of 1.09 for 2020 with respect to the years 1850 (IPCC AR6: A.3.1, 2021).

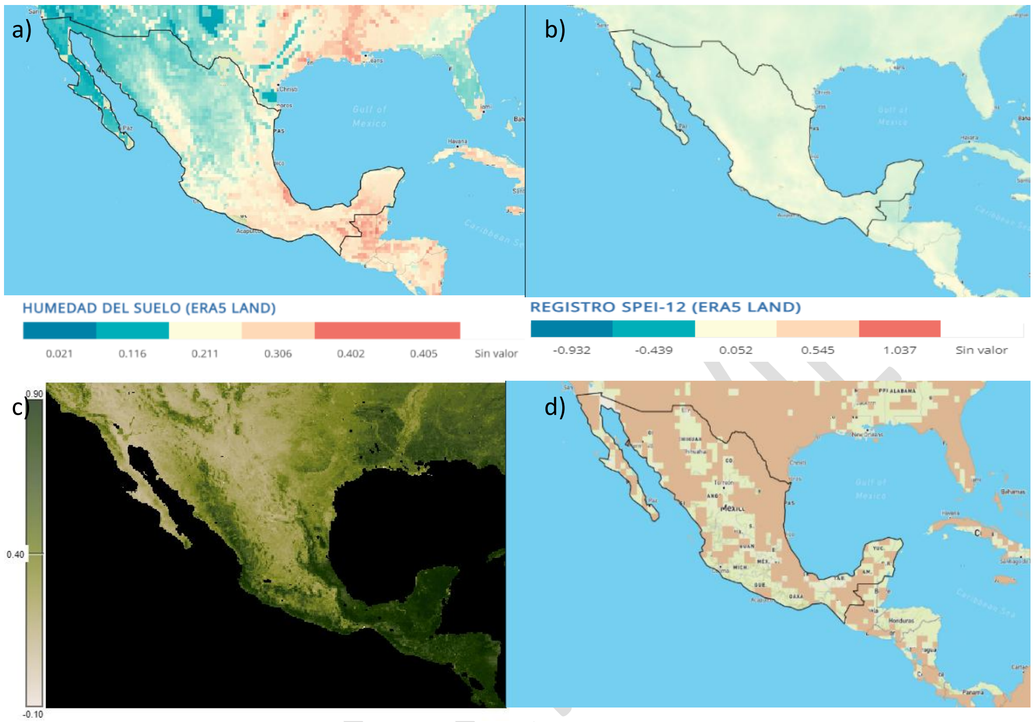


Figure 14. (a) Soil humedad (mm) and (b) SPEI, c) changes in the normalized difference vegetation index (NDVI) and d) Drought events in the SSP2-4.5 scenario for the second half of the 21st century. (CCPK and NASA 2022).

CIMP6 regional models for Mexico show that in most of mexico heat waves are more frequent and intense, while extreme cold events have decreased in frequency and intensity. This has led to very warm summers and less harsh winters, which coincides with global projections of general ocean-atmosphere circulation models (IPCC AR6: A.3.1, 2021).

In the case of Mexico, the projected regional scenarios show that Mexico's surface temperature will continue to increase from the period 2020 to the period 2080-2099 in all the GHG emission scenarios considered and exceeding the threshold of 2 °C of increase reaching values of up to almost 5 degrees in average, maximum and minimum temperatures. This coincides with the projection of AOGCM with increases of 1.5 °C and 2 °C during the XXI century (IPCC AR6:B.1, 2014). Projections show that Mexico will present with respect to the period of 1994-2014 the following increases: in the period 2081-2099 for the intermediate scenario SSP2-4.5, from 1.78 to 2.58 °C and for the high scenario SSP3-7.0 it will reach 2.75 to 3.84 °C. In the first case (2.1 to 3.5 °C) below the IPCC estimate and in the second case (2.8 °C to 4.6 °C) within the range projected by the IPCC globally (IPCC AR6:B.1.1, 2014).

In Mexico, the projected regional scenarios will reach temperature levels higher than the global ones (1.8°C) with which it is very likely that both the frequency and intensity of hot extremes (heat waves, intense rainfall, meteorological, agricultural and ecological droughts as never before observed) will increase, which coincides with what was estimated in the VI report of the IPCC (IPCC AR6: B.2.2, 2014).

Global assessments project that some mid-latitude and semi-arid regions will see the greatest increase in temperature on the hottest days, about 1.5 to 2 times the rate of global warming (IPCC AR6:B.2.3, 2014). Mexico is within these regions so the regional projections coincide with the estimate with the global projections with temperature increase in hot days in the global ranges of 1.5 to 2 times the rate of warming.

Global phenomena projected by the regional models for Mexico where it is estimated that in the present century the frequency of extreme events (heat waves, recurrent droughts, forest fires and floods) will increase as a result of the increase in temperatures and decrease in relative humidity and rainfall, agreeing with the global estimates of the AOGCM (IPCC AR6: A.3.5, 2014).

As for rainfall, the IPCC mentions that it is very likely that heavy rainfall events will intensify and be more frequent in most regions with additional global warming. On a global scale, extreme daily precipitation events due to global warming are projected to intensify by around 7% per 1 °C (IPCC AR6:B.2.4, 2014). In Mexico, only slight increases in rainfall will occur in the first projection period (2020-2039) and in the very low and low scenarios. In the rest of the scenarios the tendency will be to decrease precipitation. However, in all cases the intensity of the rains will increase. The relative humidity in all scenarios will decrease its percentage for all of Mexico.

Continued global warming is also expected to further intensify the water cycle, including its variability, monsoon rainfall, and the severity of wet and dry events (IPCC AR6:B.3, 2014). In Mexico, the initial period (2020-2039) will present increases in the amount of precipitation, but in the subsequent periods (2040-2059, 2060-2079 and 2080-2099) there will be a decrease in wet events and a greater presence of dry events, intensifying the drought with prolonged drought dyes.

There is strong evidence that the global water cycle will continue to intensify as global temperatures rise and precipitation and surface water flows become more variable in most parts of the world within seasons and from year to year. On land-based, the annual global average of precipitation is expected to increase by 0-5% in the very low scenario (SSP1-1.9), by 1.5-8% for the scenario (SSP2-4.5) and by 1 to 13% in the very high GHG scenario (SSP5-8.5) by 2081–2100 relative to 1995–2014. Rainfall is expected to increase in high latitudes, Equatorial Pacific zone and monsoon regions, but decrease in parts of the subtropics and limited areas in the tropics in SSP2-4.5, SSP3-7.0 and SSP5-8.5 (IPCC AR6:B.3.1, 2014). The regional projections for Mexico meet the global forecasts for tropical areas with decreased rainfall in the scenarios SSP2-4.5 (-5.81±7.59%), SSP3-7.0 (-10.59±12.66) and SSP5-8.5 (-12.80±16.15) in the period 2080-2099.

It is estimated that a warmer climate will intensify very wet and very dry weather, weather events and seasons, with implications for floods or droughts, but the location and frequency of these events will depend on changes in regional atmospheric circulation. It is very likely that the variability of rainfall associated with ENSO will be amplified by the second half of the century in the scenarios SSP2-4.5, SSP3-7.0 and SSP5-8.5 (IPCC AR6:B.3.2, 2014). The regional projections for Mexico of decreased soil moisture, the SPEI 12 index, NVDI and the great periods of droughts of recent decades confirm for Mexico the global estimates of intensification of very dry weather and prolonged droughts.

The monsoon season is projected to have a late start in North America (IPCC AR6:B.3.3, 2014). Regional projections estimate that the North American monsoon will increasingly be delayed as the century progresses, along with declining precipitation causing storage problems in the country's water bodies.

It is estimated that with 2 °C or more of global warming, the level of confidence and magnitude of change in droughts and intense and medium rainfall increase. Thus, an increase in meteorological, hydrological and agricultural droughts is projected in the Northern Hemisphere of America (IPCC AR6:C.2.3, 2014). This has already manifested itself in Mexico during the first two decades of this century and is projected to intensify between now and the end of the century.

Many regions are projected to experience an increased likelihood of compound events such as heat waves and more frequent concurrent droughts, even in crop-producing areas, becoming more frequent at 2°C compared to warming of 1.5°C (IPCC AR6:B.2.2, 2014). Estimates for the end of the century in Mexico under the most likely scenarios will be above 2 °C (0.8-3.5 °C) which could mean effects on crops due to events composed of heat waves; decreased humidity, precipitation, water availability and presence of droughts.

In general, in mid-latitudes and subtropical areas (Mexico's location), significant decreases in precipitation and runoff are expected, which will cause an increase in the conditions of scarcity and greater pressure on diversified water resources in the different regions. In various regions of the world and Mexico, conditions of scarcity of water resources and agricultural products are already registered; even without climate change, due to population growth, urban concentration, pollution of water bodies and overexploitation of water resources, in particular underground, coupled with a scarce water culture. To this scenario must be added the effects of climate change, which in Mexico will be mostly a reduction in the natural availability of water as a result of the increase in temperature and decrease in rainfall, which together poses very great challenges for the management and sustainable use of water, with decreases in agricultural and livestock productivity, this will jeopardize food production and food security in the country.

According to the IPCC (2007), in many regions current water management practices will not be adequate or sufficient to meet the challenges associated with climate change. Likewise, meteorological and hydrological records may no longer be used under the consideration that the statistical values of the past will be representative of the future. Mexico is one of the countries in which the public management policies implemented so far will not be sufficient to face the impacts of climate change.

On the other hand, a warmer climate will mean more intense precipitation events, even in places where average annual precipitation will likely be lower. What is already happening and will continue to happen in southern and southeastern Mexico. Indeed, the average annual rainfall may even decrease, but more intense rainfall will be recorded, which will make it more difficult to control the flows through the current channels. These extreme events will be among the most difficult to forecast in future climate change scenarios, as they have an eminently local character. It is to be expected that the impacts of global warming on runoff will be detected first in the occurrence of extreme events than in availability, which in itself has significant natural variations.

In the case of Mexico, this effect of climate change will increase vulnerability in basins in southern and southeastern Mexico where flooding problems are already recorded (Martínez-Austria and Patiño-Gómez 2012). The existence of heavier rainfall is compatible with the forecast of minor annual runoff. On the other hand, the increase in the occurrence of droughts in the north of the Mexican territory is evident, which is consistent with the predictions of decreased precipitation and runoff and is expected to occur more frequently and intensely. If important adaptation measures are not adopted, the availability of water resources in quantity and quality and, as a consequence, agricultural and livestock productivity and thus the food security and health of the population of Mexico could be at great risk.

Impacts of climate change on the agricultural sector

The agricultural frontier in Mexico has an area of 24.6 million ha, of which about 21.6 million ha are planted. Thus, in the agricultural year 2019, 20.6 million ha were planted and 19.3 million ha were harvested. In Mexico there are 302 arable plant species, occupying 21.6 million hectares. The 10 main crops of Mexico according to the area sown se present in Figure 15.

Chart 1: Areas of crops production

Crops	Ha sown
Corn grain	7,540,942.12
Pastures and meadows	2,537,312.98
Bean	1,676,230.41
Grain sorghum	1,456,329.81
Sugar cane	836,108.57
Cherry coffee	722,444.32
Wheat grain	661,744.20
Fodder oats	630,628.24
Fodder corn	590,780.68
Barley grain	361,472.85

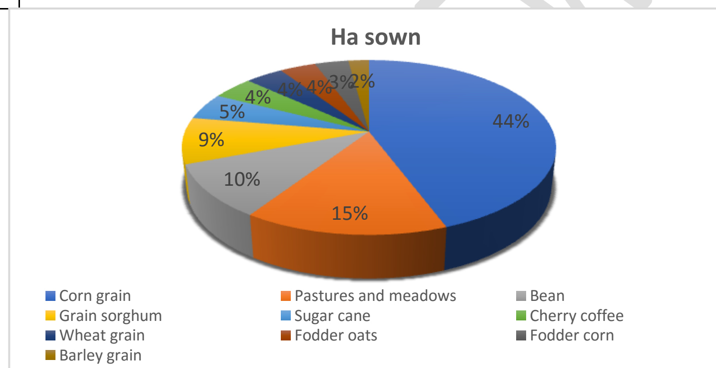


Figure 15. The top 10 crops per hectare planted in Mexico.

If currently the population in Mexico is 128 million Mexicans (2020), making a simple exercise of population growth to 2050 and 2100 of 25% (160 million Mexicans) and 20% (153 million) respectively (Figure 16). Estimating that in that same proportion the demand for agriculture in Mexico would grow without reducing poverty, or considerably increasing total and per capita PIB, 26 million ha of cultivation would be needed instead of the 21 million ha planted in 2020. However, the land suitable for cultivation is only 24.6 million, so from the outset there would already be a deficit of 1.5 million ha without considering climate change.

Based on the main 10 crops per ha planted in Mexico and their climatic requirements, estimates of possible changes in each of these crops in Mexico will be prepared.

In the case of grain and fodder maize, the optimal average daily temperature is 24-30°C, with a range of 15 to 35°C. The optimum average temperature is between 18 and 24°C and the maximum threshold for development between 32 and 35°C. It also needs a moderately humid atmosphere. The rainfall requirements, from planting to maturity are from 500 to 800 mm, depending on the variety and climate, with annual rainfall of 700 to 1100 mm. Water availability is a key factor affecting yield and regularity and temperatures above 32°C begin to be harmful to maize (Ruiz C., J.A. et al. 2013). Thus, based on the results of the regional projections of scenarios SSP2-4.5 and SSP3-7.0 where maximum temperatures range from (30 to 32±5±4 °C), relative humidity will be between (54 to 57±7%), precipitation between (805 to 900±40 mm) and SPEI indices of prolonged drought; it is very likely that as the century progresses these conditions will not favor the development and maturity of the different types of corn, so it is estimated that productivity could fall between 20 and 30% in both scenarios, depending on the breed, region, type of soil, fertilizers, in addition to the aforementioned temperature, humidity, precipitation and availability of water in the cultivation area.

Favorable conditions for growing beans are temperatures in a range of 10-35°C; with an optimum for photosynthesis of 25 to 30°C. The average optimum temperature is between 18 and 24°C and the minimum preferred should be above 15°C. It requires a moderate humid atmosphere, being affected by a very dry and warm atmosphere. Rainfall between 1000 to 1500 mm in the year is convenient; it needs 350 to 400 mm during the crop cycle and thrives in regions with annual rainfall between 600 and 2000 mm. It has been estimated that water stress reduces yield by 73%. At more than 32°C the bean is susceptible to certain diseases and the presence of mites (Ruiz C., J.A. et al. 2013). Thus, with the regional projections of scenarios SSP2-4.5 and SSP3-7.0 with maximum temperatures above the optimal for its cultivation, the relative humidity that will decrease as the century progresses and the precipitation below 1000 mm per year and with SPEI index of prolonged drought that will cause little storage of surface and groundwater it is very likely that the conditions will not favor planting, development and maturity of different varieties of beans grown in Mexico, with decreases in productivity that could reach between 30 and 50% in both scenarios, depending on the edaphic, climatic and sudden modification variables due to climate change.

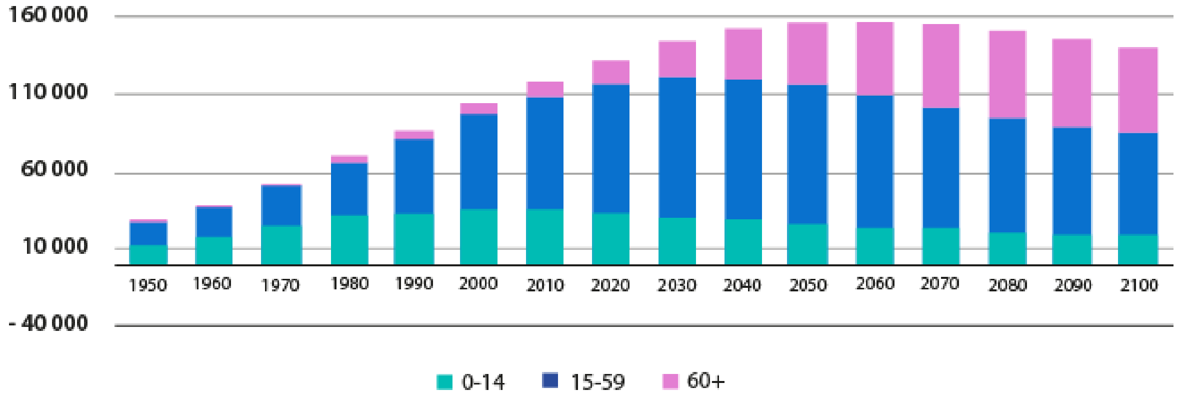


Figure 16 Total population (thousands) and projected age groups for Mexico during the XXI century. Source: World Population Survey Data 2012, UN.

In the case of sorghum cultivation, the optimum temperature for growth is between 26.7 and 29.4°C, while the minimum for germination and growth is 7.2-10°C and 15.6°C respectively. Temperatures above 38°C are harmful, tolerate heat and drought better than maize, it is muy resistant to dry atmospheres. Areas with high humidity are not desirable and rainfall of 450-650 mm/cycle is required. It has a high tolerance to drought and waterlogging periods and the ability to stop growing in the face of drought and resume it after it (Ruiz C., J.A. et al. 2013). The maximum temperatures, relative humidity and precipitation of the regional projections of scenarios SSP2-4.5 and SSP3-7.0 seem to enter the conditions in which sorghum would develop. However, care should be taken in the second half of the century where these conditions may change rapidly and affect the productivity of sorghum cultivation between 5 and 10% in both scenarios, depending on the soil, climate and climate change variables.

For sugarcane the threshold temperatures for germination are 10 and 40°C, with an optimal range of 20-32°C. Temperatures slightly above 20°C are the most favorable for growth. The relative humidity of around 50% and precipitations between 1000-2200 mm well distributed in the year, having water for complementary irrigation when the annual water deficit is greater than 150 mm. It can be successfully grown with precipitation of 1000 to 1250 mm/year, well distributed, although with lower yields. The presence of drought stimulates fiber production and lowers sugar yield. It is quite resistant to drought, but production is low in dry periods. When temperatures are close to 38°C, photosynthesis and growth in general are reduced (Ruiz C., J.A. et al. 2013). Thus, the climatic variables of the regional projections of scenarios SSP2-4.5 and SSP3-7.0 would not favor the good development of sugarcane with temperatures outside the optimal range and rainfall below ideal, perhaps the only variable that would favor its development would be relative humidity. However, the presence of SPEI indices of prolonged drought could put the crop at risk, reducing its yields between 20 and 30% in both scenarios.

The climatic conditions of coffee cultivation are in temperature ranges of 5-30°C, with optimal average temperatures between 16 and 22°C. Damage begins when passing the limits of 13° and 27°C. Average temperatures below 16°C and above 23°C are not suitable, with an optimal temperature of 18-21°C. Above 24°C, photosynthesis begins to decline and nullifies at 34°C. It prefers medium to high relative humidity (70-85%), with optimal annual rainfall of 1200-1800 mm, as long as there is good seasonal distribution and short dry periods. Although coffee trees show some degree of drought tolerance, a prolonged dry period decreases the following year's harvest. High temperatures decrease photosynthesis, accelerate the senescence of fruits, reduce growth and production. Temperatures greater than 30°C reduce photosynthesis and cause flower abortion

(Ruiz C., J.A. et al. 2013). According to the projections of scenarios SSP2-4.5 and SSP3-7.0 for Mexico, the prevailing conditions during the XXI century will not favor the development of coffee cultivation, since with temperatures outside the optimal range, rainfall well below ideal and conditions of prolonged drought will greatly harm productivity, with ranges from 10 to 40% in both scenarios, being heterogeneous in the country according to the particular soil and climatic conditions of each region.

Wheat responds to a temperature range between 5-30°C, with an optimum between 15 and 20°C. The maximum threshold temperature for development is around 25°C especially near maturity. It requires dry atmosphere, conditions of high humidity are not favorable, they favor the presence of fungal diseases. The precipitation values required are 450 to 650 mm during the crop cycle with values of 700 to 1000 mm/year. It is considered a crop moderately tolerant to drought, winter and naturally does not tolerate high temperatures; above 25-30°C it begins to have problems in its development. Rapid growth in the early stages of development generates a reserve in the wheat plant, which makes it survive even periods of severe drought and finally yield grain production, even in varieties that are not particularly resistant to drought (Ruiz C., J.A. et al. 2013). Although wheat is a crop very tolerant to climatic variations, however the temperatures projected in the SSP2-4.5 and SSP3-7.0 scenarios for Mexico will be above their optimum, likewise, the rainfall will be with deficit so these conditions will not favor its optimal development, perhaps the only variable in optimal conditions will be the relative humidity in the first half of the century, however, the second half might not be so favorable. It is estimated that productivity could fall in ranges of 10 to 20% in both scenarios, with the particularities of each region where it is grown.

Barley requires optimal temperatures that depend on the variety and stage of development. For the minimum sowing of 3-4°C, the optimal of 20 to 28°C and the maximum of 28-40°C. The appropriate average temperature is 15 to 25°C from June to October.The minimum and maximum thresholds for growth are 5°C and 30°C, respectively, with an optimum of 18°C. It requires a relatively humid atmosphere (< 60%), very humid environments, promote the presence of fungal diseases. The optimum rainfall is 700 mm/year, but it can be grown in regions up to 1000 mm/year, provided that during the harvest there is no significant rainfall. Barley is more drought tolerant than wheat, up to temperatures around 40°C already in the grain ripening stage (Ruiz C., J.A. et al. 2013). Although it can tolerate these temperatures, the yields are inferriores to those of optimal temperature, so the conditions in the scenarios SSP2-4.5 and SSP3-7.0 are not the best, since the temperatures will exceed these values, the precipitation will hardly be fair and the humidity will be among the optimal values. Thus, yields in the XXI century could decrease between 5 and 15% compared to the current ones.

Oats develop between 5 and 30°C, with an optimum of 17.5°C. It prefers relatively dry atmospheres, as high humidity is a promoter of diseases. It requires 400 to 1300 mm per cycle and tolerates unextracted droughts. Temperatures above 30°C are harmful, as it is a plant rather adapted to cool than warm temperatures (Ruiz C., J.A. et al. 2013). According to the projections of scenarios SSP2-4.5 and SSP3-7.0 for Mexico, the climatic conditions during the century will not favor the development of oats, since temperatures would be above the optimal range, rainfall below the ideal and conditions of prolonged drought will greatly harm productivity, with ranges between 10 and 30% in both scenarios, being heterogeneous in the country according to the particular conditions of each region.

In the case of pastures and meadows since there is a great variety in Mexico and in the world and each of them has been adapted to the particular conditions of the region. However, in the case of species grown in Mexico, the most suitable time for planting is in late summer or early autumn. The optimum temperature is between 10-30 ºC, with water requirements of approximately 1200 mm/year. However, there are countless varieties that can modify these values. Thus, based on the results of the regional projections of scenarios SSP2-4.5 and SSP3-7.0 with maximum temperatures between 30 and 32.5±4 °C, relative humidity between 54 and 57±7 %, precipitation between 805 and 900±40 mm and SPEI index of prolonged drought it is very likely that as it advances the century these conditions will not favor the development and maturity of the different types of pastures, although they are apparently resistant to drought, when it is prolonged it presents problems in their yields. Based on this, it is estimated that productivity could fall between 25 and 35% in both scenarios, depending on the breed, region, fertilizers and particular soil and climatic conditions in the growing area.

Averaging all the decreases in the productivity of the 10 main crops these would give approximately -22%, which would represent a deficit for low productivity of 4.84 million ha, which if we add the deficit for lack of arable land of 1.5 million ha, would give a total deficit of 6.4 million ha of crops, which would represent a very significant decrease in the production of food for both human and livestock use that would put the country's food security at risk.

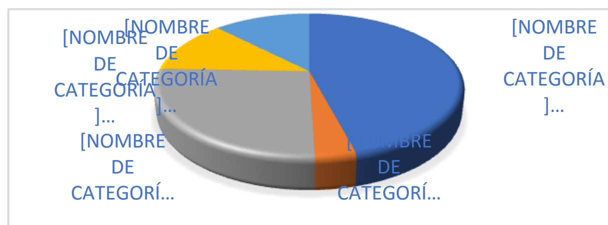
As for the livestock sector according to the Agroalimentario Atlas, in 2018, in Mexico an area of 109.8 million ha is dedicated to livestock, more than half of the national territory (55.9%). Thus, in the agricultural year 2019, 20.6 million ha were planted and 19.3 million ha were harvested, of which 5.6 million ha (29.03%) were dedicated to the cultivation of fodder, without considering the yellow corn in grain that is used, in part, to feed livestock. In terms of the area harvested, the most important forages were: Pastures and meadows, grain sorghum, green fodder oats, green fodder maize, green and achicalada alfalfa and fodder sorghum in green.

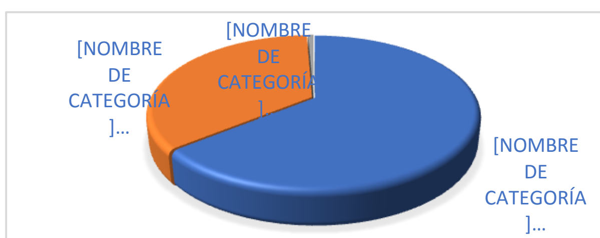
The forage crop group generated 110.7 million tons, of which almost 80.13% was concentrated in pastures and meadows (47.04%), green alfalfa (19.3%) and green fodder corn (14.07%). Regarding the livestock inventory, 591.6 million poultry, 35.7 million cattle, 18.8 million pigs, 8.8 million goats, 8.7 million sheep and 3.8 million turkeys were raised (Figure 17.)

Chart 2: Distribution regarding livestock inventory

Species	Heads 2020
Cattle meat and milk	35,653,619
Beef cattle	33,047,308
Bovine for milk	2,606,311
Porcine	18,788,002
Ovine	8,725,882
Goats	8,830,720
Poultry meat and egg	591,595,926
Poultry for meat	382,152,377
Poultry for egg	209,443,549
Turkey	3,756,962

Figure 17 Livestock inventory 2020. Own elaboration. Source CEDRSSA 2020.





Doing the same exercise as that of agricultural production, if currently the population in Mexico is 128 million Mexicans (2020) and the population projections to 2050 and 2100 are of increases of 25% (160 million) and 20% (153 million) more respectively (Figure 16). Estimating that in the same proportion the demand for livestock in Mexico would grow without reducing poverty, or considerably increasing the per capita PIB, 137.25 million ha (70.5% of the national territory) dedicated to livestock would be needed, which is considered unviable. So, it would be necessary to adapt new breeds and keep them confined with the associated consequences (lower yields, spread of diseases and death among others). Based on the main cattle species bred in Mexico and their optimal and critical temperatures (Figure 18), estimates of the possible effects on the development of the agricultural sector in Mexico are elaborated.

For cattle, the comfort temperature threshold will depend on the age and activity for which it is intended. Thus, in lactating cows it ranges from 2 to 21 °C, calves drink from 15 to 27 °C, calves from 1 month from 10 to 24 °C, and cattle dedicated to maintenance between 4 and 24 °C and those fattening between 4 and 21 °C. The critical upper threshold in all cases is 32 °C; in any of the periods of the XXI century and of the SSP2-4.5 and SSP3-7.0 scenarios, the maximum temperatures will range between (30 to 32.5 ± 4 °C), which indicates that it is very likely that as the century progresses the conditions will not favor reproduction, development and maturity of cattle, with which it is estimated that the productivity of milk and meat production will be reduced depending on the breed, region, available food, in addition to the aforementioned temperature, humidity, precipitation and availability of water in the breeding area.

Pigs have a threshold for lactating sows of 2 to 21 °C, newborns of 21 to 29 °C, infants of 12 kg of 18 to 24 °C and adult pigs of more than 100 kg of 4 to 21 °C. The upper critical threshold is 32 °C. Thus, at temperatures higher than this, cattle begin to have discomfort, decreasing their development, accumulation of weight, reproduction capacity and protein content. Thus, according to the temperatures projected in the two probable scenarios (>32 ° C), a decrease in the reproduction of livestock, a decrease in the production of pork and its derivatives would be expected.

In the case of sheep the comfort thresholds for the complete fleece is 7 to 18 °C, while baby lambs are 21 to 29 °C, growing lambs vary from 13 to 21 °C. Goats have a threshold similar to that of growing lambs. Thus, based on the results of the temperature projections in the SSP2-4.5 and SSP3-7.0 scenarios, these will exceed both the comfort and critical thresholds, and it is expected that like the other types of cattle there will be a decrease in the reproduction of sheep and goats, the number of heads and meat production and its derivatives.

As for the breeding of birds (chickens and turkeys) the comfort threshold is 13 to 24 °C and the upper critical 35 °C. The temperatures of the scenarios between now and the end of the century, although they will be below this threshold, will increase as the century progresses, so it will affect the reproduction of birds, the number of units raised and the production of egg and poultry meat.

On the other hand, livestock activities will demand on average between 11-15% more water for their development, going from the current 1.33-3.21 Million m^3/day to consume 1.53-3.69 Million m^3/day, which is very unlikely to be counted on due to the decrease in water resources as a result of climate change.

In summary, all the types of cattle analyzed here will be in conditions out of comfort as the century progresses, which will affect in two ways the agricultural sector, one in the sense of the breeding and reproduction of the same, and in the other sense in the production of protein (meat) and the derivatives of the different types of cattle such as milk and its derivatives, egg, skin and wool. This will be exacerbated by the low availability of land suitable for livestock development and by the decrease in water availability due to low relative humidity and rainfall and prolonged drought conditions that will decrease the storage capacity of surface and groundwater bodies. This makes us foresee that there will be a decrease in food of animal origin that will put food safety at risk and further complicate.

The results show that the development of the agricultural sector is unsustainable under current conditions, so it is imperative to take adaptation measures, thus, the integral management of soils and water resources, training farmers and ranchers on climate change, the promotion of good agricultural practices, crop diversification and livestock breeding, including resistant varieties are the possible pathways.

For its part, it has also been evidenced that the impacts of climate change on agricultural activities, through the impact of variations in temperature, relative humidity and precipitation will be intensified by the presence of extreme weather effects such as frost, drought, hurricanes and extreme rains (floods) in the different geographical regions of Mexico (CEDRSSA 2020).

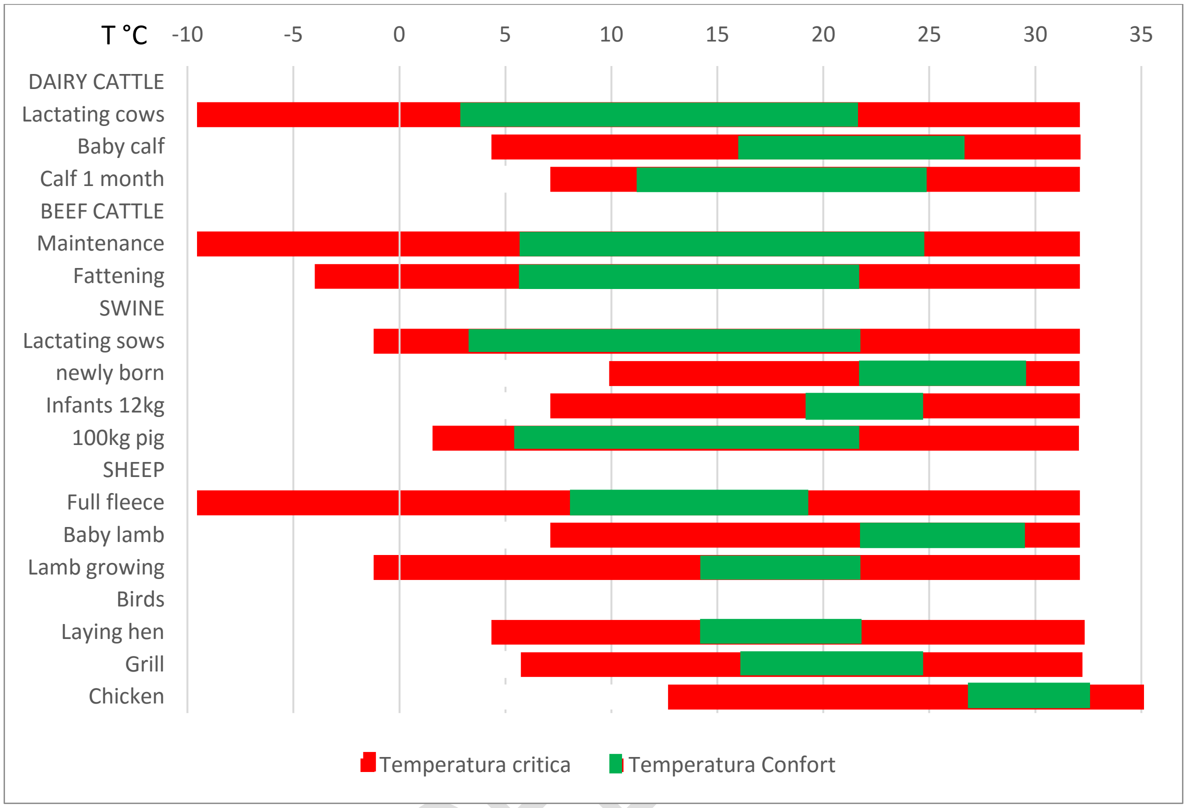


Figure 18. Zone of optimal and critical temperatures for different types of livestock at various levels of production. Own elaboration with data from World meteorological organization, 1989.

In several parts of the world, producers have begun to implement low-cost adaptation measures, such as modifying planting start dates or switching to another variety or type of crop, inserting livestock species more resistant to the effects of the climate, among others. It is believed that such voluntary adaptations will not be sufficient to address climate change and the implementation of planned adaptation measures including local, regional, national and international components will be necessary.

Within this range of categories, a large number of adaptation measures for the agricultural sector have recently been suggested. Although so far there is little empirical evidence regarding the success and effectiveness of the different measures of planned adaptation, there are several strategies that are considered recommended such as:

- increase the level of knowledge of producers about climate change; improving the education levels and skills of rural populations;
- create and introduce varieties and species resistant to temperature and smaller amounts of water;
- generate early warning systems on the temporality and severity of rains;
- strengthen formal and informal agro-technological exchange systems (seeds, reproduction systems, among others); improving physical infrastructure;
- solve the problems of lack of access to credit and lack of agricultural insurance.

Mexico has been a promoter and world leader in the implementation of public policies to address the problem of climate change. However, evidence shows that the achievements made have been limited. GHG emissions from the agricultural sector have increased substantially, as experts predicted, if GHG emissions are not stabilized, the impact of climate change on agricultural production and rural life will have serious consequences.

Climate change is a phenomenon that is difficult to re-establish, which will intensify in the future, so one of the main recommendations for the Mexican agricultural sector is to develop adaptation strategies. Agricultural and livestock areas in Mexico will have to adopt a scenario of more temperature and less water; hence, current and future production technologies will have to adapt to conditions of scarcity.

4. CONCLUSIONS

The results of the analyses suggest that climate change will adversely affect the agricultural sector and human well-being:

- In Mexico, climate change will reduce the yield of the most important crops.
- Climate change will have various effects on crop yields under irrigation in all regions of the country in a differentiated way according to the soil, climate and advance conditions of climate change.
- In Mexico, climate change will reduce the yield of the most important types of livestock.
- Climate change will have various effects on the yields of livestock reproduction and production of meat and its derivatives in all regions of the country in a differentiated way according to the soil, climatic and advancing conditions of climate change.
- Climate change will lead to additional price increases for the main crops for both human and animal consumption, such as corn, beans, rice, wheat, sorghum, barley, oats among others. This implies an increase in the costs of both human and animal feed, which will result in increased prices of agricultural products, meat and their derivatives. As a consequence, it will reduce the growth of meat consumption and a noticeable drop in cereal consumption.
- Climate change will cause that there is not enough land suitable for cultivation and grazing for the necessary and sufficient population and food scenarios of this century.
- Climate change will cause the availability of surface and groundwater demanded by the agricultural sector for the scenarios projected at the end of the XXI century not to be available.
- Finally, climate change will put Mexico's food security at risk according to the scenarios of the end of the XXI century.

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