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ORIGINAL ARTICLE

Impacts and economic costs of climate change on Mexican agriculture

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Abstract

This study quantifies the impacts of climate change on yields and the corresponding economic losses in six relevant crops that account for 65% of the harvested area in Mexico and are highly relevant in terms of consumption and economic value. The results show that crop yields could decrease considerably during this century, especially in the rainfed management system. Under a high-emission scenario, large reductions in yields are expected by the end of this century for both rainfed and irrigated management systems of maize (42%, 31.4%), rice (51.4%, 41.3%), sorghum (41.1%, 36.6%), soybean (59.1%, 44.9%), wheat (23.3%, 20.0%), and rainfed sugarcane (11.7%). At the national level, the present value of losses in the selected crops amounts to $37,934 million dollars, which represents about twice the current total national agricultural production of Mexico. Rainfed agriculture represents about 69% of these losses and reductions in maize yields account for almost 70% of the total losses. States such as Veracruz, Sinaloa, Tamaulipas, and Jalisco represent half of the total economic losses. However, about 16% of the aggregated losses occur in states with high levels of poverty and subsistence farming like Chiapas, Oaxaca, and Guerrero. Climate change will significantly increase the risks that already vulnerable subsistence farmers' face in the present. Although ambitious mitigation efforts can reduce the estimated impacts in most of the crops, residual damages are considerable, and the prompt implementation adaptation strategies is required.

Keywords Climate change · Economic costs · Food security · Yields · Mexico

Introduction

Global population growth and changes in human consumption of food, feed, fiber, timber, and energy have caused negative impacts on more than 70% of the global, ice-free land surface (IPCC 2019). Climatic fluctuations differentially impact crop yields, affecting food production. Consequently, reliable projections of crop production are crucial to design policies to tackle food security and land allocation for agriculture (Agnolucci and De Lipsis 2020).

Different biophysical-agricultural-systems models have been used to explore the effects of climate change and climatic variability on crop yields and production (Holzworth et al. 2014; Rötter et al. 2018). The Agricultural Model Intercomparison and Improvement Project (AgMIP) facilitates the comparison of these models. The goals of AgMIP are to improve the knowledge and characterization to face challenges of world food security due to climate change. Crop model outputs are aggregated as inputs to regional and global economic models to determine regional vulnerabilities in the agricultural sector. AgMIP uses intercomparisons of various types of methods to improve crop and economic models and ensemble projections to produce enhanced assessments by the crop and economic modeling communities researching climate change agricultural impacts and adaptation (Rosenzweig et al. 2013). Important results of AgMIP show decreases in crop yields mainly in tropical regions (Rosenzweig et al. 2014). However, it also pointed out that simulations with mid-century climate scenarios are

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more sensitive to the selection of the crop model than to global climate model, emissions scenario, or climate scenario downscaling method (Rosenzweig et al. 2013). The AgMIP project evaluates the impacts of climate change smallholders' production related to rainfed agriculture (Ricciardi et al. 2018). In Mexico, 70% of agriculture is based on rainfed management (SIAP 2022) making this sector especially vulnerable to climate change. The contribution of agricultural activities accounts for 3.4% of the Mexican GDP (INEGI 2022), and ~ 6 million people depend directly on this sector (SIAP 2019). However, if relatives and rural people are considered, the number would increase up to 26.9 million people which represents more than 20% of Mexico's population (INEGI 2020). Therefore, it becomes important to assess the impacts of climate change on the agricultural sector in developing countries which strongly depend on small-scale production.

Impacts of climate change on agriculture have impacted directly local economies; for example, 87% of maize farmers in the south of Mexico have reported negative effects due to climate change and weather events (Harvey et al. 2018). Moreover, those affectations reinforce processes such as rural–urban and international migration (Sánchez-Cohen et al. 2013; Nawrotzki et al. 2015). A recent study reported that the migration of low-income rural farmers tripled during drought, representing as much as a third of all historical migration (Murray-Tortarolo and Salgado 2021). The impacts of drought in rural communities in Mexico can increase in 5% the probability of becoming poor and reduce 3% female employment and male school attendance (Arceo-Gómez et al. 2020). To decrease vulnerability to climate change and enhance adaptation and mitigation, agricultural community (i.e., stakeholders, modelers, NGOs), and policymakers must work together to face some challenges like identifying the most vulnerable areas, the vulnerability drivers of such places, and the cost–benefit analysis of adaptation (Donatti et al. 2019).

In Mexico, previous have focused on assessing effects of climate change of yields and suitability land on individual crops. First studies on maize reported an increment of 18.0% of the unsuitable area for maize with an increase in temperature of 2.0 °C and − 20% in precipitation (Conde et al. 1998). Other researchers projected a nationwide maize yield reduction of up to 10%, with regional decreases of up to 80% in RCP 8.5 (Murray-Tortarolo et al. 2018) and an average maize yield of 0.25 to 0.5 t/ha for rainfed maize under the same RCP (Ureta et al. 2020). Some papers also have analyzed diverse crops which include sugarcane (Guerrero-Carrera et al. 2015; Baez-Gonzalez et al. 2018) and wheat (Hernandez-Ochoa et al. 2018). Such studies project an increase in sugarcane yield up to 13.0% under climate change scenarios (Baez-Gonzalez et al. 2018) while wheat decreases up to 7.9% in the RCP8.5 (Hernandez-Ochoa et al. 2018). However, none of the previous studies evaluated the impacts of climate change on multiple crops and on its differential production managements. Moreover, there is little understanding of the aggregated economic costs of climate change on agricultural production. In addition to political will, the assessment of the impacts of climate change on agricultural production, and their implications for the local economy is one of the factors that that could motivate proactive adaptation strategies to be incorporated into national policies.

For this study, we use the output from different crop models included in AgMIP to study the effects on yields and the economy of climate change on five cereals with the largest apparent consumption in Mexico (maize, wheat, rice, sorghum, and soyabean) and that are of importance for national food security. In addition to these cereals, sugarcane is also included as sugar ranks as the second largest agricultural industry in Mexico and has enormous socioeconomic relevance (Aguilar-Rivera et al. 2012). Other important crops for Mexico such as beans, avocado, chili, and coffee are not considered in this study because simulations are not available from AgMIP. The selection of crops was determined jointly with the Institute of Ecology and Climate Change (INECC) of the Mexican government as this study was part of Mexico's Sixth National Communication to the United Nations Framework Convention on Climate Change (SEMARNAT-INECC 2018). The objectives of this study were to (1) assess the impacts of climate change on yields of six relevant crops in Mexico and (2) quantify the economic costs of climate change on these crops. This paper contributes to filling the information gap about climate change's physical and economic impacts for Mexico's agricultural sector at the national and state levels.

Data and methods

Historical yields

We integrated information of the harvested area, production, and yield at the state level for 2003–2012 of six crops: maize, rice, sorghum, soybean, sugarcane, and wheat for two land-management systems (rainfed and irrigated). Four of these crops (sugarcane, maize, rice, and wheat) account for half of the global production in 2021 (FAO 2022) and are commonly available in the agricultural models. National crop statistics come from the National Agricultural and Fisheries Information System[1] (SIAP 2022). The information is available at the national and subnational levels. These crops in 2018 accounted for 64.8% of the harvested area and close

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[1] https://www.agricultura.gob.mx/datos-abiertos/siap.

to 20.0% of the total national agricultural production (SIAP 2022). It is important to note that official statistics are always subject to uncertainty and measurement errors which in turn contribute to uncertainties both in the calibration of crop models as well as in their projections.

Changes of agricultural yields under climate change scenarios

Future yields originate from the AgMIP7 for two scenarios, RCP8.5 and RCP2.6, for the available combinations of agricultural models, General Circulation Models (GCMs), management systems, and scenarios (Table S1). While international efforts such as AgMIP offer many simulations for different climate scenarios and biophysical models, the range of modelled crops is still limited, and several combinations of climate/crop models and emissions scenarios are not available. For maize, we consider the models EPIC and pDSSAT forced with the output of three GCMs (HADGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM) for both scenarios and two management systems. For rice, we used the combination of the EPIC and the HADGEM2-ES climate model for both scenarios and management systems. For sorghum, we included the EPIC forced with the output of the HADGEM2-ES for the RCP 8.5 scenario and both management types (Table S1). However, there was no available data for the RCP2.6 scenario. Regarding soybean, we used the combination of the EPIC and HADGEM2-ES models for the two scenarios and management systems and the IPSL-CM5A-LR and MIROC-ESM-CHEM for the RCP8.5 scenario. For the rainfed sugarcane, we analyzed the combination of the EPIC and the HADGEM2-ES models for the RCP8.5 scenario. Additionally, we added for both management systems and scenarios, the combination of LPJLM and the HADGEM2-ES, and the IPSL-CM5A-LR models. Moreover, the LPJLM model was the only one available for both management systems, and it included the CO_2 fertilization effect on yields. Regarding wheat, we used the EPIC model in combination with the HADGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM models for both scenarios and management systems. All crop model data used here is available at https://agmip.org/data-and-tools-updated/.

Since modeled and observed yields are not directly comparable (Rosenzweig et al. 2013, 2014), relative yields are used to project future yields as described by the following equation:

$$Y_{fut} = Y_{ref}^{obs}\left(1 + \frac{Y_{fut}^{mod} - Y_{ref}^{mod}}{Y_{ref}^{mod}}\right)$$

where Y_{fut} is the bias corrected future yield, Y_{ref}^{obs} is the observed yield in the reference period, Y_{ref}^{mod} is the yield calculated from the biophysical model for the reference period, and Y_{fut}^{mod} is the yield calculated from the biophysical model for the future period. Y_{fut} is calculated for each crop and for three-time horizons: short-term (2021–2030), medium-term (2031–2060), and long-term projections (2061–2099).

Climate change impacts on economic costs of crops

The economic impacts of climate change in the agricultural sector are calculated at the national and state levels. The changes in yields with respect to current conditions are used to calculate the differences in crop production due to climate change for the three-time horizons defined above. The projections in agricultural production are then linearly interpolated for the period 2008–2100. The economic impacts of climate change are calculated by multiplying the differences in production by the crop prices in the year 2012. for the six crops, although we calculated the changes in production and the economic We based our main results on the EPIC model because it is the only one with projections impacts for all the available simulations from the different crop models. For the cases in which the EPIC model simulations are available for different climate models, we used the mean of the ensemble for the calculations. The upper and lower bounds of the estimated costs include the results from the other agricultural models that were analyzed. We used a 4.0% discount rate for calculating the present value of costs over the period 2008–2100. Monetary results are expressed in 2012 dollars.

Results

Crop context and impacts of climate change on crops

Maize

Maize is the most important crop in terms of land and production in Mexico. It accounted for 35% of the national cropland during 2003–2012. In 2012, Mexico had 7.0 million ha of maize land, from which 81.0% is rainfed and 19.0% irrigated. In 2012, the mean national production was 21.3 million tons. The national mean yields for rainfed and irrigated maize were 1.7 ton ha^{-1} and 4.9 ton ha^{-1}, respectively (Figure S1). Rainfed management produces 57.2% of the total maize production.

Rainfed According to the RCP8.5 scenario, rainfed national yield decreases by 6.5%, 17.9%, and 42.6% in the short-, medium-, and long-term projections, respectively. For the

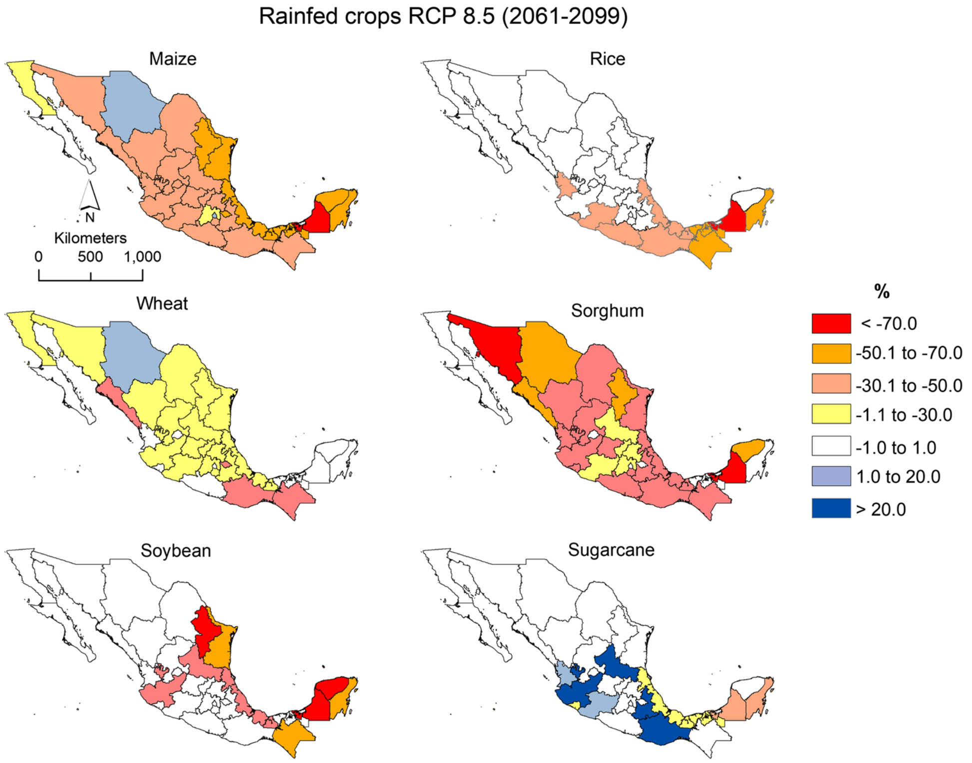


Fig. 1 Median percent changes of yields under rainfed management for the RCP8.5 scenario (2061–2099) in comparison to 1980–2012 baseline. Maize projections are based on the EPIC model and three GCMs (HADGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM), and on the pDSSAT model and three GCMs (HADGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM). Rice projections are obtained from the combination of the EPIC and HADGEM2-ES models. Wheat estimates are according to the EPIC model and three GCMs (HADGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM). Sorghum estimates are based on the combination of the EPIC and HADGEM2-ES models. Soybean projections are based on the EPIC model and two GCMs (HADGEM2-ES and IPSL-CM5A-LR). Sugarcane estimates are based the on EPIC and HADGEM2-ES models and the LPJLM model combined with three GCMs (HADGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM)

short-term projection, only two states do not depict reductions based on the median of the models. However, in the medium-term, yields in two states decrease > 30.0% (Figure S1), and in the long-term projection, eight states experience a drop > 50.0% (Figure S2). Two of them, in the south (Campeche and Tabasco), have a reduction > 65%, and the largest producer (Jalisco) would experience a decrease of 36.4% (Fig. 1). Besides, by the end of the century, only 11 states out of the 32 will have yields > 1 ton ha^{-1} (Figure S1). The decreases in the national yield are lower in the RCP2.6 scenario, in the three-time periods (2.0%, 5.7%, and 6.4%). In the long-term projection, three states in the south (Campeche, Yucatán, and Tabasco) depict a reduction of > 15% (Fig. 1). It is noticeable that the combinations between the pDSSAT model and the GCMs point to an increase in yield for two northern states (Chihuahua and Baja California), while the combinations between the EPIC and all the GCMs models project reductions (Figs. 1, S5).

Irrigated Under the RCP 8.5 scenario, it is estimated that the mean national irrigated yield decrease by 4.3%, 12.4%, and 31.4%, in the short, medium, and long term, respectively (Figure S2), which results in a national yield of 3.4 ton ha^{-1} by the end of the century (Figure S1). The short-term projection shows that 30 states out of 32 have reductions in yields (Fig. 2). The drop is more evident in the long term, when three states (Campeche, Tabasco, and Nuevo Leon) may face a reduction of > 50.0% in comparison to the mean current estimates (Fig. 2). There is only one state with increases (Chihuahua) due to the pDSSAT model, which contrasts with the EPIC model projections. According to the RCP2.6 scenario, the mean national yield would reduce 2.5%, 4.9%, and 4.9% in the three-time periods. By the end of the century, the RCP2.6 scenario depicts a reduction of > 10.0% in five states, especially in the south (Campeche, Tabasco, and Yucatan; Figure S6).

The sensitivity analysis shows that the combination of the EPIC and the HADGEM2-ES models provides more optimistic projections, contrasting to the IPSL-CM5A-LR model, especially in the irrigated management system (Figure S3). The EPIC and the pDSSAT models exhibit similar

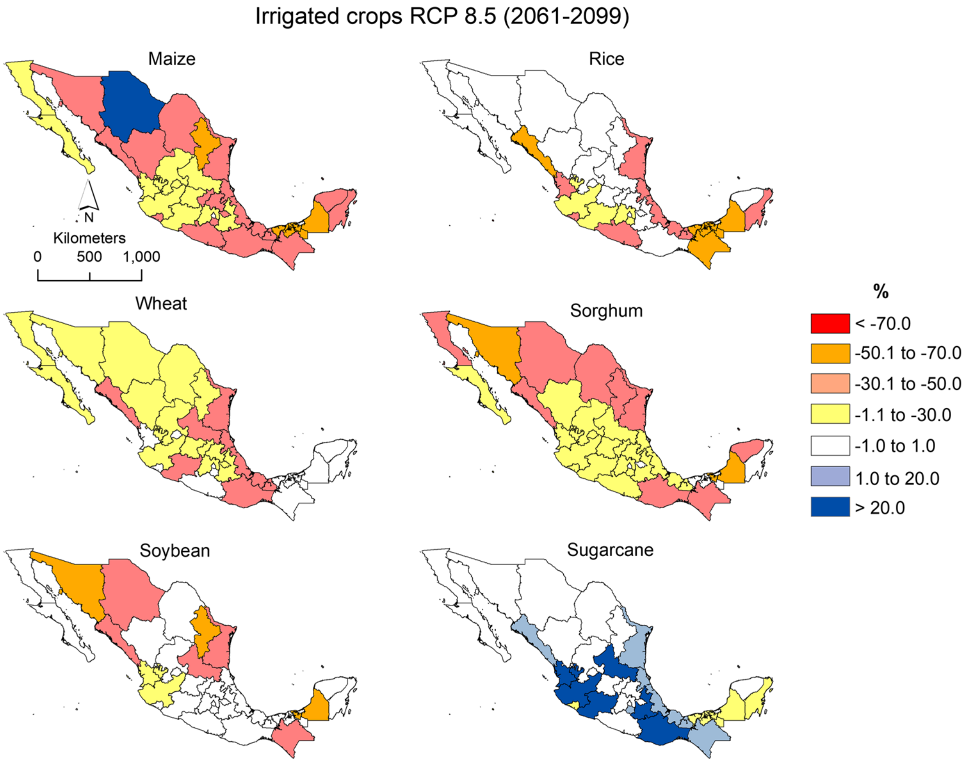


Fig. 2 Median percent changes of yields under irrigated management for the RCP8.5 scenario (2061–2099) in comparison to 1980–2012 baseline). Maize projections are based on the EPIC model and three GCMs (HADGEM2-ES, IPSL, and MIROC-ESM-CHEM), and the pDSSAT model and three GCMs (HADGEM2-ES, IPSL, and MIROC-ESM-CHEM). Rice estimates are based on the combination of the EPIC and HADGEM2-ES models. Wheat projections are based on the EPIC model and three GCMs (HADGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM). Sorghum estimates are based on the combination of the EPIC and HADGEM2-ES models. Soybean projections are based on the EPIC model and two GCMs (HADGEM2-ES and MIROC-ESM-CHEM). Sugarcane estimates consider the CO_2 fertilization effect and are based on the combination of the LPJLM and MIROC-ESM-CHEM models

results in rainfed management (Figure S3). Regarding the pDSSAT model, we can see that the simulations based on the IPSL-CM5A-LR are the most optimistic, followed by the MIROC-ESM-CHEM (Figure S3). Results are contradictory for some states between the EPIC and the pDSSAT models, as we previously specified for a northern state (Chihuahua) where the EPIC model estimates decrease, while the pDSSAT projects increase. The results for this northern state contrasts with those of the other states (Fig. 1 and Fig. 2).

Rice

From 2003 to 2012, Mexico had an annual average of 54,300 ha of harvested rice, of which 54.4% is rainfed and 45.6% irrigated. The annual production in that period was 257,255 tons. The national mean yields for rainfed and irrigated rice were 3.9 ton ha^{-1} and 6.4 ton ha^{-1}, respectively (Figure S1). Rainfed management represents 38.7%, and the irrigated rice accounts for 61.3%.

Rainfed According to the RCP8.5 scenario, in the short-, medium-, and long-term projections, the rainfed yields decrease 8.0%, 24.4%, and 51.4%, respectively (Figure S2). By the end of the century, eight out of eight states that produce rainfed rice would lose > 40% of their yields (Fig. 1), and the three largest producer states (Campeche, Veracruz, and Tabasco) reduce their yields by 58.2%, 62.9%, and 40.6%. Regarding the RCP2.6 scenario, the declines are 8.5%, 13.4%, and 13.1% for the three-time periods, respectively. Besides, the same three states would experience declines in their yield larger than 11.0% by the end of the century (Figure S7).

Irrigated The RCP8.5 scenario shows that irrigated yield decreases with 7.3%, 21.9%, and 41.3% for the short-, medium-, and long-term projections, which represents a value of 3.9 ton ha^{-1} by the end of the century (Figure S1 and Figure S2). Three states account for 57% of the irrigated production (Michoacan, Nayarit, and Campeche). By the end of the century, these states reduce their yield by 29.1%, 35.6%, and 58.2%, respectively. The impacts are evident in the south of the country and in one state by the Pacific Coast State (Sinaloa) (Fig. 2). Regarding the RCP2.6 scenario, the yield would decrease with 7.8%, 11.0%, and 10.1% for the three-time periods, respectively (Figure S8).

Wheat

From 2003 to 2012, Mexico had an annual average of 667 thousand ha of wheat, of which 19.1% was rainfed and 80.9% irrigated. The total mean production from 2003 to 2012 was 3.4 million tons. National mean yields for rainfed and irrigated wheat were 1.6 ton ha^{-1} and 4.0 ton ha^{-1}, respectively (Figure S1). Rainfed management produces 7.0% of the total production, while irrigated wheat accounts for 93.0%.

Rainfed According to the RCP 8.5 scenario, the yields of rainfed wheat would decrease by 1.2%, 14.3%, and 23.3% for the short-, medium-, and long-term projections. By the end of the century, the mean yield would be 1.2 ton ha^{-1} (Figure S1). The largest producer of rainfed wheat (Tlaxcala) and the other three main producer states (Chiapas, Oaxaca, and Sinaloa) have a reduction of > 30.0% in the long-term projection (Fig. 1). Contrastingly, there is an increase of 4.6% in a northern state (Chihuahua) due to the combination between the EPIC and two GCMs (IPSL-CM5A-LR and MIROC-ESM-CHEM) models (Fig. 1). The reduction in yields of rainfed production under the RCP2.6 scenario is lower in each period, with decreases of 3.5%, 7.5%, and 6.1%, respectively (Figures S2, S9).

Irrigated Under the RCP8.5 scenario, the reductions in the mean irrigated yield would be 2.3%, 9.0%, and 20.0% for the short-, medium-, and long-term horizons, respectively (Figure S2). By the end of the century, the three largest producers (Sonora, Baja California, and Guanajuato) would experience reductions of 24.3%, 12.9%, and 11.9%, respectively (Fig. 2). Five states located mainly in the Gulf of Mexico (Sinaloa, Michoacan, and Oaxaca) and the Pacific Coast (Tamaulipas, Veracruz) are projected to experience yield reductions larger than 30.0% (Fig. 2). The combination of the EPIC and the IPSL-CM5A-LR models is more optimistic, influencing the results for some states (Chihuahua and Baja California Sur) where the short- and medium-term projections show increases in contrast to the HADGEM2-ES and the MIROC-ESM-CHEM models (Figure S3). The reduction in yields of irrigated wheat under the RCP2.6 scenario are 3.5%, 7.5%, and 6.1%, respectively for the three-time periods analyzed (Figure S2). The most affected state is Michoacan under this scenario, reducing its yield with 13.9% by the end of the century (Figure S10).

Sorghum

From 2003 to 2012, Mexico had an annual average of 1.8 million ha of sorghum, of which 72.1% was rainfed and 27.9% irrigated. The annual mean production from 2003 to 2012 was 6.3 million tons. The national mean yields for rainfed and irrigated sorghum were 3.0 ton ha^{-1} and 5.0 ton ha^{-1}, respectively (Figure S1). Rainfed management produces 54.2%, while irrigated sorghum amounts to 45.8%.

Rainfed The RCP8.5 scenario projects a decrease in the mean rainfed national yield of 7.2%, 22.4%, and 41.1% for the short-, medium-, and long-term horizons. This represents a yield of 2.4 ton ha^{-1} and 1.8 ton ha^{-1} by the medium and long term, respectively (Figure S1). All the states that produce rainfed sorghum show a decrease larger than 12.0%, and in six states, the decrease in yields exceeds 50.0% (Figure S2 and Fig. 1). The most affected states are mainly in the north (Sonora, Chihuahua, and Nuevo Leon). The largest producer (Tamaulipas) loses 43.9% of its historical yield. Two states reduce their yields in more than70.0%, one in the south and one in the north (Campeche and Sonora) (Fig. 3).

Irrigated Regarding the irrigated production, by the medium- and long-term projection, the national mean yield decreases to 4.2 ton ha^{-1} and 3.6 ton ha^{-1}, respectively (Figure S1). This represents a reduction of 24.7% and 36.6%. Moreover, two states that account for 60.0% of the irrigated production (Guanajuato and Tamaulipas) reduce their yields by 33.9% and 15.1% in the long-term projection. Eleven states out of the 28 that produce this commodity will experience a reduction of at least 30.0%, and two of them (Sonora and Campeche) will have reductions in yield of > 50.0% (Fig. 2).

Soybean From 2003 to 2012, Mexico had an annual average of 997 thousand ha of soybean, from which 86.1% was rainfed and 13.9% irrigated. The annual production from 2003 to 2012 was 161 thousand tons. The national mean yields for rainfed and irrigated were 1.8 and 2.0 ton ha^{-1}, respectively (Figure S1). Rainfed management produces 84.0% and irrigated management 16.0%.

Rainfed According to RCP8.5 scenario, the mean rainfed national yield for rainfed soybean would decrease by 11.8%, 33.8%, and 59.1% for the short-, medium-, and long-term projections (Figure S2). The largest producer (Tamaulipas) would reduce its yield by 59.9%. Three other states, two of them in the south (Campeche and Yucatan) and one in the north (Nuevo Leon), are projected to have > 70.0% reductions in their yields. These states account for 10.6% of the rainfed production (Fig. 1).

Irrigated The reductions in mean irrigated yields based on the RCP 8.5 scenario are 5.9%, 19.9%, and 44.4% for the short, medium, and long horizons (Figure S2). The largest producer (Tamaulipas) decreases by 47.8% by the end of the century, and three more states that account for 19.9% of the irrigated production exceed reductions of 55.0% in their yields (Sonora, Nuevo Leon, and Campeche) (Fig. 2).

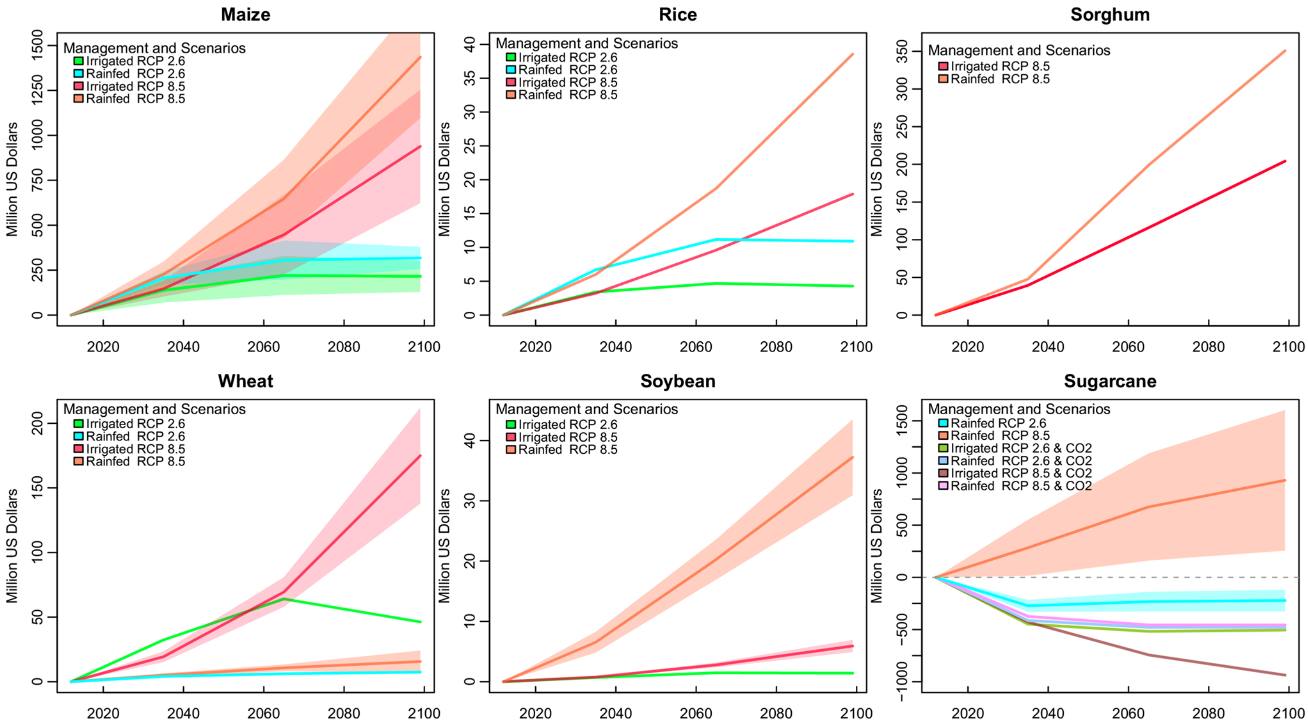


Fig. 3 Median economic costs for the six crops, based on the combination of agricultural and climatic models. The shaded area represents the uncertainty derived from multiple models, while the solid line refers to the median losses

The yield reduction of irrigated soybean under the RCP2.6 scenario is 5.8%, 10.5%, and 10.4% for short, medium, and long periods, respectively. The most affected state is Sonora, reducing its yield by the end of the century with 20.1% (Figure S11).

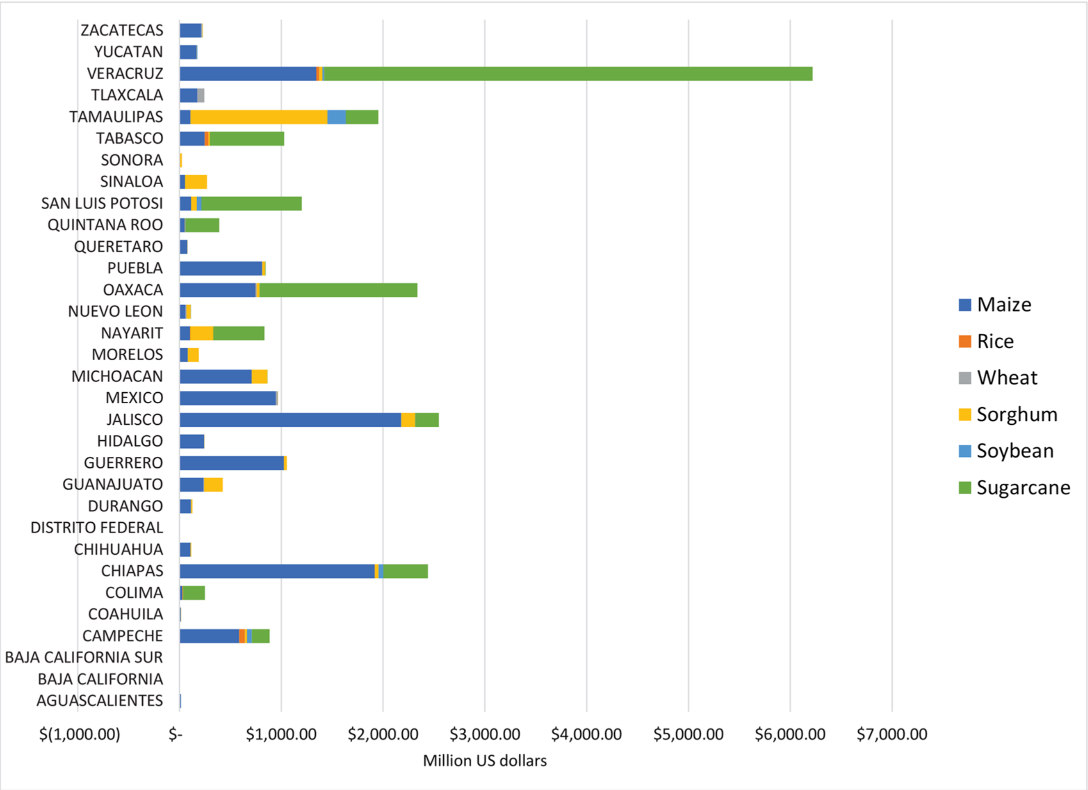
Sugarcane

From 2003 to 2012, Mexico had an annual average of 686 thousand ha of sugarcane, of which 40.1% was rainfed, and the rest irrigated. The annual production from 2003 to 2012 was 50.2 million tons. National mean yields for rainfed and irrigated sugarcane are 59.9 ton ha^{-1} and 88.0 ton ha^{-1}, respectively (Figure S1). Rainfed management represents 48.6% of the national production and the irrigated 51.4%.

Rainfed The impacts of climate change on sugarcane show high uncertainty between models. The declines in the rainfed production under the RCP8.5 are 23.7%, 52.6%, and 72.17% for the short, medium, and long horizons. However, if the CO_2 fertilization effect is considered, there are increases of 28.1%, 29.3%, and 39.7% in the short, medium, and long periods. For the RCP2.6 scenario, there are increases of 30.8% (short term), 34.1% (medium term), and 33.9% (long term) in yields. Moreover, considering the CO_2 fertilization effect, the values rise by 39.0%, 44.3%, and 44.4% in each period, respectively (Figure S2). There are contrasting results across the combination among models. The combination of the EPIC and HADGEM2-ES models estimate reductions in yields (from 16.0 to 30.0%) for the three-time horizons without the CO_2 fertilization effects under the RCP8.5 scenario (Fig. S2). Nevertheless, when combining the EPIC model with the MIROC-ESM-CHEM, as well as the LPLJM models with all the GCMs, the results show increases in yield of > 70.0% (Figure S3). The combination between EPIC and HADGEM2-ES models projects reductions. The differences are larger for two states (Puebla and Jalisco) that account for less than 5.0% of the national production. However, the combination of the models suggests that without CO_2 fertilization, five states have reductions in yields, with two of them > 30.0% (Campeche and Quintana Roo), and there is an increase in eight states, of which two of them experience increases of more than 100% (Jalisco and Puebla) (Fig. 1). The CO_2 fertilization effect positively impacts the sugarcane yields with > 50.0% increase in yields in some states (Puebla, Jalisco, Oaxaca, and San Luis Potosi) that account for 33.8% of the national rainfed sugarcane production for both RCPs scenarios (Fig. 1).

The sensitivity analysis depicts that the projections of the MIROC-ESM-CHEM and IPSL-CM5A-LR models when the CO_2 fertilization effects are considered are very similar for the rainfed management (Figure S3). Moreover, the combination of EPIC and HADGEM2-ES models shows

a) Rainfed



b) Irrigated

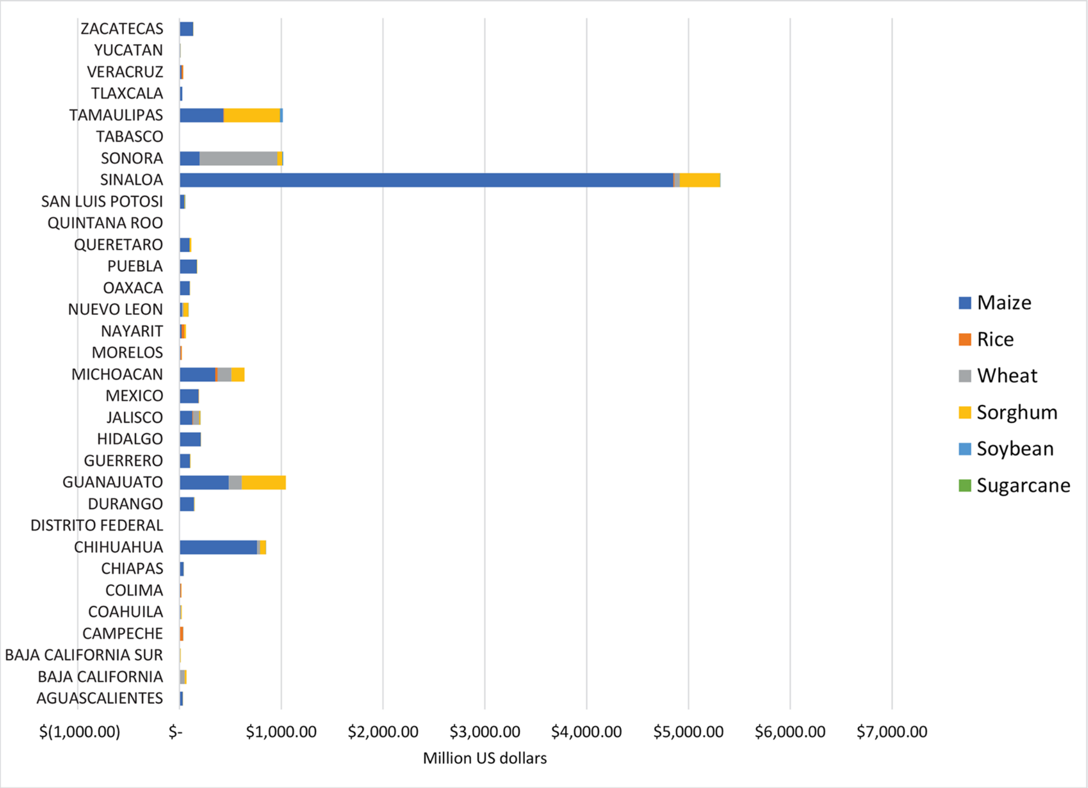


Fig. 4 Present value of the losses from climate change per crop and state. Panel **a** refers to the estimated losses for rainfed production; panel **b** shows losses for irrigated production. The present value of the total losses at the national level is $37,934 million of which $26,094 million correspond to rainfed and $11,840 million to irrigated

less optimism in the increase of yields, considering the CO_2 fertilization effects, than the LPJLM model (Figure S3).

Irrigated The RCP8.5 scenario shows increases in irrigated yields by 27.7%, 48.5%, and 59.5% considering the CO_2 fertilization effect for the short-, medium-, and long-term periods (Figure S1). The same states that enhance their yields in rainfed production depict increases in yields > 100% (Jalisco, Puebla, San Luis Potosi, and Oaxaca) (Fig. 2). The majority of the states demonstrates positive effects in both scenarios. There are eleven states with increases in yields, of which three would experience a rise of > 160% (Jalisco, Puebla, and San Luis Potosi), and only four states (Campeche, Colima, Quintana Roo, and Tabasco) experience decreases of > 12.0% (Fig. 2). According to the RCP2.6 scenario, there are increases in yields of 30.9%, 33.4%, and 33.1% in the short-, medium-, and long-term projections, respectively.

Cumulative climate change economic costs for selected crops

Projected losses over the period 2008–2100 for the mean ensemble of the crop simulations, under the RCP8.5 scenario, show rapid costs increase with higher levels of warming for most crops (Fig. 3). The mean economic costs caused by climate change impacts on maize yields reach more than $1250 million dollars per year by the end of this century, and close to 750 million per year in the case of rainfed sugarcane without CO_2 fertilization effects, while when fertilization is considered one of the models suggests benefits for this crop close to $1000 million per year (Fig. 3).

Economic impacts of climate change on agriculture at the national level

Under the RCP8.5 scenario, the present value of the yield changes in all crops and both management systems is $37,934 million; it represents about twice the total annual value of the whole agricultural sector in Mexico in 2012 ($18,798 million). Considering the projections from the different combinations of agricultural models and GCMs, the total present value of losses ranges from $8271 to $42,799 million (Table S2). If the effects of CO_2 fertilization are accounted for in sugarcane production with irrigation, the lower bound of this range could imply benefits for $7681 million. The uncertainty in sugarcane modeling and the response of this crop to increases in atmospheric CO_2 levels is considerable. Rainfed production accounts for 69.0% of the total costs, while irrigation only 31.0% (Tables S2-S4). Reductions in maize yields represent 56.0% of the total costs, followed by sugarcane (27.0%), sorghum (12.0%), and wheat (3.0%). Soybean and rice contribute 1.0% each.

Economic impacts of climate change on agriculture at the state level

At the state level, Veracruz, Sinaloa, Tamaulipas, and Jalisco have the largest losses representing about 16.5%, 14.7%, 7.8%, and 7.3% of the total national costs, respectively (Figure S4). These four states concentrate 46% of the total national losses. States in which high levels of poverty and subsistence farming prevail, such as Chiapas (6.5%), Oaxaca (6.4%), and Guerrero (3.1%), account for a considerable fraction (16.0%) of the costs of climate change impacts on agricultural yields.

Losses are highly heterogeneous among states, crops, and management systems (Fig. 4). The highest costs are from maize and sugarcane for the rainfed management (Table S3). There are eight states (Veracruz, Tamaulipas, Tabasco, San Luis Potosi, Oaxaca, Jalisco, Guerrero, and Chiapas) that reach present values over a billion dollars. The most affected crops in irrigated management systems are maize, sorghum, and wheat, and the states with losses exceeding a billion dollars are Sinaloa, Sonora, Tamaulipas, and Guanajuato (Table S4; Fig. 4).

Economic impacts of climate change on crops

Maize

Under the RCP8.5 scenario, the present value of the total costs of climate change in maize production (rainfed and irrigated) is $21,138 million (Table S2). Considering the different combinations of the agricultural models and GCMs (EPIC and pDSSAT), the range of the economic costs extends from $7536 to $25,730 million (Table S2).

The present value of the losses of rainfed maize amounts to $12,499 million (about 60.0% of the total costs for maize), while for irrigation, it is $8,639 million (Tables S3-S4). The uncertainty ranges for these present values are between $8108 and $16,001 million for rainfed management and between – $572 and $9729 million for irrigated production. The largest losses in rainfed production occur in Jalisco ($2178 million), Chiapas ($1918 million), Veracruz ($1345 million), Guerrero ($1027 million), Puebla ($811 million), and Oaxaca ($748 million). At the country level, the aggregated losses are comparable to 3.21 times the annual value of national rainfed maize production in 2012 (Table S2).

For irrigated maize production, the losses are more concentrated in a few states (Table S4). The highest losses are in Sinaloa ($4853 million), which accounts for 56.0% of national losses, followed by Chihuahua ($763 million), Guanajuato ($485 million), Tamaulipas ($432 million), and Michoacán ($351). The magnitude of the present value of the losses in irrigated maize is about three times the national annual value of this crop and management regime.

The projections based on the pDSSAT model are more optimistic, leading to a present value of total changes in maize production of \$11,103 million in losses for the ensemble mean, under the RCP8.5 scenario (Table S5). Two states that marginally contribute to national production (Baja California and Mexico City) show small benefits, relative to those projected for Chihuahua (\$2,981 million), which accounts for 4.0% of the national production.[2]

According to the RCP2.6 scenario, Mexico would exhibit gains, in terms of avoided losses, in maize production compared with the RCP8.5 (Tables S6-S11). Based on the combination of the EPIC and HADGEM2-ES models, the present value of the avoided losses is \$8616 million (\$5231 and \$3385 for rainfed and irrigated management, respectively; Tables S11, S9-S10). Benefits are comparable to 1.28 times the value of the national maize production in 2012. Sinaloa (\$1914 million), Jalisco (\$1053 million), Chiapas (\$854 million), and Veracruz (\$485 million) are the states that would benefit the most, accounting for about 50.0% of the total avoided losses (Table S11). The present value of the avoided losses in rainfed maize is equivalent to 1.35 times the total value of the national production of this crop and modality in 2012. The states with the highest benefits are Jalisco (\$1003 million), Chiapas (\$835 million), Veracruz (\$478 million), Guerrero (\$383 million), and Oaxaca (\$296 million; Table S9). The present value of the total avoided losses for the irrigated production is \$3385 million (about 1.19 of the annual value of the national production of irrigated maize in 2012). Sinaloa (\$1893 million; about 56% of total benefits), Chihuahua (\$328 million), Guanajuato (\$199 million), Tamaulipas (\$190 million), and Michoacán (\$130 million; Table S10). The present value of the avoided losses obtained combining the pDSSAT and HADGEM2-ES models is used to explore the uncertainty in avoided damages. These results suggest that disagreements between the EPIC and pDSSAT models are significantly smaller when the differences in projections of the two scenarios are evaluated (Table S9-S11). The present values calculated with the EPIC and pDSSAT models differ by 18.0% for total maize production. This difference is even smaller for rainfed maize (6.0%). However, for the irrigated production, the present value of avoided losses is 42% larger in the EPIC model than in the pDSSAT. This disagreement is mainly caused by the results from one state (Chihuahua) for which pDSSAT projects significant benefits for irrigated maize under the RCP8.5 scenario.

Rice

The present value of the changes in rice yields in Mexico amounts to \$283 million under the RCP8.5 scenario (Table S2). Rainfed and irrigated management nearly account for half of the total value each (\$136 million and \$147 million, respectively; Tables S3-S4). While the estimated losses are small compared with other crops, the total losses are equivalent to 5.1 times the annual value of national rice production in 2012. In the case of rainfed and irrigated production, the present values of losses are comparable to 7.3 and 4.5 times the annual rice production for the corresponding modality in 2012. Campeche, Tabasco, and Veracruz contribute with 89.0% of losses in rainfed production (Table S3), while Campeche, Nayarit, Michoacán, Veracruz, and Morelos account for 72.0% of the losses in irrigated production (Table S4). The states with the largest total losses (rainfed and irrigated) are Campeche (\$89 million), Veracruz (\$43 million), and Tabasco (\$42 million; Table S5).

According to the RCP2.6 scenario, the economic losses in rice production would decrease 40.0% in comparison with the RCP85 scenario (38.0% and 44.0% in rainfed and irrigated production, respectively; Tables S6-S8). The present value of the avoided losses is \$116 million. Under this scenario, some states could reduce the projected losses by more than 40.0% in comparison with the RCP85 scenario (Nayarit, Michoacán, Veracruz y Tabasco. Tables S9-S11).

Wheat

The present value of the total costs of climate change in wheat production in Mexico amounts to \$1376 million, with an uncertainty range of \$1128 million to \$1687 million, based on three general circulation models and the EPIC crop model under the RCP8.5 scenario (Table S2). Irrigated production accounts for about 90% of the estimated losses, and rainfed management only for 10% (Tables S3-S4). The uncertainty at the national level for irrigated wheat production ranges from \$1108 million to \$1485 million, while rainfed losses are estimated between \$20 million and \$202 million. Total losses represent about 1.5 times the annual value of the national wheat production in 2012. Rainfed and irrigated production losses are equivalent to 2.4 and 1.5 times the national value, respectively. The economic losses in rainfed wheat production are concentrated in five states, which account for 90.0% of the total. Tlaxcala (\$68 million), Mexico (\$19 million), Zacatecas (\$11 million), Oaxaca (\$10 million), and Nuevo León (\$10 million). Tlaxcala accounts for 52% of the national rainfed losses. Losses are also highly concentrated in five states in irrigated production. Sonora (\$761 million; about 61% of the national losses in irrigated wheat production), Guanajuato (\$129 million), Michoacán

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[2] https://www.gob.mx/aserca/articulos/maiz-grano-cultivo-representativo-de-mexico.

($138 million), Jalisco ($61 million), and Sinaloa ($52 million) represent about 92% of the national losses in this production modality (Table S4). A large fraction of the total losses in wheat production (rainfed and irrigated) occur in the states that produce the largest shares of irrigated wheat (Sonora, Guanajuato, Michoacan, and Jalisco; Table S5) and rainfed production in Tlaxcala. These states represent about 85.0% of the total losses, and Sonora alone accounts for 55%.

The present value of the total avoided losses (rainfed and irrigated) of the RCP2.6 scenario at the national level amounts to $257 million (of which $62 and $194 million are from rainfed and irrigated production, respectively; Table S11). Michoacan and Guanajuato account for 65.0% of the benefits under irrigated management (51.0% of total avoided losses), while Tlaxcala receives 57.0% of the benefits achieved in rainfed production (Tables S9-S11).

Sorghum

The present value of the changes in sorghum yields (rainfed and irrigated) amounts to $4,464 million under the RCP8.5 scenario (Table S2). About 60% of these losses ($2,703 million) come from rainfed production. Losses are highly heterogeneous among states and management (Tables S3-S4). Tamaulipas accounts for 50.0% of the country's total present value of losses in rainfed sorghum (Table S5). About 27.0% of the remaining losses occur in the states located on the Pacific coast (Sinaloa, Nayarit, Jalisco, and Michoacan), and two states in the central part of Mexico (Guanajuato and Morelos) account for 10.0% of losses. Moreover, 78.0% of the losses from irrigated management are concentrated in three states (Tamaulipas, Sinaloa, and Guanajuato; Table S4). Five states account for 82.0% of the total losses of sorghum (rainfed and irrigated; Table S5): Tamaulipas ($1,892 million), Guanajuato ($614 million), Sinaloa ($613 million), Michoacan ($282 million), Nayarit ($244 million).

Soybean

The present value of the costs of climate change on soybean production during this century amounts to $395 million (Table S2), from which the majority (88.0%) occurs in rainfed production (Tables S3-S5). The states with larger losses (rainfed and irrigated) are Tamaulipas (53% of the total losses, representing $210 million), while Campeche, San Luis Potosi, and Chiapas have losses of about $48 million each (Table S5). Regarding irrigated soybean, Tamaulipas and Sonora have losses of $29 and $9 million, respectively, but the rest of the only contribute slightly to the national losses (Table S4). In the case of rainfed management, 92.0% of losses occur in Tamaulipas ($181 million), San Luis Potosí ($45 million), Campeche ($47 million), and Chiapas ($47 million; Table S3). The present value of the losses in soybean (rainfed and irrigated) over this century is comparable to 3 times the value of national production of this crop in 2012. The present values of changes in yields from rainfed and irrigated management represent about 3.1 and 2.3 times the corresponding values of the national production of soybean in 2012. Projections under the RCP2.6 scenario are available for irrigated production (Table S7), showing that losses decrease about 50.0%.

Sugarcane

The projections of changes in sugarcane yields are characterized by high levels of uncertainty, as we have mentioned before, and different agricultural models provide divergent results. These variations become more pronounced if irrigation and the potential fertilization effects of CO_2 are considered (Table S4). According to the combination of the EPIC and HADGEM2-ES models, under the RCP8.5 scenario, the present value of losses in rainfed sugarcane production for Mexico would amount to $10,277 million, and all the states that currently produce rainfed sugarcane would face losses (Table S3). Three states account for about 71.0% of the total costs: Veracruz with about 47.0% of the total ($4,797 million), Oaxaca with 15.0% ($1,551 million), and San Luis Potosí with 9.5% ($985 million).

The combinations of the LPJLM agricultural model and three GCMs (IPSL-CM5A-LR, MIROC-ESM-CHEM, and HADGEM2-ES) suggest that the RCP8.5 scenario would produce considerable benefits in the range of $2476 to $7345 million, with a mean value of $5407 million (Table S2). However, if the effects of CO_2 fertilization are considered, the present value of the benefits over this century could be even higher ($9720 million with the MIROC-ESM-CHEM model). In this scenario, only Tabasco ($171 million), Quintana Roo ($78 million), Campeche ($37 million), and Colima ($23 million) show losses that are small in comparison with the benefits of states such as Oaxaca ($1946 million), Veracruz ($1182 million), and San Luis Potosí ($1158 million). For irrigated sugarcane, including the CO_2 fertilization effects, the present value of the projected benefits would reach $11,638 million (Table S2, S5). As such, the total benefits in sugarcane production (rainfed and irrigated) of climate change (RCP8.5) over this century, if the effects of CO_2 fertilization are included, could amount to $21,358 million. A large share of these benefits occurs in Jalisco (26.0%), Veracruz (17%), San Luis Potosí (14.0%), Oaxaca (13.0%), and Puebla (11.0%); only Tabasco would experience losses ($44 million; Table S5).

Projections for sugarcane under the RCP2.6 are only available for the LPJLM model. Without considering the fertilization effects of CO_2, the present value obtained from the ensemble average of the projections for rainfed sugarcane

(IPSL-CM5A-LR, MIROC-ESM-CHEM, and HADGEM2-ES) shows a benefit of \$702 million in comparison to the RCP8.5 scenario (Table S9). The uncertainty is high as this figure could go up to \$2353 million (IPSL-CM5A-LR) or imply losses of about \$443 million (HADGEM2-ES). The differences between RCPs are highly heterogeneous. For example, states like Veracruz have benefits for \$710 million while another state (Oaxaca) has costs of \$281 million (Tables S5-S10).

According to the RCP2.6 scenario and the CO_2 fertilization effect, the losses decrease. For rainfed production, losses would amount to \$1209 million, and two states (Oaxaca and San Luis Potosi) account for 75.0% of these losses (Table S9). Losses are considerably larger for irrigated sugarcane than rainfed, with a present value of \$2429 million at the national level (Table S10). One state on the Pacific coast (Jalisco) accounts for 77.0% of these losses (\$1867 million).

Discussion

To improve strategies to cope with climate change, we need to identify where climate change impacts more severely the main crops. This information would guide policies to enhance resilience, mitigation, and adaptation of agricultural production systems (Leng and Huang 2017). Our results suggest that climate change projections under the RCP8.5 scenario will importantly impact agricultural yields in Mexico with significant consequences on national food security and with high economic costs.

Impacts of climate change on maize yields are reported in many regions, and tropical zones seem to be the most affected (Pugh et al. 2016). It has been projected that maize yield decreases by 21%, 33%, and 50% under climate change scenarios of 1, 2, and 4 °C, respectively (Tesfaye et al. 2018), which is mainly due to increasing temperature (Bassu et al. 2014). In Mexico, this has been supported by Ureta et al. (2020), who found that temperature is a determinant factor for rainfed maize. Contrastingly, Murray-Tortarolo et al. (2018) suggested that negative impacts on maize yield are mainly associated with water availability and dry season length for rainfed management. Their results are supported by ours in which the same critical regions (northeast and south) of the country are the most affected for rainfed maize under the RCP8.5 scenario. This relates to the reduction in the area with the highest suitability for rainfed maize reported from 2.4 to 5.5% in five states, namely Jalisco, Campeche, Oaxaca, Chiapas, and Michoacan (López-Blanco et al. 2018).

Production depends on the demand, which can be for self-consumption or trade. In the case of the rainfed maize production is highly related to self-consumption (SIAP 2019). Rainfed maize is mainly produced by 2.6 million small producers who grow it in farms with a mean size of ~ 5 ha (Jaramillo Albuja et al. 2018). The impacts of declining yields would negatively affect these small producers whose food source would diminish, putting them at higher risk of reinforcing the poverty in the south of Mexico. Besides, a reduction in yields could directly impact the land-use/cover change to keep up with the food requirements for self-consumption. Irrigation in agriculture has been pointed out as a good strategy to mitigate climate change impacts (Kukal and Irmak 2018). However, most of the farmers cannot afford to cultivate intensified or irrigated maize (Guzmán et al. 2014). In Mexico, Sinaloa is the state that best represents the high technification and irrigation in agriculture, supported by the government, receiving > 90% of the benefits of the agricultural incentives (Eakin et al. 2015). However, this technification has not taken into consideration the environmental impacts. For example, Sinaloa increased its agricultural extent by 300% between 1990 and 2008, mainly as technified monocultures with lands > 20 ha (Eakin et al. 2015). Currently, this state produces 30.0% of the maize in Mexico, resulting in a primary source of income (Eakin et al. 2015). Jalisco is the main rainfed production state for large-scale trade. This contrasts with the fact that many states based their production on rainfed management by smallholder farmers that produce maize for self-consumption or small and local trade. These characteristics related to rainfed maize are more prevalent in the State of Mexico and Chiapas where maize production represents 7.0% and 23.0% to their incomes (Eakin et al. 2015). These areas in Mexico have been abandoned from governmental agricultural support for decades. The reduction of yields can lead to at least two possible scenarios. One scenario in which there is food scarcity triggering the expansion of the agricultural area to compensate the decline of yields, and a second scenario that reinforces the food dependence based on the need of buying maize from other states like Sinaloa, or the US. Food dependence is already high as Mexico currently imports ~ 37% (FAO 2022). This option, in synergy with climate change and economic costs, would contribute to a depletion of diversity among maize races (Ureta et al. 2012) and imply high environmental costs.

The available projections for rice yields are contradictory; some authors report an increase of 10% to 15% (Tao and Zhang 2013), while others suggest decreases of 7 to 10% per every 1 °C increase in temperature (Peng et al. 2004; Krishnan et al. 2007). According to our results, in the long term, rice is the second most affected crop out of the six analyzed in this study. Our findings are more pessimistic (24% and 36% in the period 2031–2060) than others reported for the Mediterranean areas (> 12% in the 2070s) (Bregaglio et al. 2017). These results are of concern due to possible synergies with other severe challenges, such as the fact that rice is one of the crops with less governmental production support (Navarrete 2016). This situation has already caused that the Mexican internal demands depend on imports (82% of the domestic supply comes from imports) (FAO 2022). Thus, Mexico could likely increase its imports in this crop if strategies to reduce the climate change impacts are not implemented, especially in the state of Campeche.

Mexico has been the home of the green revolution for wheat. For instance, Mexico was one of the first countries to adopt new varieties and technologies developed by the International Maize and Wheat Improvement Center (CIMMYT) (Lobell et al. 2005). Mexico's wheat yields are above the international average, but the country requires large imports (~70%) to keep satisfying its domestic supply (FAO 2022). A previous study on wheat yield reduction in Mexico under climate change (RCP8.5) suggested a decrease of ~15% for rainfed wheat and ~7.5% for irrigated wheat by the 2050s, which is strongly associated with the increasing temperature (Hernandez-Ochoa et al. 2018). In the same study, the authors point out that the most affected region is the northwest, especially for irrigated production, and two states in the northeast under rainfed production. These results are similar in magnitude to our findings. However, there are differences in the spatial distribution of changes, particularly for the rainfed management. For example, Tlaxcala, which is the largest rainfed producer, is one of the most affected states in our study followed by two southern states (Chiapas and Oaxaca) and one in the north (Sinaloa). Contrastingly, Hernández-Ochoa et al. (2018) do not report negative impacts in those areas. Other findings to highlight is our result that rainfed wheat could increase in Chihuahua under a particular combination of crop and climate models. This finding occurs because, according to Hernández-Ochoa et al. (2018), the combination the EPIC and the HADGEM2-ES models is the most optimistic for wheat projections. Besides the differences between models, irrigated wheat could be severely affected because (1) it is the most popular in Mexico, accounting for > 90% of the production, and its economic and environmental investment is higher; (2) it is spread on dry and hot conditions, which will become hotter and drier, especially in Sonora and Baja California, where the droughts are prone to increase (Escalante-Sandoval and Nuñez-Garcia 2017); and (3) limitations in water resources linked to the most productive areas as Sonora (Moreno 2012).

Mexico is one of the largest producers of sorghum in the world. Yet, Mexico needs to import large quantities because it is also one of the major consumers, ranking the 2nd in 2015 (FAO 2022) which relates to the supply of bovine production. The profitability of the livestock sector drives sorghum crop demand which needs large investments in machinery and hybrid seeds (Moctezuma 2019). Nevertheless, the profitability of this crop would decrease under climate change scenarios. Studies have suggested that different regions in the world would exhibit large yield reductions that range from 16 to 20% by the middle of the century (Sultan et al. 2014). These figures are close to our findings.

Soybean was the most affected crop in yield reductions in this study. According to FAO (2022), Mexico is the second country in domestic supply; however, it only produces ~9% of its demand. Such small production can be related to low national yields associated with rainfed management that is the most popular management system at the national level. Studies have reported decreases in soybean yields > 20%, but there are exceptions in cold areas where increases can be expected, particularly when the CO_2 effects are considered (Yin et al. 2015). The negative impacts and costs due to climate change on soybean and sorghum could be more likely afforded by farmers in comparison to other crops because these crops are feed for the bovine to produce meat which is more profitable than maize.

Sugarcane is the world's largest crop in stock (FAO 2022), and Mexico is the seventh producer, although its production depends on large areas under rainfed management with low yields. For instance, according to FAO (2022), Mexico ranks 36 in in yields. Considering the low yields and the constraints that climate change can impose in areas like Veracruz, we could expect a cropland expansion. Nevertheless, technology to improve yields can reduce costs of production (Aguilar-Rivera et al. 2012) and help to transition to mixed or irrigated management. This alternative can be another option to overcome the water stress that reduces plant productivity (Santillán-Fernández et al. 2016).

National programs to support agriculture have focused on the agroindustry, specifically in Sinaloa (Eakin et al. 2015). Even with the investments and technified agriculture in some northern states, Mexico relies on imports, especially from the USA. Mexico is dependent on the USA for wheat, rice, sorghum, and soybean in more than 50% of the domestic supply and > 37% in maize. These dependencies could increase, considering the consequences of climate change on these crops. For instance, only sugarcane could represent an opportunity in terms of production and exports. To overcome the impacts of climate change, Mexico needs to develop strategies to minimize the environmental impacts. Although it has been suggested to expand some of these croplands (Maldonado et al. 2010; Hernandez-Ochoa et al. 2019), we suggest that it is not the best option, on the basis that land-use change is the major driver of biodiversity loss in Mexico. Alternatives like agricultural intensification should be also carefully considered, as Eakin et al. (2015) pointed out, the intensification in Sinaloa cannot and should not be replicated elsewhere in Mexico for many reasons. Support and investment of many poor regions with rainfed agriculture in the south of the country would allow improving production. Moreover, the use of fertilizers as a national strategy is not enough nor sustainable to tackle the impacts of climate change in Mexico (Buechler 2009; Haro et al. 2021). These strategies should integrate the migration of crops and varieties under future conditions (Sloat et al. 2020) and impacts that these new conditions have on land-use changes (Ritchie et al. 2020). Crop migration and land-use planning can promote mitigation strategies to decrease the impacts of climate change, but this will depend on socio-economic and political factors in addition to land suitability and climate (Sloat et al. 2020).

This study highlights states of six important worldwide crops that will be more affected due to new climatic conditions. However, the results cannot be used to address strategies for farms or localities because this approach does not allow us to identify the impacts of climate change on municipalities or local areas where the adaptation strategies should be implemented. We encourage further studies should overcome some limitations of this work like (1) including relevant crops for Mexico as avocado and berries (Lagunes-Fortiz et al. 2020; Cho et al. 2021), (2) downscale results at the municipality level to prioritize geographical and political entities to address resources to implement specific strategies to alleviate impacts of climate change, and (3) assess the uncertainty of national crop data.

Conclusions

This paper provides a first step towards addressing the existing information gap about climate change's physical and economic impacts for Mexico's agricultural sector at the national and state levels. Our results show that climate change could significantly limit the agricultural production capacity of some relevant crops in Mexico and impose severe risks and impacts to an already vulnerable sector of its population. Mexico cannot fulfill the current demands of maize, rice, sorghum, soybean, and wheat. Consequently, it highly depends on the imports, especially from the US. This dependency will increase considering the impacts of climate change on these crops. Only sugarcane seems to represent a potential opportunity in production and exports under climate change. Moreover, the present value of the costs of climate change on the six analyzed crops would be about twice the total annual value of the country's agricultural sector. To overcome the negative consequences of climate change, Mexico needs to develop strategies to minimize the environmental impacts and to carefully analyze agricultural expansion or intensification options. Support and investment in regions based on rainfed management would help to promote mitigation and adaptation strategies to decrease the impacts of climate change. These strategies should integrate crop migration, varieties under future conditions, and land-use planning.

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