Agricultural Systems 177 (2020) 102697

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Maize yield in Mexico under climate change

Carolina Ureta[a,b,*], Edgar J. González[c], Alejandro Espinosa[d], Alejandro Trueba[e], Alma Piñeyro-Nelson[f,g], Elena R. Álvarez-Buylla[a,g,*]

[a] Departamento de Ecología Funcional, Instituto de Ecología, Universidad Nacional Autónoma de México, Mexico City, Mexico
[b] Departamento de Ciencias Atmosféricas, Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, Mexico City, Mexico
[c] Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México, Mexico City, Mexico
[d] Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias, Campo Experimental Valle de México (INIFAP, CEVAMEX), Km 13.5 Carretera Los Reyes – Texcoco, C.P. 56250, Coatlinchan, Texcoco, Estad de México, Mexico
[e] Dirección General de Educación Tecnológica Agropecuaria-SEP, Mexico City, Mexico
[f] Departamento de Producción Agrícola y Animal, Universidad Autónoma Metropolitana-Xochimilco, Mexico City, Mexico
[g] Centro de Ciencias de la Complejidad, Universidad Nacional Autónoma de México, Mexico City, Mexico

ARTICLE INFO

Keywords:
Climate change
Crop yields
Maize
Irrigation
Rainfed

ABSTRACT

Understanding the effects of climate change on maize yield in Mexico is important from both a national and international perspective. Maize is Mexico's staple food crop, thus, decrements in national production would strongly compromise food security in the country.

Internationally, maize is the most important grain crop in terms of human consumption and the conservation *in situ* of its germplasm should be a global priority. Mexico harbors half of the known genetic diversity for this crop in the American continent, which is instrumental for future genetic improvement efforts that could generate new, environmentally resilient varieties. In this study, we analyze the link between maize yield and several climate variables in rainfed and irrigated crop areas in Mexico to project yield variations under future climate change scenarios. We used municipality-level data for seven states that account for ~65% of the annual maize production in Mexico and cover an important amount of national climatic variability. We used public data published by the Mexican government on yield and climate from 2003 to 2015 and built linear models to assess the impact of climate on maize yield. We considered the municipality to be a random effect and accounted for potential autocorrelation in the 13-year time series. We also evaluated how many municipalities reached their states' breakeven point in order to project the geographic areas that will earn higher profits due to increased yields. Our results showed that the municipality had a significant effect on yield, and consequently, our results could not be extrapolated to other geographic areas in the country. We found temperature to be the most influential factor on yield under rainfed conditions, while precipitation was the most influential factor for irrigated crops. Like earlier studies at a global scale, we found higher yield stability for irrigated fields than for rainfed fields when considering different climate change scenarios. Our projections indicate that yields from rainfed fields will be reduced significantly under future scenarios. We argue that average yield data in rainfed fields does not include data on the diversity of native maize varieties or their potentially different responses to changes in the environment. Finally, under current conditions, there are by far more municipalities reaching their breakeven point in rainfed fields than in irrigated fields, suggesting that higher yields do not necessarily translate into greater profits for farmers because costs can also increase depending on the type of agriculture practiced.

1. Introduction

Climate change has become increasingly recognized as an important threat to agriculture (IPCC, 2014). Maize *(Zea mays L.)* is one of the most important crops in terms of production volume for direct and indirect human consumption around the world (Ranum et al., 2014), and negative impacts on its yield due to temperature increase and changes in precipitation patterns have already been detected (Cakir, 2004; Cicchino et al., 2010; Ray et al., 2015). In Mexico, maize's center of origin and diversification (domesticated ~8000 years ago; Matsuoka

* Corresponding authors at: Ciudad Universitaria, 04510, Instituto de Ecología, Mexico City, Mexico.
E-mail addresses: carolinaus@atmosfera.unam.mx (C. Ureta), eabuylla@gmail.com (E.R. Álvarez-Buylla).

https://doi.org/10.1016/j.agsy.2019.102697
Received 15 December 2018; Received in revised form 12 September 2019; Accepted 16 September 2019
Available online 17 October 2019
0308-521X/

et al., 2002; Vigouroux et al., 2008; Kato et al., 2009), this grain is the country's staple crop, thus, negative impacts on its yield could have important consequences for local, regional and global food security. Even when climate projections in Mexico are very heterogeneous in terms of precipitation depending on the geographic area evaluated, there is still a general tendency of temperature increase (Hijmans et al., 2005); and most studies dealing with possible climate change effects on Mexican maize have detected negative impacts (Conde et al., 1997, Mercer and Perales, 2010, Monterroso et al., 2011, Ureta et al., 2012, Ray et al., 2015, Ureta et al., 2016).

Despite corn being the staple crop in Mexico (representing over 50% of the caloric intake for the poorest sectors of the population; Bourges, 2013) and that Mexico is one of the top ten producers in the world (ASERCA, 2018), the country imports 34.12% of its maize; the second highest maize import rate in the world (FIRA, 2016). Over the past 10 years, average maize yield in Mexico has been 2.9 t/ha (SIAP, 2018), significantly lower than the world's average of 5.1 t/ha (2003–2014; FAO, 2017). If yield increases, Mexico could be self-sufficient in its maize requirements, but climate change could be an impediment (Conde et al., 1997; Mercer and Perales, 2010; Monterroso et al., 2011; Ureta et al., 2012; Ray et al., 2015; Ureta et al., 2016). A deficit in maize production in Mexico could have additional negative implications, as it is culturally and culinarily important for a large part of its population (Florescano, 2003; Fernández Suárez et al., 2013).

From a global perspective, Mexico represents one of the greatest reservoirs of maize genetic diversity, harboring approximately 50% of known genetic diversity for the American continent (Vigouroux et al., 2008). In Mexico, most maize is cultivated on rainfed fields by farmers on plots smaller than 5 ha; some of these farmers still grow maize in a traditional agroecosystem called *milpa* in which several species are being grown simultaneously (Mercer et al., 2012). These farmers are the ones preserving maize diversity *in situ* and it should be made possible for them to attain enough yield from native maize varieties. However, during the last three decades changes in temperature and precipitation have made maize yield in Mexico one of the most variable in the world (Ray et al., 2015), consequently, it is important to better understand the relationship between maize yield and changes in different climate variables so that more accurate projections of yield are available to policy makers.

Previous studies that have investigated the impacts of climate change on maize in Mexico have focused on shifts in the suitability of geographic areas by projecting the plants' climate threshold (Conde et al., 1997; Monterroso et al., 2011) or have focused on the impact of changes in climatic variables on specific native races (Ureta et al., 2012) or varieties (Mercer and Perales, 2010). The concept of "races" was coined in the 1940s and corresponds to a unit of analysis that has been very useful to organize and study maize diversity in Mexico (Anderson and Cutler, 1942). Races have been defined as "a group of related individuals with enough characteristics in common to permit their recognition as a group" (Anderson and Cutler, 1942); they share phenological, morphological and to an extent, agroecological similarities. Thus, a race comprises several varieties or landraces. Ureta et al. (2012) projected the potential distribution area of all Mexican races of maize and their wild relatives that had enough information to be projected under different climate change scenarios through ecological niche modeling to evaluate the potential impacts in their geographic distribution. They found that the potential distribution area of most races was negatively impacted by climate change. Work by Mercer and Perales (2010) discussed the role of phenotypic plasticity, evolution and gene flow in maintaining productivity in specific landraces (native varieties). They found that when grown at mid-elevations, the productivity of highland varieties strongly decreased. The main focus of Mercer and Perales (2010) was to analyze the plant's ecological strategies to reduce the impacts of climate change impacts, and both studies (Ureta et al., 2012; Mercer and Perales, 2010) focused more on analyzing climate thresholds, distribution and adaptation possibilities than on yield.

Two approaches have been used to explicitly evaluate possible impacts of climate change on maize production in Mexico (Conde et al., 1997; Ureta et al., 2016; Eakin et al., 2018): a CERES-maize approach and an ecological niche modeling approach. Conde et al. (1997) applied the former by using seven locations to create CERES-maize models (Jones and Kiniry, 1986) in rainfed fields only. This kind of modeling is site-specific and does not allow extrapolations, and therefore cannot be used to project future yields beyond the field studied. They found that six out of seven sites presented negative impacts on yield from climate change, but they also recognized that their approach lacked some data necessary for a thorough and accurate model (Conde et al., 1997).

The study performed by Ureta et al. (2016) used the ecological niche-centroid theory (Maguire Jr, 1973; Martínez-Meyer et al., 2013) to project yield changes under climate change for nine native races. They considered it was important to recognize that the niche centroid can be related to higher yield values when evaluating individual races (Ureta et al., 2016). Their projections indicate that under climate change, the evaluated races would have higher yields in geographic regions different from where they are currently being sown.

Another recent study related seven climate variables with maize yield in Mexico using data from 1980 to 2000 to calibrate their model (Eakin et al., 2018). However, the model was created at a state scale, which is quite a coarse measure considering the heterogeneity in maize yield inside any one state. Furthermore, even when their study gives some insight pertaining to fluctuations in yield under different climatic conditions, they did not project potential impacts on yield under future climate change scenarios.

Thus, to date, available studies evaluating climate change impacts on maize yield in Mexico have been site or race-specific or focused only on identifying whether a relationship between climate and yield had existed during the last decades of the twentieth century. Consequently, there is a need for a study focused on evaluating the impacts of climate change on Mexican maize yield at a broader scale, additionally comparing irrigated and rainfed fields.

Yields from rainfed and irrigated fields are expected to be affected by climate change; however, rainfed fields might be more susceptible because of their dependence on precipitation (SAGARPA a, 2016). In this study we analyzed the link between maize yield and climate variables for both rainfed and irrigated fields at a municipality level in seven out of the 32 Mexican states. The states analyzed were selected because they account for ~65% of maize production in the country and together encompass an important amount of climatic variability (Trueba, 2012), representing five different Mexican regions proposed by the Mexican ministry of agriculture (SADER, 2019). We also considered information about breakeven points (UNISEM, 2017) in irrigated and rainfed fields under current and future climate change conditions with the purpose of evaluating if higher yields directly translate into greater profits (low input *vs.* high input agriculture; FIRA, 2007).

2. Materials and methods

2.1. Modeling data

Yield data were obtained from the Mexican government database (SIAP, 2018). These data were recorded for each municipality between 2003 and 2015 and divided into rainfed (4442 data points) and irrigated (2240) fields. We used yield data from the following states, encompassing around 400 municipalities: Sinaloa, Tamaulipas, Guanajuato, Jalisco, Michoacán, México and Chiapas (Fig. 1). Yield data used here were originally recorded without reporting maize variety or race (Appendix A) due to a lack of detailed information in the SIAP database; still, these data are very useful to gain insight of future yield fluctuations in different areas of the country. Observed data showed that rainfed areas with greater yields were found in Jalisco and Michoacán, followed by Estado de México. Other states evaluated presented

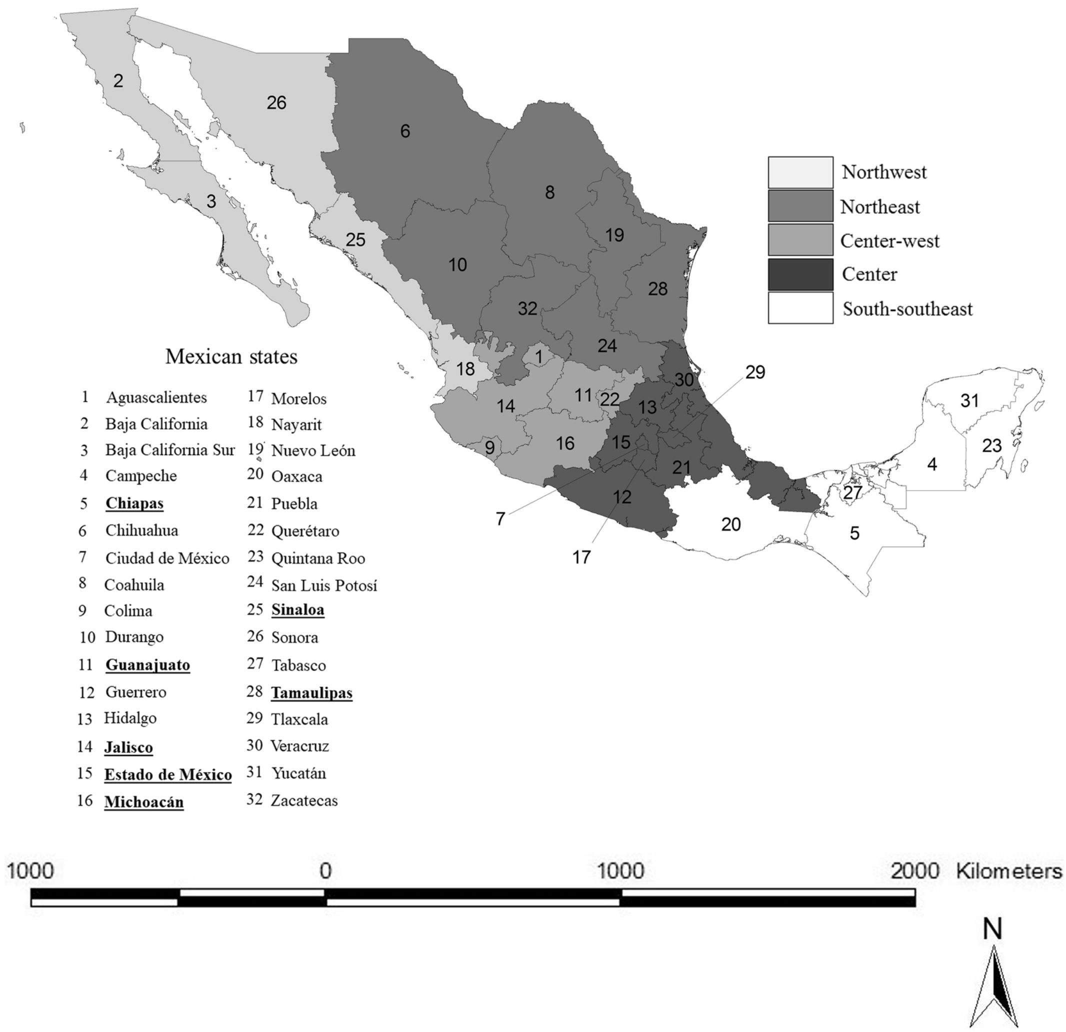

Fig. 1. Regionalization of the country. The ministry of agriculture of the Mexican government regionalized the territory in order to apply different agricultural policies depending on several characteristics of the geographic area including climatic features. In the map is possible to identify every state's name and the region to which it belongs. The states that were taken into account for this study have been highlighted in the states list.

average yields < 2 t/ha (Fig. 2). In irrigated fields, greater average yields were found in Sinaloa, Guanajuato and Jalisco (Fig. 3). Interestingly, Jalisco has greater yields under both agricultural systems: rainfed and irrigated.

We requested the climate data recorded by local meteorological stations from the Mexican Meteorological Service (SMN, 2017) for 2003–2015. With this information, we created the 19 bioclimatic variables most commonly used for ecological niche modeling to reflect annual trends, limiting conditions and seasonality (Nix, 1986; Hijmans et al., 2005). We discarded nine of these variables due to strong correlations ($r \geq 0.85$) with the geographic area from our projections. Less collinearity between predicted variables increases extrapolation performance (Steen et al., 2017). The 10 climate variables considered to build the models were: annual mean temperature, maximum temperature of the warmest month, minimum temperature of the coldest month, temperature annual range, mean temperature of the driest quarter, mean temperature of the warmest quarter, mean temperature of the coldest quarter, annual precipitation, precipitation of the driest month and precipitation of the driest quarter.

In the evaluated states, the precipitation and temperature observed during the thirteen years studied was very different depending on the geographic area. For example, Chiapas has an average annual precipitation of 2069 mm in rainfed areas, while Sinaloa only reaches 739 mm. In terms of mean annual temperature, differences are also very broad between states. In rainfed areas, Sinaloa has a mean annual temperature above 25 °C, while Estado de México is below the 16 °C. Similarly, in irrigated areas, differences among states in terms of precipitation and temperature were also documented. Irrigated areas in Chiapas have average annual precipitations around 1400 mm, while the lowest annual precipitation was found in Guanajuato with 614 mm. This information suggests that maize is being grown under very different environmental conditions and that higher yields do not necessarily coincide with higher precipitations or warmer temperatures as it could be expected (Khan et al., 2001; Sánchez et al., 2014).

2.2. Predicting yield under current and future climate conditions

We related (log-transformed) yield data to climate through linear-mixed models (LMMs). We considered the municipality as a random effect and accounted for potential autocorrelation in the 13-year time series through an autoregressive process of order 1. In comparison to regular linear models that only have fixed effects, LMMs allow controlling possible sources of variability coming from unmeasured characteristics. In our study, LMMs helped estimate the variability between and within municipalities and integrate it into the calculation of model parameters. We used municipalities as a random effect because each municipality presents characteristics that makes it different from others.

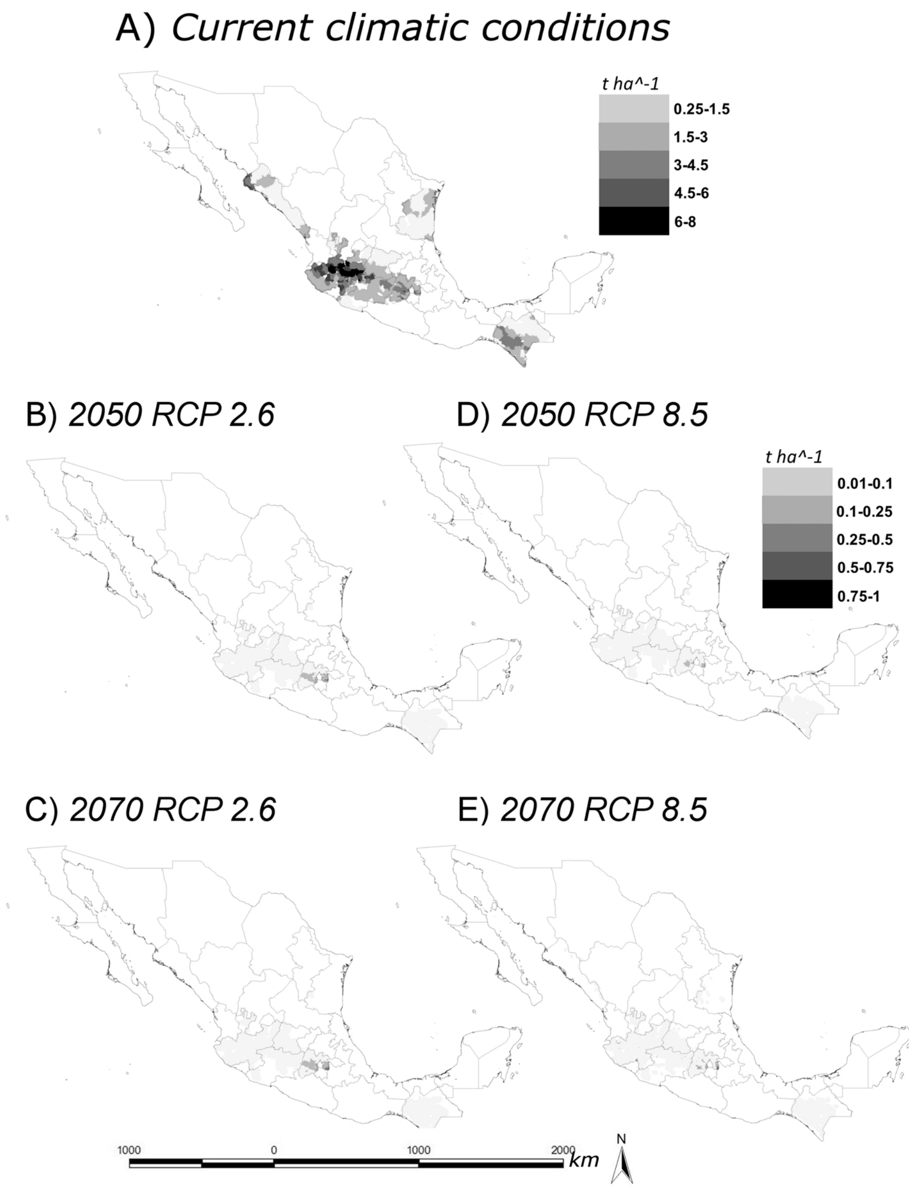

Fig. 2. Current and future yield under rainfed growing conditions. This figure shows five maps of Mexico (A, B, C, D and F) that represent different climate scenarios. Seven states were evaluated: Chiapas, Estado de México, Michoacán, Guanajuato, Jalisco, Sinaloa and Tamaulipas. Modeled yield data coming from rainfed fields are represented with a gray scale; a darker hue of gray indicates a higher yield value.

We excluded zero yield values because we could not determine if such values were related to the total loss of harvest, a decision not to cultivate in that municipality, or a lack of recorded data. We generated all possible linear models combining up to 10 bioclimatic variables, building a total of 1023 models for each agricultural condition (rainfed and irrigated). Model selection was performed with the sample corrected Akaike information criterion (AICc, see Appendix B; Burnham and Anderson, 2002). When compared with the best model, a model having a ΔAICc value < 2 (Burnham and Anderson, 2002) was considered to have a descriptive power like the best one. We then calculated the conditional and marginal R^2 (R^2_c and R^2_m; Nakagawa and Schielzeth, 2013) for each model to evaluate its goodness of fit with and without including the municipality random effect, respectively.

To project yield in the studied municipalities under future climatic conditions, we used the best-supported model and a 5-km^2 climatology from Worldclim (Hijmans et al., 2005) with three different general circulation models: HADGEM2-ES, GFDL-CM3 and MPI-ESM-LR (IPCC, 2014). The performance of these general circulation models has been evaluated, and they are considered to be the best models for reproducing climate in Mexico (Conde and Gay, 2008). Projections were made under two out of four different climate pathways proposed by the IPCC (IPCC, 2014): +2.6 and +8.5 W/m^2. These pathways or representative concentration pathways (RCPs) represent scenarios of different greenhouse gas concentrations in the atmosphere that relate to differences in the solar energy being absorbed by the planet and the energy radiated back to space. The two chosen pathways represent the best- and worst-case scenarios. These scenarios were projected under two temporal horizons: 2041–2060 and 2061–2080. With the best yield model for each agricultural method, we wanted to project yield for each municipality under current and future conditions, and depending on R^2 values, the projected yield in the entire country.

Future predicted yields for each general circulation model were averaged to produce ensemble results. Modeling ensembles have been used as an alternative to deal with uncertainty coming from different climate change models (Araújo and New, 2007). Alternatives to mitigate uncertainty coming from general circulation models are very important because it is one of the main sources of uncertainty in climate change studies (Steen et al., 2017). Finally, we also decided to use the

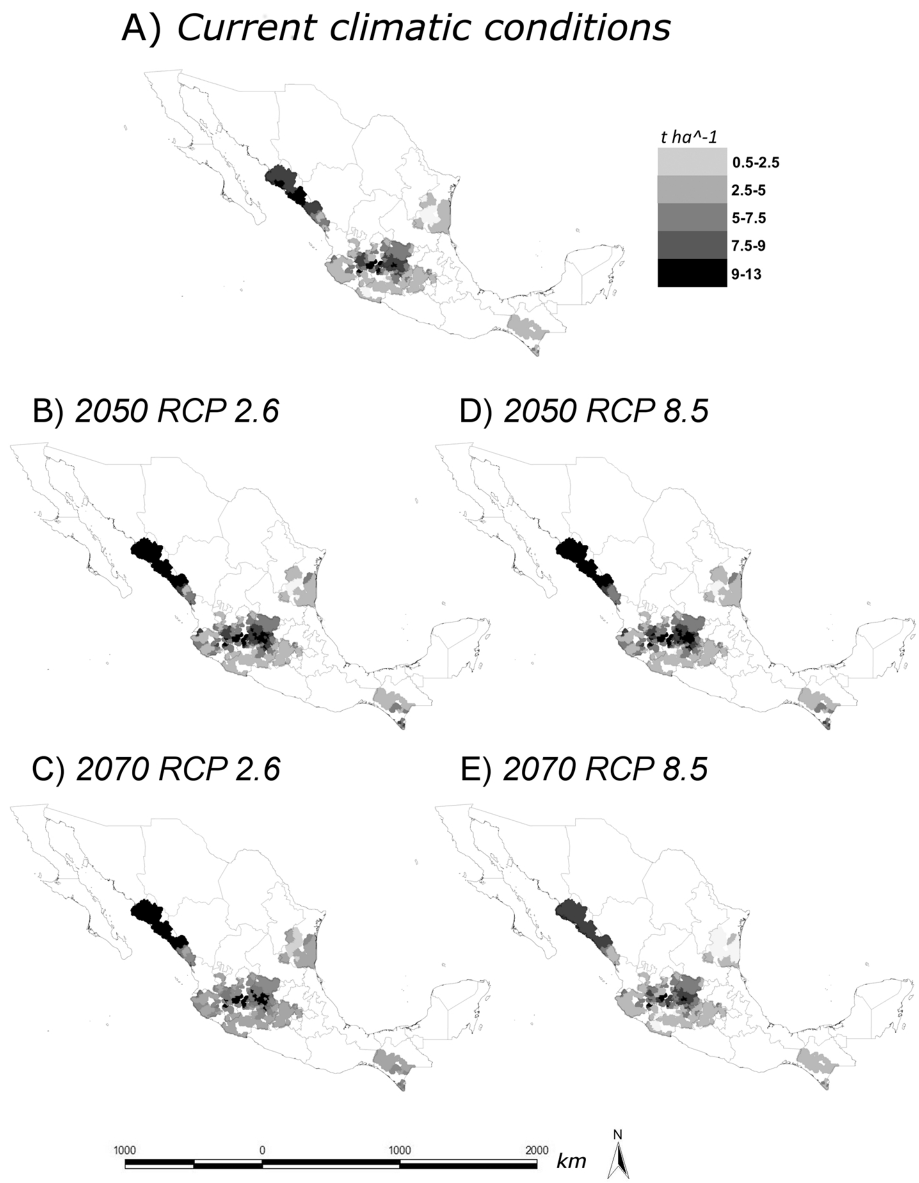

Fig. 3. Current and future yield distribution with irrigation. This figure shows five maps of Mexico (A, B, C, D and F) that represent different climate scenarios. Seven states were evaluated: Chiapas, Estado de México, Michoacán, Guanajuato, Jalisco, Sinaloa and Tamaulipas. Modeled yield data coming from irrigation fields are represented with a gray scale; a darker hue of gray indicates a higher yield value.

ExDet tool (Mesgaran et al., 2014) to evaluate range change under the future scenarios considered for the bioclimatic variables we used. ExDet facilitates the visualization of geographic areas where future changes are expected to be greater and where extrapolation might be troublesome because climate ranges change or variables are combined in different ways (Mesgaran et al., 2014).

2.3. Analyzing the breakeven point under current and future conditions

Once we had the modeled yields projected onto the geography under current and future climate conditions, we tried to localize geographic regions reaching their breakeven point (when costs equal profits). With this analysis, it was possible to have an idea of which geographic areas are economically viable in terms of production under the two agricultural conditions investigated here: irrigated and rainfed. For irrigation we used two breakeven points: The first is a specific yield value for each state based on studies carried out by FIRA (2007) (Chiapas ~ 5 t/ha, Guanajuato ~ 7 t/ha, Jalisco ~ 6 t/ha, Michoacán ~ 6 t/ha, Sinaloa ~8.5 t/ha and Tamaulipas ~ 5 t/ha), and the second is the average breakeven points of all states evaluated (6.2 5 t/ha). In irrigated fields, breakeven points varied significantly among states because of different variables such as: water costs, field lease (a fraction of farmers are not landowners) and farm-worker salaries.

For rainfed fields we used a 2-t/ha yield as the breakeven point. Rainfed fields are commonly grown by small-hold farmers (< 5 ha) who own their land and have lower investment inputs. A previous study estimated 3 t/ha as the breakeven point for rainfed growing conditions, considering the cost of using hybrid seeds (UNISEM, 2017); nevertheless, most rainfed fields are cultivated using native races that reproduce their own seeds (Trueba, 2012). Given that no single specific breakeven point has been suggested for rainfed fields, we carried out a sensibility analysis beginning with 1 t/ha and finishing with 4 t/ha, getting an idea of the percentage of municipalities that reached a yield category in a particular year. The model was created with observed data at the municipality level. Afterwards, we used observed data and projected yields under future climatic conditions to calculate the number of municipalities that reach their breakeven point under rainfed and irrigated conditions.

3. Results and discussion

3.1. Yield best models

After model selection, we obtained one best model for irrigated and one best model for rainfed conditions. In both cases, all other competing models had ΔAICc values > 2. We calculated two R^2 values: the conditional (R_c^2), which takes into account the random effect of the municipality factor, and the marginal (R_m^2), which does not. For the best irrigation model, large differences between these two determination coefficients existed, with $R_c^2 = 0.775$ and $R_m^2 = 0.001$. Similarly, for the rainfed maize model, we obtained an $R_c^2 = 0.729$ and an $R_m^2 = 0.023$. Even when the states under study were chosen in order to encompass enough climate variability to potentially allow us to extrapolate our results to the entire Mexican territory, the municipality identity had such a large effect on yield that the extrapolation could not be performed. It is likely that other environmental and social factors associated with the municipality's location have important effects on yield. As it has been documented in other studies (Mercer and Perales, 2010; Ureta et al., 2013), maize cultivation and distribution in Mexico is also related to environmental factors, such as soil type (fertility, organic matter, slope, texture and deepness) and altitude (Turrent Fernández et al., 1997), which we did not integrate into our model because we wanted to evaluate the effect of climate change in particular. Additionally, given the average nature of our yield data, recorded at the municipality level, incorporating other factors, such as soil type and altitude into our model would require adding assumptions because several types of soil and different altitudes can be found in one single municipality. The municipality is also related to social factors, such as ethnic group or socioeconomic level that can affect maize distribution and yield (Mercer and Perales, 2010; Ureta et al., 2013). Still, there is evidence that supports that climate variables have an influence on yield (Wilson, 1987; Grant et al., 1989; Ray et al., 2015; Ureta et al., 2016). Even without spatial extrapolation, the seven states under study included hundreds of municipalities that in conjunction are very important for Mexico in terms of overall production and conservation of the diversity of maize (Trueba, 2012; SIAP, 2018). Given that the climatology used for future climatic conditions is a 5-km cell map, we averaged the values for each bioclimatic variable, taking into account the number of cells that are included in every municipality.

Results evaluating whether the range of climate variables changed over time show that the states studied will not present important range changes (Appendix C). From the climate variables included in our models, only two showed changes in their range under future conditions: maximum temperature of warmest month and mean temperature of warmest quarter. The areas where these changes are expected to occur are not widely distributed in the states evaluated (Appendix C) consequently, uncertainties derived from time extrapolation in our results were not important.

3.2. Yield changes in rainfed fields under current and future conditions

In the following model we show that in rainfed fields, temperature, not precipitation, is by far the most important variable affecting yield:

$$y = 1.20538 + 0.0001 \cdot x_1 - 0.0005 \cdot x_2 - 0.02301 \cdot x_3 + 0.00411 \cdot x_4 + 0.00139 \cdot x_5 \quad (1)$$

where y is the log-transformed yield, x_1 is the precipitation of the driest month, x_2 is the mean temperature of the coldest quarter, x_3 is the mean temperature of the warmest quarter, x_4 is the minimum temperature of the coldest month and x_5 is the maximum temperature of the warmest month. As shown by our model, the warmer it gets during the year, the lower the yields are in the rainfed fields. Conversely, yield increased with more precipitation and less extreme colds, but the more influential variable was mean temperature increases in the warmest and coldest quarters of the year. The important impact that warmer temperatures have on crop yields is in accordance with a recently published work by Tigchelaar et al. (2018), where decreased corn yields were reported worldwide due to higher temperatures derived from climate change. At a local scale, there are also studies showing how landraces from higher altitudes (colder temperatures) have more difficulties being grown in lowlands than the other way around (Mercer and Perales, 2010, 2018); meaning that it might be more difficult to adapt to warmer conditions.

Our study contradicts what was found by Eakin et al. (2018), who found that temperature did not play an important role in rainfed yields. However, in their study, they failed to consider that during the period they analyzed (the 1990s), there was an important reduction in the rate of temperature increase, thought to be a result of the implementation of the Montreal Protocol (diminishing the use of ozone-depleting substances) and due to changes in agricultural practices in Asia (translated into a reduction in methane emissions) (Estrada et al., 2013); obscuring temperature's role on yield fluctuations.

Higher temperatures at specific plant stages can be very detrimental for their development and consequently negatively impact yield (Lobell et al., 2011; Sánchez et al., 2014). For example, flowering and grain-filling stages are very heat sensitive in maize and sterility increases with higher temperatures (Sánchez et al., 2014). There is a temperature optimum beyond which yield decreases dramatically. In maize, the optimum temperatures for most of its developmental phases range between 26 and 32 °C (Sánchez et al., 2014). However, Mexican native maize races show an important amount of optimum climate conditions (Ureta et al., 2012, 2016) and thresholds (Ureta et al., 2012). For example, the races Ancho, Blando de Sonora, Bofo, Chapalote, Conejo, Elotero de Sinaloa, Olotillo, Pepitilla, Reventador, Tabloncillo, Tabloncillo Perla, Tuxpeño and Vandeño have maximum temperature thresholds that go up to 40 °C (Ureta et al., 2012). These climatic thresholds were obtained by overlapping geographic records with temperature layers. Although this is an indirect approach (in comparison to direct physiological studies) of the plant's heat tolerance, these thresholds can still provide some insight because they help document the maximum temperature of a site where a given race has been grown. As an adaptation strategy to climate change, it would be important to focus attention on the native races listed above because they have been grown under thermal stress and seem to survive it relatively well, thus, they could be an additional basis for genetic improvement focused on heat tolerance (Bellon et al., 2003; Smale et al., 2003). In this line of thought, the maintenance of genetic diversity of maize and its local adaptation through a continuous evolutionary process in the field is of paramount importance for its adaptation to future climate conditions (Mercer et al., 2012; Bellon et al., 2018). Consequently, the dynamic *in situ* preservation of the diversity of maize by small-hold farms is an evolutionary service that should be rewarded (Bellon et al., 2018). Alternatively, the incorporation of irrigation in specific areas could be considered because it has been observed that irrigation reduces the negative impacts of temperature changes (Butler and Huybers, 2013). This last strategy could nevertheless be unfeasible for most Mexican fields because of future threats to our water supply (Kotschi, 2007).

Another explanation for rainfed areas being more influenced by temperature than by precipitation, particularly in Mexico, is that rainfed fields are commonly located in places that are suitable for maize growth (Montesillo-Cedillo, 2016). Consequently, although some native maize races are able to give good yield in areas with low precipitation (Bellon et al., 2003; Smale et al., 2003), in most of these fields, precipitation is not necessarily scarce if we consider that the mean annual precipitation average is of 1160 mm (SMN, 2017). In these rainfed areas, the average precipitation is 23 mm and 118 mm for the driest month (depending on the geographic area) and the dry quarter of the year (three months), respectively. Consequently, most of the rain falls during the rainy season, when maize is being grown. Of course, this situation does not necessarily mean that dry spells do not occur (Mendoza et al., 2006; Méndez and Magaña, 2010), and droughts are expected to become more intense under climate change conditions

(Mendoza et al., 2006). Another possible explanation to the more deleterious effects on yield of temperature rather than precipitation could be that higher temperatures increase rates of evapotranspiration both from the crop and from the substrate, increasing photosynthetic stress and removing moisture from the soil (Taiz and Zeiger, 2006), as well as potentially affecting the most sensitive stages in maize: flowering (Bellon, 1991).

The fact that reductions in yield in rainfed fields were strongly related to temperature increases reveals their vulnerability to climate change (there is a strong consensus about temperature increases among general circulation models; IPCC, 2014). As shown in Fig. 2, under current climate conditions, the highest yield category for rainfed agriculture goes from 6 to 8 t/ha, while the highest yield category in the future decreases substantially to 0.75–1 t/ha. Under current climate conditions, the highest yields are visible in rainfed areas in Jalisco, but under future climatic conditions most of the rainfed territory is predicted to have an average yield of 0.25 to 0.5 t/ha.

It is also important to bear in mind that our dramatic results under different climate change scenarios do not take into account the important role that diversity in general and particularly maize agrobiodiversity has on adapting to a changing environment, while also not considering the dynamic management of native maize races by farmers who exert an ongoing selection pressure for plants that will produce seed under even the most stressful conditions (Bellon et al., 2018). For example, Smale et al. (2003) found that the race Bolita was being grown in Oaxaca because of its resistance to the *canicula* (a period of extreme warm weather in the middle of the rainy season; Smale et al., 2003). There are also other native races adapted to hydric stress, such as Chapalote, Dulcillo del Noroeste, Gordo, Tablilla de Ocho, Cónico Norteño and Tuxpeño Norteño (Ruiz Corral et al., 2008 and Ruiz Corral et al., 2013). The length of life cycle is another characteristic to consider because varieties with shorter life cycles fulfill their development in a shorter period of time and growing them once the rainy season has started represents a strategy that has been applied by peasants in Mexico to attain a harvest even when the rainy season starts late (Munguía-Aldama et al., 2015). Also, short life cycles increase the probability of finishing the setting of seed before or shortly after the canicular period and avoiding heat stress during flowering (Bellon, 1991). This strategy has already been selected upon and is common in native races, such as Apachito and Nal-Tel, while other races have very long-life cycles, such as Tehua, Jala, Tuxpeño and Chalqueño (Ortega Paczka, 2007). Additionally, it is important to stress that native races are also being grown because of their better grain quality and lower susceptibility to pests in the field and under storage (Trueba, 2012), as well as their capacity to grow well in places where improved modern varieties do not fare well.

Most rainfed fields are cultivated by small-hold farmers (with < 5 ha, producing 1.6–2 t/ha) who primarily use native races (Cruz Delgado et al., 2012; Perales and Golicher, 2014); these varieties contain the majority of the genetic diversity recorded for maize (Vigouroux et al., 2008). The great adaptive capacity of these races is obscured by a lack of detail on the municipality data, where only average yield but not maize type or race used is reported (SIAP, 2018). Furthermore, during the last three decades of anthropogenic-induced climate change, small-hold, rainfed areas have shown to be resilient in terms of maize cultivation and production (Eakin et al., 2018). Consequently, the human factor plays a very important role in maize production's resilience, as it is being shown not only by small farmers facing climate change, but also by large-scale producers who report high yields despite cultivating land which is not highly suitable from a climatic standpoint (Eakin et al., 2018). It should be noted, however, that large-scale producers are at a great economic and technical advantage over small-hold farms because the large-scale producers get the majority of direct and indirect subsidies for maize production in Mexico (Eakin et al., 2018).

3.3. Yields in irrigated fields under current and future conditions

Irrigated fields show greater yield stability than rainfed fields under different climate conditions, but they can be affected by specific climatic variables (their best model depended only on two climate variables instead of the five variables considered for rainfed fields). Surprisingly, precipitation had greater influence on their yield than temperature:

$$y = 1.5218 + 0.00134 \cdot x_1 - 0.00018 \cdot x_2 \tag{2}$$

where y is the log-transformed yield, x_1 is the precipitation of the driest month and x_2 is the minimum temperature of the coldest month. Thus, both precipitation and temperature influence maize yield even when there is access to irrigation. The more it rains during the driest month of the year, the more they can yield. We also found a negative correlation between yield and the minimum temperature of the coldest month. A possible explanation for this result is that water coming from irrigation helps diminish negative impacts from extreme temperatures (cold and hot) (personal observations).

The dependence of irrigated fields on precipitation could be explained by the fact that irrigation was first implemented in Mexico as a way to expand the agricultural frontiers in arid and semiarid areas (Montesillo-Cedillo, 2016). That is why even when this activity is consuming around 75% of the country's water (CONAGUA, 2014), these fields still require precipitation. Furthermore, with the exception of a few municipalities, irrigation in the country is inefficient (Vélez and Saez, 2012). Fields irrigated with more water produce higher yields across the country. As a result, federal resources, such as subsidies for water and its transport, are targeted toward farmers with the capacity to irrigate (Huacuja, 2015).

Our geographic projections show that the highest yield category (9–13 t/ha) under irrigation was widely distributed in Sinaloa and it would actually increase under predicted climate conditions (Fig. 1). However, yields do not increase in the same way in all scenarios or at all time-scales. Yield in 2050 scenarios show increases in Sinaloa, Jalisco, Guanajuato and even Tamaulipas and Chiapas. These increments are reduced by the year 2070 under the RCP 8.5 W/m^2 scenario. The variable precipitation of the driest month, which was the most influential for yield in irrigated fields, is expected to increase in the area evaluated under future climate conditions (Hijmans et al., 2005). The lowest value in the future is expected for the year 2070 RCP 8.5 W/m^2 scenario, as are the lower yield values.

Our results in irrigated fields are in line with what has been found globally: more intensively managed fields are less susceptible to climate change (Tigchelaar et al., 2018). This apparent stability could be related to the fact that climate scenarios represent average climate conditions in the future, akin to a photograph of the future (IPCC, 2014) that does not account for climate variability. Nevertheless, variability is expected to increase and in a more variable world, genetic diversity will be indispensable (Kotschi, 2007; Visser, 2008) not only for adaptation to changes in climate but also to withstand other factors derived from climate change, like new potential pests (Rosenzweig et al., 2001; Lamichhane et al., 2015). Under these circumstances, monocultures of genetically homogenous plants, even with irrigation, become vulnerable to any change in their environment. We agree that greater and improved technology, such as the use of irrigation, machinery and fertilizers increases adaptive capacity (Chhetri et al., 2012); this is evident from our results showing a lesser impact on yield from climate change in irrigated fields. However, we argue that under a variable world undergoing rapid change, agrobiodiversity will be as important, if not more important, than technology (Conde et al., 1997; Kotschi, 2007; Visser, 2008). In irrigated areas, the genetic diversity of hybrid and improved varieties could also be incremented. Nowadays, there are > 300 hybrid maize varieties in the Mexican market, but very few are being grown everywhere (Trueba, 2012). The great importance of biodiversity in a changing world has not been sufficiently stressed in

Table 1
Sensibility analysis for rainfed municipalities reaching different possible breakeven points.

Yield (t/ha)	Evaluated municipalities reaching the breakeven point (%)
> 1	97
> 1.5	92
> 2	82
> 2.5	72
> 3	39
> 3.5	49
> 4	36

Evaluated area reaching the breakeven point: The percentage of area (5 km) that could reach the breakeven point under current climatic conditions in rainfed areas.

global studies addressing possible climate change impacts on crops (Ray et al., 2015; Tigchelaar et al., 2018). Unfortunately, given the nature of our yield data, the importance of agrobiodiversity has been obscured and could not be integrated, but it remains a central subject in a changing world.

3.4. Reaching the breakeven point under current and future conditions

Although rainfed maize fields yield less, a higher percentage of the municipalities growing maize this way is able to reach their breakeven point compared with those using irrigated fields (see Tables 1 and 2). Given that there is an estimate of 3 t/ha counting hybrid seeds' cost for rainfed fields (UNISEM, 2017), a 2 t/ha could be expected because most rainfed farmers use native races and produce their own seeds. At a breakeven point of 2 t/ha, 82% of the municipalities evaluated reached it. If cost reduction is further considered due to a minor use of fertilizers and pesticides, a 1 t/ha could be a breakeven point that 97% of municipalities analyzed could reach (Table 1). Practices such as seed selection after each cultivation cycle, seed exchange and local selection efforts, not only help maintain the genetic diversity of maize *in situ* (Mercer and Perales, 2010), but they also make it more profitable to produce in this way (Fig. 4, Table 1). In addition, rainfed fields do not have the cost demands associated with the electricity and fuel costs required to pump water for irrigation. Thus, policies and management need to take into account the considerable contribution made by farmers who use rainfed fields (Mercer et al., 2012).

Table 2
Geographic area reaching the breakeven point under current and future climatic conditions.

% Area above break-even point				
Current	RCP 2.6		RCP 8.5	
	2050	2070	2050	2070
Irrigation				
30	37	37	37	38
Irrigation average				
30	34	36	36	37
Rainfed				
82	0	0	0	0

RCP 2.6: best case climate change scenario, RCP 8.5: worst case climate change scenario, 2050: 2050 scenario (2041–2060), 2070: 2070 scenario (2061–2080). Breakeven point: yield at which costs and profit are in equilibrium. Irrigation: maize grown under irrigation. Each evaluated state had its own breakeven point, as suggested by several studies carried out by FIRA in different regions of the country (2017) (Chiapas = 5 t/ha, Guanajuato = 7 t/ha, Jalisco = 6 t/ha, Michoacán = 6 t/ha, Sinaloa = 8.5 t/ha, Tamaulipas = 5 t/ha and Estado de México = 6 t/ha. Irrigation Average: Percentage of area reaching the average yield from studied cities that was 6.2 t/ha.

The estimated breakeven points in irrigated fields of the states evaluated here are: Chiapas ~ 5 t/ha, Guanajuato ~ 7 t/ha, Jalisco ~ 6 t/ha, Michoacán ~ 6 t/ha, Sinaloa ~8.5 t/ha and Tamaulipas ~ 5 t/ha (FIRA, 2007). Estado de México was the only state that did not have a specific breakeven point reported, thus we used the average of the other states' breakeven points (6 t/ha) as a proxy. The second threshold we used for all evaluated states was the average yield for the seven states: 6.2 t/ha. In irrigated fields, farmers are barely producing enough maize under current conditions to cover production costs (Trueba, 2012). Under current climate conditions, only 30% of the municipalities evaluated that have irrigation systems reached their specific states' breakeven point (Fig. 4) or the averaged breakeven point (6.2 t/ha). States such as Sinaloa—the one with the highest yields in the country—did not reach its own breakeven point (8.5 t/ha) in a large number of its fields (Fig. 4). Meanwhile, in other high yield states, like Jalisco and Guanajuato, the breakeven point is only attained in less than half of the municipalities surveyed. If we consider the averaged breakeven point (6.2 t/ha) as reference for comparison, a larger geographic area would achieve breakeven status. Nevertheless, we found that in some states, such as Chiapas, Estado de México and Tamaulipas, it is not profitable to grow maize under irrigation in either current or future climatic conditions (Table 2).

Our results show that irrigated fields have much higher yields than rainfed fields, but irrigated maize production is not economically viable in 70% of the studied municipalities (Fig. 4). This is because despite the higher yield of irrigated plots, production costs consume most of the profit, making subsidies indispensable for agriculture under irrigation (Huacuja, 2015). These results suggest that both subsidizing and giving technical support to improve agricultural practices in rainfed maize fields could be a more strategic way of attaining food security at a lower economic cost, while simultaneously promoting the active conservation of maize agrobiodiversity. In line with our results, a study carried out by Guzmán Soria et al. (2014) showed that maize production in Guanajuato under irrigation is not competitive because even when yields increase in 50% in comparison to rainfed fields, costs increase by 65%.

Thus, it is currently too expensive to cultivate maize in the way Mexican farmers are doing it under intensified, irrigated monocultures (Guzmán Soria et al., 2014). Under future climatic conditions, the cost-benefit relationship is projected to worsen. A way to start reducing costs would be to avoid buying seed every year. In the short term, farmers would probably have reduced yield due to segregation of characters in hybrids (Reyes, 1990), but it would still be economically convenient due to cost reductions. Currently, 92% of commercial seed used in high production states in Mexico is commercialized by large corporations whose prices are unregulated (Trueba, 2012), translating into having one of the highest prices for maize hybrid seeds worldwide (Espinosa et al., 2003). Under climate change conditions, there will be unprecedented volatility in maize prices (Tigchelaar et al., 2018) and consequently on maize seeds. This situation strongly suggests that Mexico should not depend on imports for staple crops, which are now above 30% of what is being consumed in the country (SAGARPAb, 2016). It is time for farmers to start saving their own seeds and for the Mexican government to enhance the development of national hybrids and other improved varieties, stimulate national hybrid production, and provide farmers with seed supply options. There should also be guidance for proper management in terms of pesticides and fertilizers (Lechenet et al., 2014), which could also reduce costs. It would be very helpful for farmers to have specific production guidance for each geographic area in order to be more efficient (Trueba, 2012), including knowing which kind of improved seeds can be grown at each location. With this kind of support, hybrid diversity and local selection and improvement efforts could also be increased. Additionally, other strategies of genetic improvement have focused on generating open pollinated varieties rather than hybrids, which are inherently unstable in subsequent generations. This approach should be actively promoted and financed.

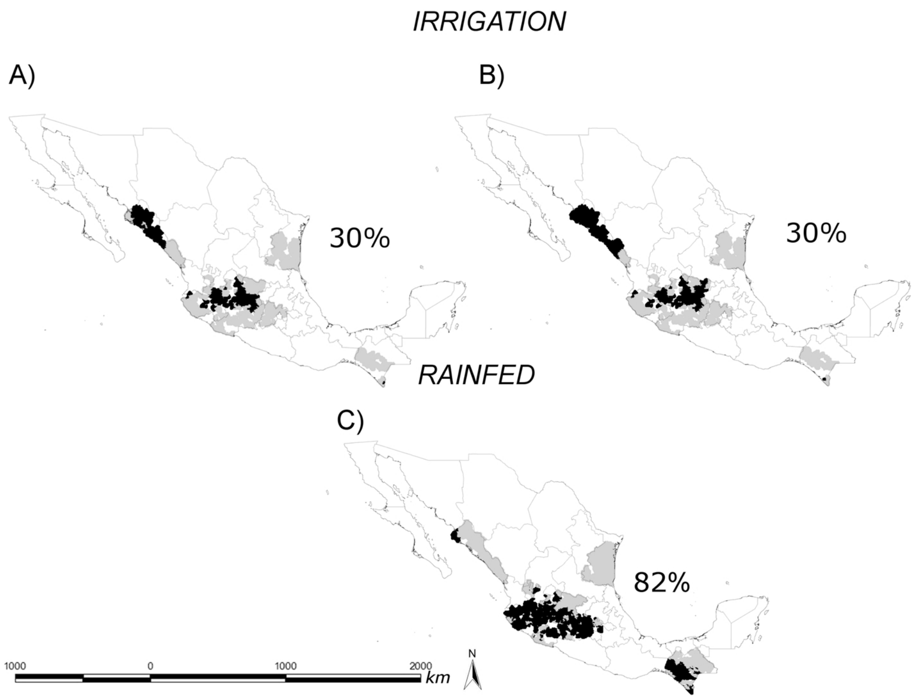

Fig. 4. Areas reaching the Breakeven point. A) Geographic area with irrigation that reaches the specific breakeven point of each state under current climatic conditions, B) Geographic area with irrigation that reaches the average breakeven point of each state under future climate conditions, C) Geographic area under rainfed conditions that reaches 2 t/ha under current climate conditions.

3.5. Limitations

The use of yield data collected at the municipality level presents two main problems for modeling its relationship with climate change. On the one hand, climate variables were taken from meteorological stations, and in many cases, there were more than one station per municipality. In these cases, we had to average this information. Additionally, there were several stations with incomplete information. Furthermore, while extreme climate events, such as droughts and storms, which play a very important role in yield (Deryng et al., 2014), are expected to increase in frequency and intensity (IPCC, 2013); as far as we know, there are still no geographic layers representing these extreme climatic events.

Additionally, we acknowledge that our study lacks a detailed description of the plant's physiology through time under different climatic conditions and along its entire lifecycle. However, this is a trade-off between being able to project the plants ecological response into spatio-temporal macro scales and having a better understanding of its ecology at a microscale. Both approaches answer different questions and are of relevance to gain understanding about the plants' biology.

Finally, given the lack of information about which native varieties are being sown where and a lack of distinction among these kinds of materials and improved or hybrid varieties when collecting yield estimates, the role of agrobiodiversity under a changing environment is being obscured. Proper yield information about specific races and/or hybrid varieties does not exist or is not publicly available. The CONABIO database has some yield data for native races, but it is still incomplete (CONABIO, 2017). If yield data from specific hybrid varieties or native races could be collected in a broad enough scale to allow for extrapolation, specific adaptive strategies could be analyzed per geographic region. However; guidelines are still needed to undertake this kind of survey. Nevertheless, we think this investigation gives some insights on the limitations of maize production in Mexico under current and future scenarios.

4. Conclusions

This study is the first attempt to evaluate the relationship between yield and 10 different climate variables at the municipality scale over seven Mexican states that represent the five regions of the country encompassing 65% of national maize production. It is also the first study that evaluates the impacts of climate change on rainfed and irrigated maize fields. We conclude that climate change will have strongly negative impacts on yield for rainfed fields, while irrigated fields will remain stable. In general, temperature increase will negatively affect yield in rainfed fields, while precipitation will have a larger impact on irrigated fields. In rainfed areas the variable that influenced yield the most was the temperature of the warmest quarter (mostly related to the spring-summer season). From all the variables evaluated, five influenced yield in rainfed areas and only one was associated with precipitation (precipitation of the driest month) and its contribution to decrements in yield was small. On the other hand, in irrigated areas, only two variables had an influence over yield value: one precipitation variable (precipitation of driest month) and one temperature variable (minimum temperature of coldest month). However, the influence of precipitation is greater than the influence of temperature. The fact that irrigated fields even showed yield increases under three evaluated scenarios is possibly related to a future increase in the precipitation of the driest month in three scenarios, except for 2070 RCP 8.5 W/m^2 scenario in which decreases in precipitation and yield are expected. Our climatic mixed model helped us visualize that when the municipality was taken into account: the climatic variables used can explain a great amount of yield variability ($R_c^2 = 0.729$ and $R_c^2 = 0.775$, for rainfed and irrigated conditions, respectively). Consequently, yield extrapolation to future scenarios in the municipalities evaluated could be projected but this extrapolation to other geographic areas of the country was not possible. We also demonstrated that higher yield does not necessarily result in higher profits for maize producers, particularly in irrigated conditions because production costs are high.

To abate negative impacts on yield such as those projected by climate change scenarios, we should increase the ability of small-hold farmer to adapt through more equitable water distribution. Costs in irrigated field can be offset by increasing the use of locally adapted, domestic hybrid seeds. While we could not evaluate it explicitly, we want to highlight that we could take advantage of the standing Mexican maize agrobiodiversity and its known capability of reacting differently under different circumstances. In irrigated fields where such diversity is scarce, it should be increased by generating different hybrid varieties, as well as improved native races. We should also explore new germoplasm to breed for higher resistance under heat and hydric stress.

Declaration of Competing Interest

None.

Acknowledgements

We would like to thank DGAPA, Instituto de Ecología (UNAM) and CONACyT (Cátedras CONACyT) for the economic support to Carolina Ureta. We would also like to thank Cecilio Mota and the group of Análisis de Riesgo y Bioseguridad (CONABIO) for their help. Finally, we would like to acknowledge financial support from the following grants: CONACYT240180, 2015-01-687; UNAM-DGAPA-PAPIIT: IN211516, IN208517, IN205517, IN204217, IE-485.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agsy.2019.102697.

References

Anderson, E.F., Cutler, H.C., 1942. Races of *Zea mays*: I. their recognition and classification. Ann. Mo. Bot. Gard. 29, 69–88.
Araújo, M.B., New, M., 2007. Ensemble forecasting of species distributions. Trends in Ecology and Evolution. 22 (42–27).
ASERCA, 2018. Maíz grano cultivo representativo de México. Agencia de Servicios a la Comercialización y Desarrollo de Mercados Agropecuarios (Accessed September 2019). https://www.gob.mx/aserca/articulos/maiz-grano-cultivo-representativo-de-mexico?idiom=es.
Bellon, M.R., 1991. The ethnoecology of maize variety management: a case study from Mexico. Hum. Ecol. 19, 389–418.
Bellon, M.R., Berthaud, J., Smale, M., Aguirre, J.A., Taba, S., Aragón, F., Díaz, J., Castro, H., 2003. Participatory landrace selection for on-farm conservation: an example from the central valleys of Oaxaca, Mexico. Genet. Resour. Crop. Evol. 5, 401–416.
Bellon, M.R., Mastretta-Yanes, A., Ponce-Mendoza, A., Ortiz-Santamaría, D., Oliveros-Galindo, O., Perales, H., Acevedo, F., Sarukhán, J., 2018. Evolutionary and food supply implications of ongoing maize domestication by Mexican campesinos. Proceedings of the Royal Society in Biological Science. 285, 20181049.
Bourges, H., 2013. El maíz: su importancia en la alimentación de la población mexicana. In: Álvarez-Buylla, E.R., Piñeyro Nelson, A. (Eds.), El maíz en peligro ante los transgénicos: un análisis integral del caso de México. UNAM, UCCS, UV, pp. 231–248.
Burnham, K.P., Anderson, D.R., 2002. Model Selection and Inference: A Practical Information-Theoretic Approach, 2nd edition. Springer-Verlag, New York. https://doi.org/10.1007/b97636.
Butler, E.E., Huybers, P., 2013. Adaptation of US maize to temperature variations. Nat. Clim. Chang. 3, 68.
Cakir, R., 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. Field Crop Res. 89, 1–16.
Chhetri, N., Chaudhary, P., Tiwari, P.R., Yadaw, R.B., 2012. Institutional and technological innovation: understanding agricultural adaptation to climate change in Nepal. Appl. Geogr. 33, 142–150.
Cicchino, M., Edreira, J., Uribelarrea, M., Otegui, M., 2010. Heat stress in field-grown maize: response of physiological determinants of grain yield. Crop Sci. 50, 1438–1448.
CONABIO, 2017. Proyecto Global de Maíces. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. (Accessed September 2019). https://www.biodiversidad.gob.mx/genes/proyectoMaices.html.
CONAGUA, 2014. Diagnóstico del programa presupuestario K141. Rehabilitación y modernización de infraestructura de riego y rainfed tecnificado. Comisión Nacional del Agua (Accessed September 2019). https://www.transparenciapresupuestaria.gob.mx/work/models/PTP/Reingenieria_Gasto/imagenes/Ventanas/Ramo_16/16K141.pdf.
Conde, A.C., Gay, C., 2008. Guía para la Generación de Escenarios de Cambio Climático a Escala Regional. Centro de Ciencias de la Atmósfera, UNAM, México, D.F.
Conde, C., Liverman, D., Flores, M., Ferrer, R., Araújo, R., Betancourt, E., Villareal, G., Gay, C., 1997. Vulnerability of rainfed maize crops in Mexico to climate change. Clim. Res. 9, 17–23.
Cruz Delgado, S., Gómez Valdez, M., Ortiz Pulido, M.E., Entzana Tadeo, A.M., Suárez Hernández, C., Santillán Moctezuma, V., 2012. Situación actual y perspectivas del maíz en México 1996–2012. Servicio de información agroalimentaria y pesquera, México, D.F.
Deryng, D., Conway, D., Ramankutty, N., Price, J., Warren, R., 2014. Global crop yield response to extreme heat stress under multiple climate change futures. Environ. Res. Lett. 9, 034011.
Eakin, H., Sweeney, S., Lerner, A.M., Appendini, K., Perales, H., Steigerwald, D.G., Dewes, C.F., Davenport, F., Bausch, J.C., 2018. Agricultural change and resilience: agricultural policy, climate trends and market integration in the Mexican maize system. Anthropocene. 23, 43–52.
Espinosa, A., Sierra, M., Gómez, N., 2003. Producción y tecnología de semillas mejoradas de maíz por el INIFAP en el escenario sin la PRONASE. Agronomía mesoamericana. pp. 14.
Estrada, F., Perron, P., Martínez-López, B., 2013. Statistically derived contributions of diverse human influences to twentieth-century temperature changes. Nat. Geosci. 6, 1050.
FAO, 2017. Data. Organización de las Naciones Unidas para la Alimentación y la Agricultura. (Accessed September 2019). http://www.fao.org/faostat/en/#data/QC.
Fernández Suárez, R., Morales Chávez, L.A., Gálvez Mariscal, A., 2013. Importancia de los maíces nativos de México en la dieta nacional: Una revisión indispensable. Rev. Fitotec. Mex. 36, 275–283.
FIRA, 2007. Rentabilidad y Costos. Fideicomisos Instituidos en Relación con la Agricultura. (Accessed September 2019). http://www.fira.gob.mx/Nd/Rentabilidad_y_Costos.jsp.
FIRA, 2016. Dirección de Investigación y Evaluación Económica y Sectorial. Panorama Agroalimentario. Fideicomisos Instituidos en Relación con la Agricultura, México (Accessed September 2019). https://www.gob.mx/fira/documentos/panorama-agroalimentario.
Florescano, E., 2003. Imágenes y significados del dios del maíz. In: Marielle, Esteva G.Y.C. (Ed.), Sin maíz no hay país. CONACULTA, Mexico City, pp. 36–55.
Grant, R.F., Jackson, B.S., Kiniry, J.R., Arkin, G.F., 1989. Water deficit timing effects on yield components in maize. Agron. J. 81, 61–65.
Guzmán Soria, E., de la Garza Carranza, M.T., González Farías, J.P., Hernández Martínez, J., 2014. Análisis de los costos de producción de maíz en la Región Bajío de Guanajuato. Análisis Económico. 29.
Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high-resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.
Huacuja, F.E., 2015. Government Subsidies for Price Risks: The Case of Maize Producers in Mexico. (Papeles de Geografía:1).
IPCC, 2013. Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J. ... Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
IPCC, 2014. Summary for policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E. ... White, L.L. (Eds.), Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Jones, C.A., Kiniry, J.R., 1986. CERES-Maize: A Simulation of Maize Growth and Development. Texas A&M University Press, College Station.
Kato, T.A., Mapes, C., Mera, L.M., Serratos, J.A., Bye, R.A., 2009. Origen y diversificación del maíz: una revisión analística. Universidad Nacional Autónoma de México, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, México, DF.
Khan, M.B., Hussain, N., Iqbal, M., 2001. Effect of water stress on growth and yield components of maize variety YHS 202. Journal of Research Science. 12, 15–18.
Kotschi, J., 2007. Agricultural biodiversity is essential for adapting to climate change. GAIA-Ecological Perspectives for Science and Society. 16, 98–101.
Lamichhane, J.R., Barzman, M., Booij, K., Boonekamp, P., Desneux, N., Huber, L., Kudsk, P., Langrell, S.R., Ratnadass, A., Ricci, P., 2015. Robust cropping systems to tackle pests under climate change. A review. Agron. Sustain. Dev. 35, 443–459.
Lechenet, M., Bretagnolle, V., Bockstaller, C., Boissinot, F., Petit, M.-S., Petit, S., Munier-Jolain, N.M., 2014. Reconciling pesticide reduction with economic and environmental sustainability in arable farming. PLoS One 9, e97922.
Lobell, D.B., Bänziger, M., Magorokosho, C., Vivek, B., 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. Nat. Clim. Chang. 1, 42.
Maguire Jr., B., 1973. Niche response structure and the analytical potential of its relationships to the habitat. Am. Nat. 107, 213–246.
Martínez-Meyer, E., Díaz-Porras, D., Peterson, A.T., Yáñez-Arenas, C., 2013. Ecological niche structure and rangewide abundance patterns of species. Biol. Lett. 9, 20120637.
Matsuoka, Y., Vigouroux, Y., Goodman, M., Sánchez Gonzáles, J.J., Buckler, E.D., Doebley, J., 2002. A single domestication for maize shown by multilocus microsatellite genotype. Proceedings of the National Academy of Science of the United States of America. 99, 6080–6084.
Méndez, M., Magaña, V., 2010. Regional Aspects of Prolonged Meteorological Droughts over Mexico and Central America. pp. 1175–1188.
Mendoza, B., Velasco, V., Jáuregui, E., 2006. A study of historical droughts in southeastern Mexico. J. Clim. 19, 2916–2934.
Mercer, K.L., Perales, H.R., 2010. Evolutionary response of landraces to climate change in centers of crop diversity. Evol. Appl. 3, 480–493.
Mercer, K.L., Perales, H., 2018. Structure of local adaptation across the landscape: flowering time and fitness in Mexican maize (*Zea mays L.* subsp. *mays*) landraces. Genet. Resour. Crop. Evol. 1–19.
Mercer, K.L., Perales, H.R., Wainwright, J.D., 2012. Climate change and the transgenic adaptation strategy: smallholder livelihoods, climate justice, and maize landraces in Mexico. Glob. Environ. Chang. 22, 495–504.
Mesgaran, M.B., Cousens, R.D., Webber, B.L., 2014. Here be dragons: a tool for quantifying novelty due to covariate range and correlation change when projecting species distribution models. Divers. Distrib. 20, 1147–1159.
Monterroso, R.A., Conde, A.C., Gómez Díaz, J.D., Gay, C., 2011. Assessing current and

potential rainfed maize suitability under climate change scenarios in Mexico. Atmósfera. 24, 53–67.
Montesillo-Cedillo, J.L., 2016. Rendimiento por hectárea del maíz grano en México: distritos de riego vs temporal. Economía Informa. 398, 60–74.
Munguía-Aldama, J., Sánchez-Plata, F., Vizcarra-Bordi, I., Rivas-Guevara, M., 2015. Estrategias para la producción de maíz frente a los impactos del cambio climático. Revista de Ciencias Sociales (Ve) 21.
Nakagawa, S., Schielzeth, H., 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods Ecol. Evol. 4, 133–142.
Nix, H.A., 1986. A Biographic Analysis of Australian Elapid Snakes. Australian Government Publishing Service. Australia, Canberra.
Ortega Paczka, R., 2007. La diversidad del maíz en México. Sin maíz no hay país. Consejo Nacional Para la Cultura y las Artes, México, D.F, pp. 123–154.
Perales, H., Golicher, D., 2014. Mapping the diversity of maize races in Mexico. PLoS One 9 (12), e114657.
Ranum, P., Peña-Rosas, J.P., Garcia-Casal, M.N., 2014. Global maize production, utilization, and consumption. Ann. N. Y. Acad. Sci. 1312, 105–112.
Ray, D.K., Gerber, J.S., MacDonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6, 5989.
Reyes, C., 1990. El maíz y su cultivo. AGT-EDITOR S.A, México D.F.
Rosenzweig, C., Iglesias, A., Yang, X.B., Epstein, P.R., Chivian, E., 2001. Climate change and extreme weather events; implications for food production, plant diseases, and pests. Global Change and Human Health. 2, 90–104.
Ruiz Corral, J.A., Durán Puga, N., Sánchez Gonzáles, J.J., Ron Parra, J., González Euiarte, R., Holland, J.N., Medina García, G., 2008. Climatic adaptation and ecological descriptors of 42 Mexican races. Crop Sci. 48, 1502–1512.
Ruiz Corral, J.A., Sánchez González, J.J., Hernández Casillas, J.M., Willcox, M.C., Ramírez Ojeda, G., Ramírez Díaz, J.L., González Eguiarte, D.R., 2013. Identificación de razas mexicanas de maíz adaptadas a condiciones deficientes de humedad mediante datos biogeográficos. Revista Mexicana de Ciencias Agrícolas. 4, 829–842.
SADER, 2019. Oficinas de Operación Territorial. Secretaría de Agricultura y Desarrollo Rural. (Accessed September 2019). https://www.gob.mx/agricultura.
SAGARPA a, 2016. Sube a 12 mil hectáreas siniestradas totalmente por las heladas. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (Accessed September 2019). https://www.gob.mx/agricultura%7Csinaloa/articulos/sube-a-12-mil-hectareas-siniestradas-totalmente-por-las-heladas.
SAGARPA b, 2016. Planeación Agrícola Nacional 2017-2030. Maíz grano blanco y amarillo mexicano. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (Accessed September 2019). https://www.gob.mx/cms/uploads/attachment/file/256429/B_sico-Maiz_Grano_Blanco_y_Amarillo.pdf.
Sánchez, B., Rasmussen, A., Porter, J.R., 2014. Temperatures and the growth and development of maize and rice: a review. Glob. Chang. Biol. 20, 408–417.
SIAP, 2018. Anuario Estadístico de la Producción Agrícola. Servicio de Información Agroalimentaria y Pesquera (Accessed September 2019). http://infosiap.siap.gob.mx/aagricola_siap_gb/icultivo/index.jsp.
Smale, M., Bellon, M.R., Aguirre, J.A., Rosas, I.M., Mendoza, J., Solano, A.M., Martínez, R., Ramırez, A., Berthaud, J., 2003. The economic costs and benefits of a participatory project to conserve maize landraces on farms in Oaxaca, Mexico. Agric. Econ. 29, 265–275.
SMN, 2017. Información climatológica. Servicio Meteorológico Nacional. (Accessed September 2019). https://smn.conagua.gob.mx/es/informacion-climatologica-por-estado.
Steen, V., Sofaer, H.R., Skagen, S.K., Ray, A.J., Noon, B.R., 2017. Projecting species' vulnerability to climate change: which uncertainty sources matter most and extrapolate best? Ecology and Evolution. 7, 8841–8851.
Taiz, L., Zeiger, E., 2006. Plant physiology. Sinauer. Sunderland, U.S.A.
Tigchelaar, M., Battisti, D.S., Naylor, R.L., Ray, D.K., 2018. Future warming increases probability of globally synchronized maize production shocks. Proceedings of the National Academy of Sciences 201718031.
Trueba, C., 2012. Semillas mexicanas mejoradas de maíz: su potencial productivo. Colegio de Posgraduados, México, Estado de México.
Turrent Fernández, A., Montiel, N.G., Díaz, J.R., Andrade, H.M., Corona, A.O., Flores, M.L., 1997. Plan de investigación del sistema maíz-tortilla en los Estados Unidos Mexicanos. Document for internal agency circulation. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, México, DF.
UNISEM, 2017. Unidos Sembrados. (Accessed September 2019). http://www.semillastodoterreno.com.
Ureta, C., Martínez-Meyer, E., Perales, H.R., Álvarez-Buylla, E., 2012. Projecting the effects of climate change on the distribution of maize races and their wild relatives in Mexico. Glob. Chang. Biol. 18, 1073–1082.
Ureta, C., González-Salazar, C., González, E.J., Álvarez-Buylla, E.R., Martínez-Meyer, E., 2013. Environmental and social factors account for Mexican maize richness and distribution: a data mining approach. Agric. Ecosyst. Environ. 179, 25–34.
Ureta, C., Martínez-Meyer, E., González, E.J., Álvarez-Buylla, E.R., 2016. Finding potential high-yield areas for Mexican maize under current and climate change conditions. J. Agric. Sci. 154, 782–794.
Vélez, E.P., Saez, E.M., 2012. Water use for agriculture in Mexico. Water Resources in Mexico. Springer, Germany, Berlin.
Vigouroux, Y., Glaubitz, J., Matsuoka, Y., Goodman, M., Sánchez González, J.J., Doebley, J., 2008. Population structure and genetic diversity of New World maize races assessed by DNA microsatellites. Am. J. Bot. 95, 1240–1253.
Visser, M.E., 2008. Keeping up with a warming world; assessing the rate of adaptation to climate change. Proc. R. Soc. Lond. B Biol. Sci. 275, 649–659.
Wilson, E.O., 1987. The little things that run the world (the importance and conservation of invertebrates). Conserv. Biol. 1, 344–346.