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IMPACT OF CLIMATE CHANGE ON MAIZE (*Zea mays* L.) PLANTING DATES IN THE EASTERN REGION OF PUEBLA, MEXICO

Rogelio **Bernal-Morales**[1], José Pedro **Juárez-Sánchez**[1*], Benito **Ramírez-Valverde**[1],
Ignacio **Ocampo-Fletes**[1], María de los Ángeles **Velasco-Hernández**[2]

[1]Colegio de Postgraduados Campus Puebla. Boulevard Forjadores de Puebla 205, Santiago Momoxpan, San Pedro Cholula, Puebla, Mexico. C. P. 72760.
[2]Benemérita Universidad Autónoma de Puebla. Instituto de Ciencias. Boulevard Valsequillo y Avenida San Claudio, Edificio 112, Ciudad Universitaria, Colonia Jardines de San Manuel, Heroica Puebla de Zaragoza, Puebla, Mexico. C. P. 72570.
* Author for correspondence: pjuarez@colpos.mx

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ABSTRACT

Climate change affects crop production, resulting in economic losses. One of the most significant changes caused by this phenomenon is a shift in the optimal planting date, so it is important to identify the optimal planting dates under the new climatic patterns, or at least appropriate ones that allow the selection of the indicated maize (*Zea mays* L.) variety (for example, short, intermediate, or late cycle genotype) that would be best to plant in order to obtain higher yields. Therefore, this research hypothesized that climate change would lead to shifts in the planting dates of rainfed maize. The objective was to assess the impact of climate change on planting dates in the eastern region of Puebla, Mexico. For this purpose, daily precipitation (PCP), as well as maximum and minimum temperature data from 13 climatological stations covering the period 1961–2020, were analyzed. Data quality was assessed using RClimDex software, and reference evapotranspiration (ETo) was estimated using the Penman–Monteith method. The optimal planting date was defined as the point when PCP ≥ 0.5 ETo, indicating sufficient water availability for seed germination. Results revealed that climate change increased variability in planting dates during the 1991–2020 period compared to 1961–1990. A spatially differentiated impact of climate change on planting dates was observed. In the 1991–2020 period, the earliest planting dates shifted toward the northwest, while the latest remained in the southern part of the region. These differentiated effects highlight the need for localized climate change adaptation strategies to support agricultural planning.

Keywords: Rainfed agriculture, evapotranspiration, climate variability.

INTRODUCTION

According to the United Nations Framework Convention on Climate Change (UNFCCC), climate change is defined as the “change in climate attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods." On the other hand, climate variability denotes variations in the mean state and other statistical characteristics, such as extreme events or standard deviations of climate, at all spatial and temporal scales (IPCC, 2018). Climate predictions indicate a warmer world over the next 50 years, with a 2 °C increase in temperature impacting yields of major crops (IPCC, 2014). Projections indicate that rainfed agricultural yields will decrease (Ureta *et al*., 2020).

By 2050, the world's population is projected to reach 9.3 billion inhabitants. To meet demand for food, annual production must increase by 5100 million Mg, implying a 60 % increase (FAO, 2015). In Mexico, rainfed maize (*Zea mays* L.) during the spring-summer cycle occupied the largest area planted in 2023, with 4 880 622.85 ha, representing 60 % of the total agricultural area, followed by beans (11 %). In the state of Puebla, the area planted to rainfed maize represented 78 % by 2023, and in the central-eastern part of Puebla, 88 % (SIAP, 2025).

In Mexico, the area planted with rainfed maize has decreased. In 2020, 5 439 354.2 ha were planted, and by 2023, 4 880 622.85 ha. Yields increased from 2.51 Mg ha^{-1} in 2020 to 2.75 Mg ha^{-1} in 2023. In 2023, the highest number of hectares lost was recorded (474 700.32 ha), followed by 2020 (303 292.21 ha), 2021 (134 270.67 ha), and 2022 (93 104.31 ha) (SIAP, 2025). Rainfed maize production is expected to increase by 11 % by 2030 compared to 2015, which is possible due to the increase in planted area (12 %) (Govaerts *et al*., 2019).

The increase in temperature and changes in precipitation distribution in the coming years will have a negative impact on the maize crops. In this regard, Han *et al*. (2022) found that high temperatures reduced yield; delayed planting significantly increased the risk of frost (>80 %) in mid- and high-latitude areas. Farmers struggle to establish their plantings due to the high spatial and temporal variability of precipitation, as well as its non-uniform distribution. In a projected warmer climate, the scheduling of agricultural practices will be affected, accelerating planting dates.

Climate change complicates determining the optimal planting date (Laux *et al*., 2008). Bigolin and Talamini (2024) evaluated climate change scenarios in a soybean-maize double cropping system and found a delay in the onset of the rainy season that delays planting. Producers define planting dates considering rain availability and the presence of frost. In this context, in northeast In China, adjusting planting dates is important to adapt to climate change, but there is little evidence on how well producers have done it (Zhu *et al*., 2022). Hence, it is important to provide scientific evidence on the impact of climate change on planting dates to design adaptation strategies.

Climate change affects rainfed agricultural productivity, and its impact will depend on variations in climatic variables and seed sensitivity to these variables. For Lamichhane and Soltani (2020), an optimal sowing date contributes to having the best environmental conditions during their growth phases, which is reflected in higher yields. Furthermore, there is potential to increase crop productivity and adapt to warming (Huang *et al*., 2024). Choosing the right planting date is a strategy to reduce the effects of climate change in agriculture, as the plant will not experience high temperatures and heat stress during its growth (Jafari *et al*., 2024). In this regard, Chassaigne-Ricciulli *et al*. (2021) studied the effect of four planting dates on hybrid maize seed yield and found that the earliest date achieved higher yields, since the grain filling period coincided with hot days and cool nights.

Some methodologies for assessing climate change impacts and planting dates use climate scenarios to quantify their effects on crop yields. In this context, Xu *et al*. (2024) considered climate projections based on CMIP6 models, reduced under four Shared Socioeconomic Pathways (SSP) scenarios. Alimagham *et al*. (2024) evaluated the potential impact of climate change on rainfed maize, millet, sorghum, and wheat using five global circulation models over three time periods (1995–2014 as baseline, 2040–2059, and 2080–2099) and two scenarios (SSP3-7.0 as typical and SSP5-8.5 as pessimistic).

The perception and strategies carried out by maize producers in the face of climate change have also been examined by using interviews, confirming that they have adjusted planting dates based on climatic conditions (Ramírez-Huerta *et al*., 2021). Tang *et al*. (2024) argue that water stress and planting dates have a significant impact on maize yield, based on a randomized complete block plot design in an experiment with five planting dates and six hybrids. The adoption of weather-resistant crop varieties plays a prominent role (Oriekhoe *et al*., 2024). Zimmermann *et al*. (2017) mention that farmers can adapt their sowing dates and crop thermal weather requirements to minimize yield losses.

Wang *et al*. (2024) argue that optimizing planting dates is a potential strategy to adjust maize production to climate change and increase yield. Meanwhile, Baum *et al*. (2020) indicate that sowing date and choice of crop variety are important factors in determining crop yield potential. However, there is a knowledge gap about how weather scenarios affect these choices, so selecting the best planting date can be used as an alternative to reduce these risks (Bigolin and Talamini, 2024). Therefore, the objective of the study was to identify the impact of climate change on planting dates of rainfed maize in the eastern region of Puebla. The hypothesis proposed was that with climate change a change in planting dates of rainfed maize is expected.

MATERIALS AND METHODS

The study region is located between 18° 37′ 30“ and 19° 20′ 29″ N and 97° 12′ 01“ and 97° 48′ 35″ W. It includes 11 municipalities in the eastern region of the state of Puebla (Figure 1) and is made up of plains, hills and mountains, with altitudes ranging from 1800 to 3200 m. Frosts occur frequently and unexpectedly; the season typically lasts from September to March, with an average of 90 days. The rainy season is from March to September, with an annual rainfall of 390 to 1200 mm (Juárez-Sánchez and Ramírez-Valverde, 2006). The most abundant soil type is ochric Regosol in 55.5 % of the territory, followed by ochric Andosol in 21.1 %, with Feozem and Rendzina in smaller proportions (Velázquez-López *et al*., 2019).

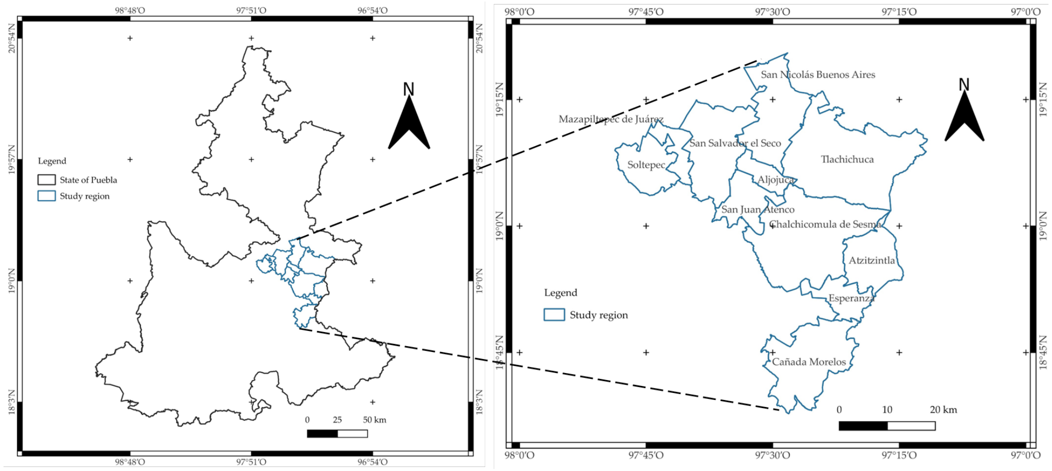

Figure 1. Municipalities comprising the study region in the state of Puebla, Mexico.

In 2023, 19 rainfed crops were planted in the region, with maize, beans, and grain barley accounting for 87.8 % (75 735 ha), 8.2 % (7081 ha), and 1.6 % (1148 ha), respectively, of the total rainfed area planted. Maize and beans are planted in all municipalities (SIAP, 2025). The optimal planting date is considered when precipitation (PCP) is ≥0.5 to the reference evapotranspiration (ETo), implying that the amount of water is sufficient for seed germination (FAO, 1997). The period from 1961 to 1990 has been maintained as the regulatory reference period for long-term climate change assessments (WMO, 2017). It is possible to determine whether climate change is present in the study region by comparing the normal (historical) daily values for PCP, ETo, and temperature from 1961–1990 to 1991–2020. These variables allow us to identify the dates of the beginning of the growing season for the periods evaluated.

For estimating evapotranspiration, the Penman-Monteith model stands out for its accuracy for different climatic conditions and regions. In this regard, Choque-Tarqui (2021) estimated evapotranspiration from satellite data, evaluating the Penman-Monteith, Thornthwaite, Hargreaves, Turc and Blaney, and Criddle methods, concluding that the Thornthwaite model has a very similar behavior to the Penman-Monteith model. Ortiz and Chile (2020) evaluated nine methods for estimating evapotranspiration, concluding that the best is the Penman-Monteith method.

Pipatsitee *et al*. (2023) used precipitable water vapor and temperature data derived from the Global Navigation Satellite System (GNSS-PWV), which proved to be suitable for daily evapotranspiration estimation and could be implemented for drought assessment and water resource management. Reyes-González *et al*. (2019) estimated evapotranspiration with remote sensing and validated it with *in situ* measurements, finding that both methods can be used to improve irrigation scheduling and preserve water resources in agriculture. Degano *et al*. (2024) estimated evapotranspiration with satellite and reanalysis data using the Google Earth engine and concluded that this method is a valid tool for estimating evapotranspiration.

To identify planting dates, daily precipitation (PCP), maximum temperature (*Tmax*), and minimum temperature (*Tmin*) data from 13 climatological stations from 1961 to 2020 (SMN, 2024) were used. The RClimDex software was used to analyze data quality, which allowed selecting climatological stations with less than 20 % of missing data and at least 10 years of uninterrupted data in the evaluated period. Reference evapotranspiration (ETo) was calculated on a daily scale with the Penman-Monteith method recommended by FAO (2006). The procedures and recommendations for limited climatic data were used, eliminating the need to use other methods and creating a consistent and transparent basis for a universal standardization of crop water requirement calculations.

ETo is calculated using daily data of *Tmax* and *Tmin*, actual vapor pressure (e_a), net radiation (R_n), and wind speed measured at 2 m (u_2). Missing humidity data were estimated assuming that the dew point temperature is similar to the daily minimum temperature using the following equation:

$$e_a = e^0(T_{min}) = 0.611exp\left[\frac{17.27T_{min}}{T_{min} + 237.3}\right]$$

where e_a is the actual vapor pressure, e^0 (*Tmin*) is the vapor saturation pressure and *Tmin* is the minimum temperature.

The solar radiation derived from thermal differences, i.e., the difference between *Tmax* and *Tmin*, was estimated and can be used to determine the fraction of extraterrestrial radiation reaching the earth's surface. The following equation was used for this purpose:

$$R_s = k_{R_s}\sqrt{(T_{max} - T_{min})R_a}$$

where R_s is the solar radiation [MJ m^{-2} d^{-1}], R_a is the extraterrestrial radiation [MJ m^{-2} d^{-1}], *Tmax* is the maximum temperature (°C), *Tmin* is the minimum temperature (°C), and k_{Rs} is the adjustment coefficient (0.16...0.19).

The adjustment coefficient is empirical and is differentiated for inland areas and coastal regions. For the former, the landmass dominates, and the air masses are not influenced by a large body of water, so $k_{Rs} \approx 0.16$. For coastal locations, situated near a large body of water, the air masses are influenced by a nearby body of water, so $k_{Rs} \approx 0.19$. In case of unavailability of wind data within the same region, a value of 2 m s^{-1} can be used as a temporal estimate. This value is the average of 2000 meteorological stations worldwide (FAO, 2006).

Once the optimal planting date (PCP ≥ 0.5 ETo) was estimated for each of the climatological stations, the QGIS geographic information system was used to interpolate the information using the weighted inverse distance method. During interpolation, sample points are weighted so that the influence of one point relative to the others decreases as the distance from the unknown point being created increases. The weighting is assigned to the sample points by using a weighting coefficient that controls how the influence of the weighting decays as the distance to the new point increases. The larger the weighting coefficient, the less effect the points will have if they are far from the unknown point during the interpolation process. As the coefficient increases, the value of the unknown points approaches the value of the closest observation point (QGIS, 2023).

RESULTS AND DISCUSSION

The results show a change in sowing dates when comparing the base period (1961–1990) with the recent period (1991–2020). During the base period, Chalchicomula de Sesma recorded the earliest average planting date, occurring on Julian day 121 (May 1). This was followed by Mazapiltepec de Juárez and San Juan Atenco, where sowing typically occurred on Julian day 132 (May 12), and by Aljojuca, Soltepec, and San Salvador el Seco on Julian day 133 (May 13). In Tlachichuca, sowing dates were more variable, occurring on Julian days 133, 139 (May 19), and 143 (May 23). Similarly, in San Nicolás Buenos Aires, planting began on Julian days 135 (May 15) and 139 (May 19). The municipalities with the latest sowing dates were Atzitzintla, with dates recorded on Julian days 133, 138 (May 18), and 141 (May 21); Esperanza, on Julian days 138, 140 (May 20), and 146 (May 26); and Cañada Morelos, on Julian days 141, 145 (May 25), and 147 (May 27) (Figure 2). Precipitation and temperature are fundamental for estimating evapotranspiration. The changes in dates in the base period are due to the fact that in the areas with the earliest planting dates, climatic conditions for seed germination are established first.

In relation to the planting dates of the recent period, the earliest planting dates were registered in San Juan Atenco, on average, on Julian day 128 (May 8), followed by Soltepec on Julian days 134 (May 14) and 140 (May 20), Mazapiltepec on Julian day 141 (May 21), and San Salvador el Seco on Julian days 138 (May 18), 141, and 143 (May 23). In Chalchicomula, planting dates began on Julian days 133 (May 13), 135 (May 15), 138, and 143. In San Nicolás Buenos Aires, they began on Julian days 132 (May 12), 138, 144 (May 24), and 150 (May 30); in Tlachichuca on Julian days 134, 140, 143, 147 (May 27), and 153 (June 2); in Atzitzintla on Julian day 143; and in Esperanza on 145 (May 25) and 147, while the latest dates continued to occur in Cañada Morelos, beginning on Julian days 148 (May 28), 153, and 158 (June 7) (Figure 3).

Changes in the sowing dates of the 1961–1990 period compared to 1991–2020 are due to the decrease in precipitation and the increase in maximum temperature, which is reflected in a higher daily evapotranspiration. Therefore, more days are required to have sufficient water for seed germination, considering that the optimal sowing date occurs when PCP ≥ 0.5 ETo. The climatological station 21026 Ciudad Serdán, located in the municipality of Chalchicomula de Sesma, was used to compare both periods

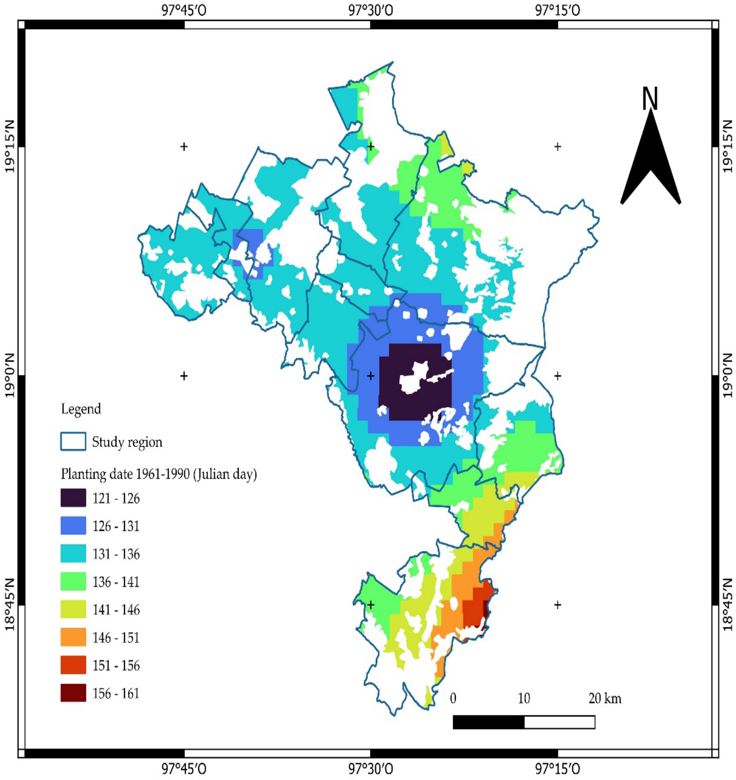

Figure 2. Optimal planting dates recorded during the base period (1961–1990) in the evaluated municipalities of the state of Puebla, Mexico. The colored areas represent rainfed agricultural areas, where maize (*Zea mays* L.) represents 87.8 % (75 735 ha) of the total. Areas in white represent other land uses.

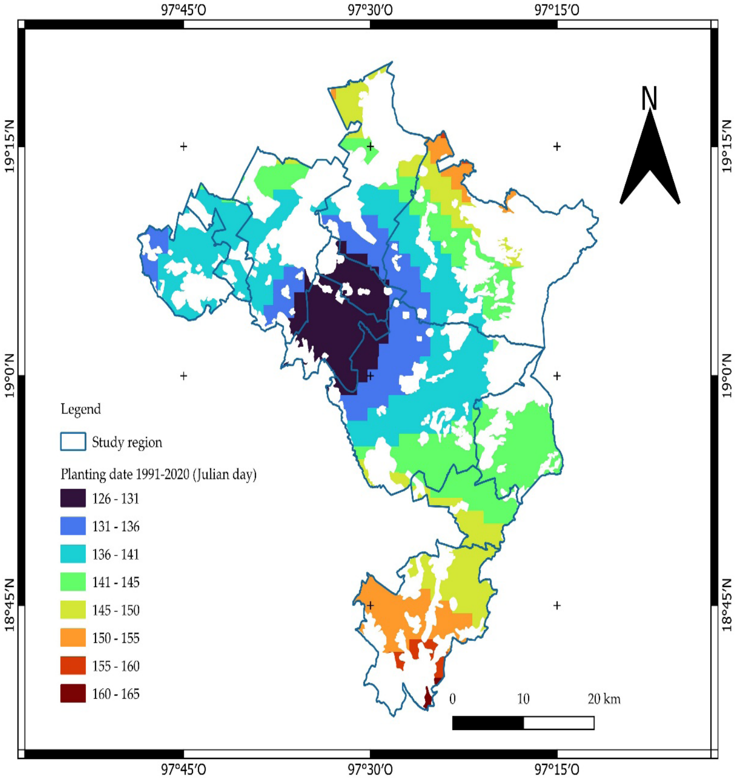

Figure 3. Optimal planting dates for the most recent period evaluated (1991–2020) in the evaluated municipalities of the state of Puebla, Mexico. The colored areas represent rainfed agricultural land, where maize (*Zea mays* L.) represents 87.8 % (75 735 ha) of the total. The areas in white represent other land uses.

to the same planting date. For 1961–1990, it began on Julian day 121 (May 1), and the final growth date was considered to be September 30, because growers expect the first frosts on this date. During the growing season, there was a PCP of 660.8 mm, a *Tmax* of 22.5 °C and an ETo of 716.8 mm.

When comparing the climatic values for the period 1991–2020 with the same dates from May 1 to September 30, PCP values of 458.4 mm, *Tmax* of 24.7 °C, and ETo of 744.8 mm were observed, indicating a decrease in PCP of 202.4 mm, an increase in *Tmax* of 2.2 °C, and an increase in ETo of 27.6 mm during the growing season. ETo values would go from 4.7 to 4.9 mm per day, which causes a higher average evapotranspiration. More PCP is now required to establish the ideal conditions for planting, resulting in an average of 10 days to move planting dates in the recent period.

When comparing the recent period of station 21026, which lasted from Julian day 121 (May 01) to 131 (May 10), the PCP was 438.5 mm, *Tmax* was 24.6 °C, and ETo was 727.4 mm per day. When comparing these climatic values of the base period growing season, a decrease in precipitation of 222.3 mm, an increase in *Tmax* of 2.1 °C, and an increase in ETo of 10 mm per day were found, so that the daily ETo went from 4.7 to 5.1 mm per day. For the most recent period, climate change has had a differentiated impact in the study region in terms of planting date shifts, as there are areas where planting dates are later and areas where they are earlier (Figure 4).

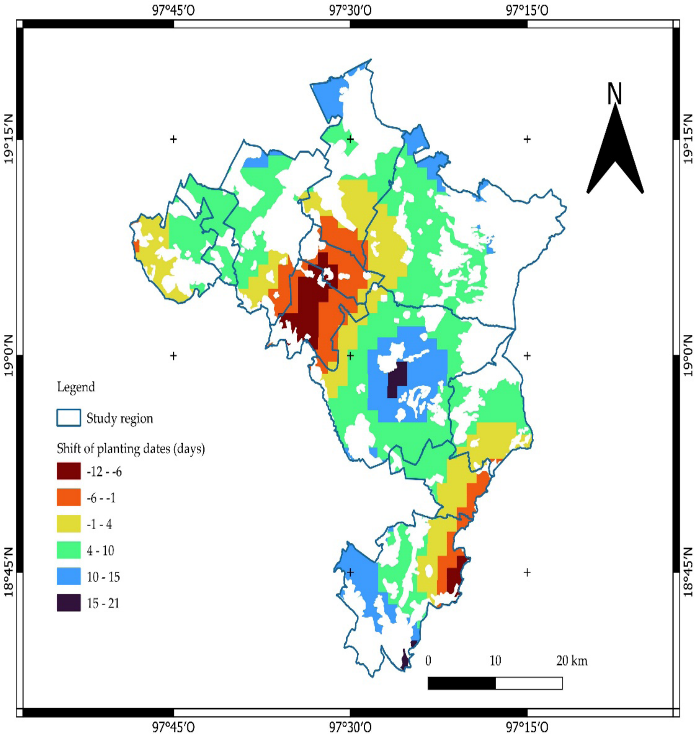

Figure 4. Shift of planting dates for the period 1991–2020 versus 1961–1990 in the evaluated municipalities of the state of Puebla, Mexico. The colored areas represent rainfed agricultural land, where maize (*Zea mays* L.) represents 87.8 % (75 735 ha) of the total. The areas in white symbolize other land uses.

During the base period, ideal conditions for seed germination occurred in the central zone, Chalchicomula, extending to the north through San Juan Atenco, Aljojuca, San Salvador el Seco, Mazapiltepec, Soltepec, the southern zone of Tlachichuca, and San Nicolás Buenos Aires, then in the northern zone of San Nicolás Buenos Aires, Tlachichuca, and Atzitzintla, and finally in the southern zone of Atzitzintla, Esperanza, and Cañada Morelos. From 1991 to 2020, the ideal conditions for seed germination moved to the northwest, starting in San Juan Atenco and Aljojuca and extending to the municipalities of Soltepec, Mazapiltepec, San Salvador el Seco, and the northwest zone of Chalchicomula, then to the northern zone of San Nicolás Buenos Aires, the northeast of Tlachichuca, Atzitzintla, and Esperanza, to finally settle in Cañada Morelos.

There is no research work that identifies planting dates using the approach used, laying the groundwork for what may be expected in the future when analyzing planting dates using climatic scenarios. The changes in sowing dates identified confirm the strategies that producers have carried out due to the delay in rainfall, which leads to a shift in sowing dates (Pérez-Magaña *et al*., 2021). Ramírez-Huerta *et al*. (2021) indicate that some producers advanced planting dates due to earlier than normal rainfall. On the other hand, Osorio-García *et al.* (2012) mention that the farmers' argument for the adoption of intermediate planting dates (before May 15) is due to changes in the rainfall pattern in the region, which have caused production systems under residual moisture (early plantings) to become increasingly scarce. According to Navarro-Hinojoza *et al*. (2023), in many localities in the country's north, weather conditions such as rainfall patterns, amount of precipitation, and climatic variations are causing the development of strategies to counteract uncertainty, such as changing planting dates and using short-cycle seeds to avoid yields being affected by frosts expected in late September and early OctoberWhen quantifying the impact of the change in planting date, in the particular case of the study region, a field trip was carried out on September 28, 2025. A farmer in the community of San Juan Arcos Ojo de Agua carried out a 10-day differentiated planting, and the result was that the first planting did not have enough water, which caused the maize crop (cacahuazintle) to be damaged by the presence of red spider mite. In comparison to the crop that was planted 10 days later, it was predicted it would have a good yield. In this sense, Bigolin and Talamini (2024) indicate that a delay in the planting date translates into fewer days of rain to complete its cycle, so it is important to plant varieties of a shorter genotype so that the production of the maize crop is not affected.

The most significant changes in planting dates were recorded in Chalchicomula, where planting is increasingly late and takes up to 21 days, followed by Tlachichuca and San Salvador el Seco, which have late dates of up to 15 days, and Atzitzintla, where late dates are up to 10 days later. Mazapiltepec has later dates ranging from 4 to 10 days. The municipalities with the earliest plantings are San Juan Atenco and Aljojuca, with dates ranging from 1 to 12 days earlier. Cañada Morelos has areas with earlier dates up to 12 days earlier and later dates of up to 15 days. In San Nicolás Buenos Aires, there are earlier dates of up to 6 days before and later dates of up to 15 days, while

Esperanza and Soltepec have earlier dates of up to 6 days before and later dates of up to 10 days.

In terms of the impact of climate change on planting dates in both periods, there was less variability in 1961–1990, indicating that producers sowed systematically almost on the same date, whereas there is greater variability in 1991–2020 (Figure 5), causing problems for farmers who must wait for favorable moisture conditions to be established before beginning the agricultural cycle. An analysis of variance was performed to determine if the variability in both periods is the same or has changed, with a significance level of 0.05. A *p*-value of 7.5714×10^{-11} was obtained, indicating significant statistical differences between both periods, with greater variability in the recent period and showing that the region is being affected.

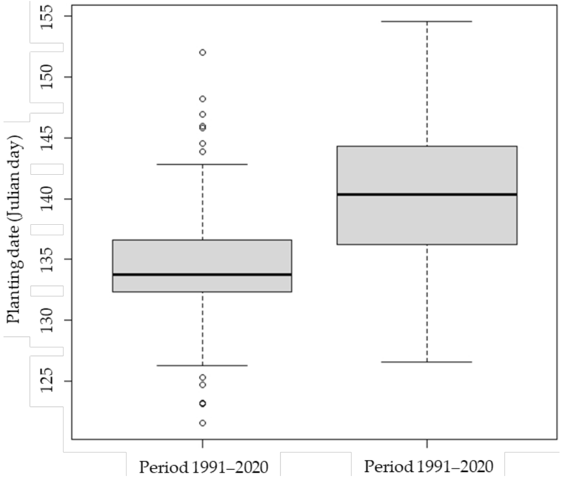

Figure 5. Variability of the planting date of the base period (1961–1990) compared to the most recent period (1991–2020) in the evaluated municipalities of the state of Puebla, Mexico.

Chassaigne-Ricciulli *et al.* (2021) recommend differential sowing dates based on information on the degree days (°D) of development. Given this, once the optimal date was identified, the degree days for the period 1991–2020 were calculated in relation to the reference period for each climatological season, and September 30 was considered as the final date of the growing season. The DegDay software (Snyder, 2002) was used for this purpose. There is a differentiated impact on the dynamics of thermal capacity in the growing season in the period 1991–2020 in relation to the base period (Figure 6). According to the Neild and Newman (1987) variety classification of maize genotypes, the accumulated degree days during the growing season require 1150 to 1315, 1315 to 1590, and 1590 to 1760 °D for short-, intermediate-, and long-cycle genotypes, respectively. In the study region, short-cycle genotype varieties are required, since the

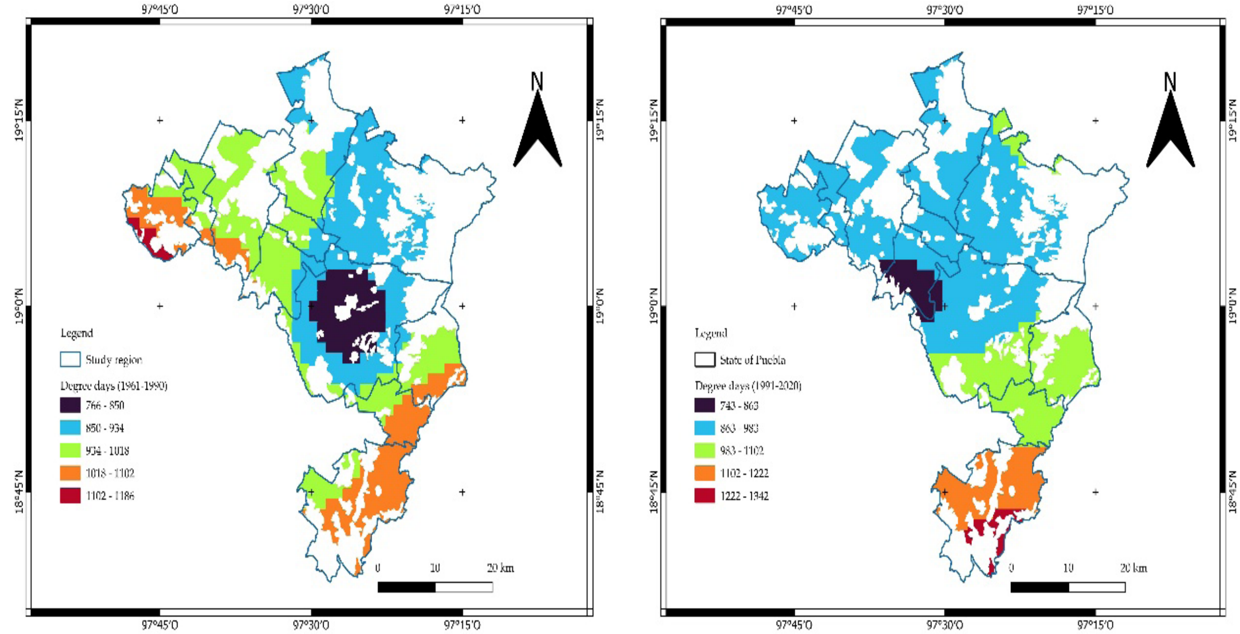

Figure 6. Degree days (°D) of maize (*Zea mays* L.) crop development during the period 1961–1990 (left) compared to the period 1991–2020 (right) in the evaluated municipalities of the state of Puebla, Mexico.

highest degree days accumulated during the growing season are 1342 °D, relatively above the upper limit of the requirements for a short-cycle genotype. Degree days are another important climatic variable that should be considered for planning agricultural activities, so it would be important to quantify the degree day requirements of the different Criollo seeds.

The findings show that degree days have increased, but they have also decreased in certain areas. In Soltepec, Mazapiltepec, San Salvador el Seco, and San Juan Atenco, values ranged from 28 to 248 °D, while in Chalchicomula they have decreased/increased from -138 to 193 °D. In Tlachichuca and Esperanza, they have decreased/increased from -28 to 193 °D; in Atzitzintla, they have decreased/increased from -28 to 83 °D; in San Nicolás Buenos Aires and Aljojuca, they have decreased/increased from -138 to 83 °D; and in Cañada Morelos, they have the largest increases, ranging from -28 to 303 °D (Figure 7). As a result of the decrease in precipitation and increase in temperature during the growing season, it is concluded that short-cycle and drought-resistant genotypes must be used in the study region.

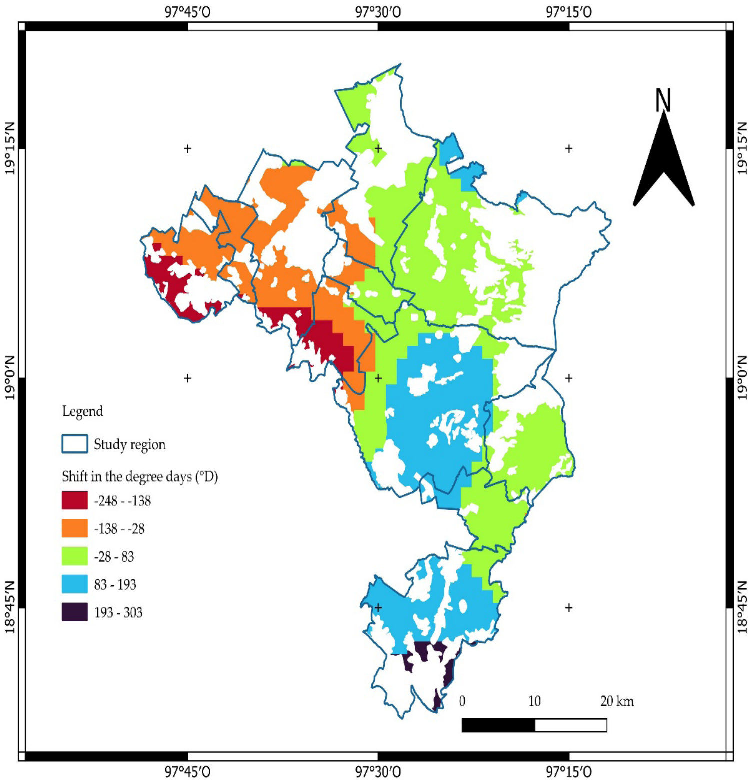

Figure 7. Changes in the dynamics of the degree days (°D) of maize (*Zea mays* L.) crop development in the period 1991–2020 compared to the period 1961–1990 in the evaluated municipalities of the state of Puebla, Mexico.

CONCLUSIONS

A significant impact of climate change on planting dates was identified during the recent period (1991–2020) compared to the reference period (1961–1990). The increased climatic variability observed in recent decades has made it difficult for producers to determine optimal or favorable dates to initiate the agricultural cycle, as temperature and humidity conditions become less predictable. This differentiated impact has caused a spatial displacement of planting dates, since the earliest planting dates tend to be located towards the northwest, while the latest ones persist in the southern part of the study region. As a result, producers are forced to adopt shorter-cycle varieties to avoid early frost damage.

It is essential to validate the planting dates estimated in this study with those actually used by producers in order to evaluate the degree of current adaptation to the new climatic conditions. Understanding these adjustments will allow the design of more effective local adaptation strategies to climate change. Finally, it is recommended that future studies and planning tools consider probable rainfall values instead of 30-year historical averages for the estimation of planting dates or the beginning of the growing season, as this would provide greater precision in the face of increasing climatic variability.

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