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CLIMATE CHANGE

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Potential impact of future climate change on sugarcane under dryland conditions in Mexico

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Abstract

Assessments of impacts of future climate change on widely grown sugarcane varieties can guide decision-making and help ensure the economic stability of numerous rural households. This study assessed the potential impact of future climatic change on sugarcane grown under dryland conditions in Mexico and identified key climate factors influencing yield. The Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model was used to simulate sugarcane growth and yield under current and future climate conditions. Management, soil and climate data from farm sites in Jalisco (Pacific Mexico) and San Luis Potosi (Northeastern Mexico) were used to simulate baseline yields. Baseline climate was developed with 30-year historical data from weather stations close to the sites. Future climate for three decadal periods (2021–2050) was constructed by adding forecasted climate values from downscaled outputs of global circulation models to baseline values. Climate change impacts were assessed by comparing baseline yields with those in future decades under the A2 scenario. Results indicate positive impacts of future climate change on sugarcane yields in the two regions, with increases of 1%–13% (0.6–8.0 Mg/ha). As seen in the multiple correlation analysis, evapotranspiration explains 77% of the future sugarcane yield in the Pacific Region, while evapotranspiration and number of water and temperature stress days account for 97% of the future yield in the Northeastern Region. The midsummer drought (*canicula*) in the Pacific Region is expected to be more intense and will reduce above-ground biomass by 5%–13% (0.5–1.7 Mg/ha) in July–August. Harvest may be advanced by 1–2 months in the two regions to achieve increases in yield and avoid early flowering that could cause sucrose loss of 0.49 Mg ha^{-1} month^{-1}. Integrating the simulation of pest and diseases under climate change in crop modelling may help fine-tune yield forecasting.

KEYWORDS
ALMANAC model, CP 72-2086, Mexican sugarcane, midsummer drought, sugarcane flowering

1 | INTRODUCTION

Future climate change is expected to have impacts on the cultivation of sugarcane for food and bioenergy. Assessments of these impacts can guide decision-making at government, industry and farm levels and help ensure the economic stability of numerous rural households in sugarcane-producing countries, such as Mexico, where the crop is grown in fifteen states. Predictions of crop response to climate change are useful in developing policy measures, making recommendations for greater system resilience (Jones & Thornton, 2003; Singels et al. 2014) and planning appropriate adaptation strategies (Singels et al. 2014).

Observations from climate stations worldwide indicate an increase in temperature and regionally differentiated patterns of increases and decreases in precipitation (Bormann, 2011; IPCC 2007). The negative impact of heat stress on major world food crop yields is well documented (Battistil & Naylor, 2009; Lobell & Field, 2007; Rosenzweig & Parry, 1994; Teixeira, Fischer, van Velthuizen, Walter, & Ewert, 2013). Heat and drought can reduce leaf photosynthesis and enhance leaf senescence rates (Siebert, Ewert, Rezaei, Kage, & GraB, 2014). However, various studies also show that future rises in atmospheric CO_2 may increase the productivity of C_4 crops, such as sugarcane (e.g. Allen, Vu, Andersonand, & Ray, 2011; Marin et al., 2013). Assessments of the possible impacts of changing climate on the crop are thus essential as they can lead to recommendations on how to take advantage of the potential benefits and minimize potential adverse impacts of climate on crop production (Marin et al., 2013). In this regard, climate scenarios are constructed to investigate possible consequences of climate change; they represent future conditions that account for both human-induced climate change and natural climate variability (IPCC 2001). Linking climate scenarios with crop models that simulate crop growth and yield may help determine factors that will constrain or else enhance crop yields and resource use efficiency (Siebert et al., 2014).

Climate change impact studies have been conducted at global (e.g. Jones & Thornton, 2003), national (e.g. Marin et al., 2013) and regional (e.g. Thornton et al., 2010) levels. However, large-scale studies need to be verified through more detailed modelling at the field and homogeneous regional scales (Folberth et al., 2014). Moreover, more effort is needed for assessments that target highly vulnerable farming systems and address the needs of poor farm households dependent on agriculture (Jones & Thornton, 2003; Thornton, Jones, Alagarswamy, Andresen, & Herrero, 2010). Hence, this study applies the biophysical crop growth model ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria; Kiniry, Williams, Gassman, & Debaeke, 1992) to (i) assess the potential impact of future climatic change on CP 72-2086 sugarcane widely grown under dryland conditions in two different regions of Mexico and (ii) to identify climate factors likely to influence future sugarcane yield in these regions.

2 | METHODS

2.1 | Study area

Mexico is the sixth greatest sugarcane producer in the world (Official Journal of the Federation 2014). Sugarcane production in six regions spanning 15 states (Official Journal of the Federation 2014; ZafraNet 2015) generates jobs and income for approximately half a million Mexican families (CNIAA 2011 cited by Secretaria de Economia, 2012). The crop is grown from the Tropic of Cancer to the southern border of the country, in tropical and subtropical regions, on flat topography and hillsides with different soil types of generally good quality (COLPOS, 2008), altitude ranging from sea level to 1,600 m, annual precipitations of 1,000–2,200 mm, annual average temperature of 20–32°C and minimum temperatures higher than 10°C.

The study was conducted in sugarcane mill regions ("ingenios") in two of the country's most productive sugarcane states: (i) Ingenio Plan de Ayala mill region in the state of San Luis Potosi in Northeastern Mexico and (ii) the Ingenio Jose Maria Morelos mill region in the state of Jalisco in Pacific Mexico (Figure 1). Characteristics of these regions are presented in Table 1. In these mill regions, the majority of producers are "ejidatarios" (shareholders of common land) while the rest are small farm owners (Manual Azucarero Mexicano 2004).

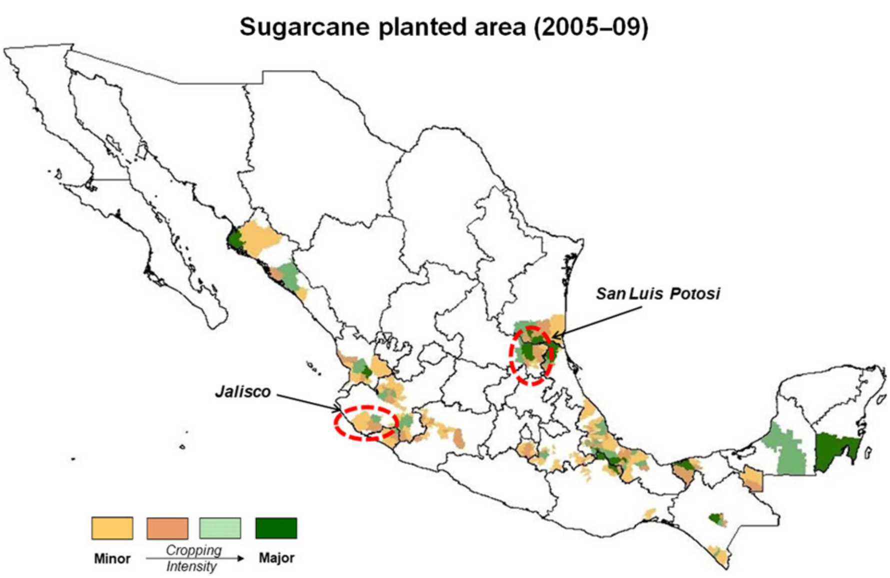

FIGURE 1 Location of Pacific and Northeastern Sugarcane Regions in Mexico included in the analysis of climate change impacts on future sugarcane yields. Adapted from World Agricultural Outlook Board Joint Agricultural Weather Facility, USDA and SAGARPA in http://www.usda.gov/oce/weather/pubs/Other/MWCACP/Graphs/Mexico/MexSugarcaneProd_0509.pdf. (accessed 3 June 2015)

TABLE 1 General characteristics of the sugarcane mill regions Ingenio Plan de Ayala in San Luis Potosi (Northeastern Mexico) and Ingenio Jose Maria Morelos in Jalisco (Pacific Mexico)

Characteristic	Ingenio Plan de Ayala, San Luis Potosi, Northeastern Sugarcane Region	Ingenio Jose Maria Morelos, Jalisco, Pacific Sugarcane Region
Latitude and longitude	21°59′N, 99°01′W	19°44′N, 104°08′W
Elevation	54 m asl	952 m asl
Precipitation (mm)	Mean annual 1,372	Lowest annual 483
		Highest annual 1,203
Type of farmers	75% ejidatarios[a], 30% small farm owners	64% ejidatarios, 36% small farm owners

[a]Shareholders of common land.

2.2 | Sugarcane cultivar

Sugarcane cultivar CP72-2086 was selected for this study because it is one of the three main cultivars in Mexico (Milanes-Ramos, Ruvalcaba, Caredo, & Barahona, 2010). In Oaxaca State, this cultivar and Mex 69-290 cover 94% of the sugarcane area (Bravo-Mosqueda, Baez-Gonzalez, Tinoco-Alfaro, Mariles-Flores, & Osuna-Ceja, 2014). It is also grown in other countries, such as Venezuela (Rea, De Souza, & Gonzalez, 1994), United States (Sinclair et al., 2004), Nicaragua (Schuenneman, Miller, Gilbert, & Harrison, 2008), Zimbabwe (Shoko, Zhou, & Pieterse, 2009), Costa Rica (Chavarria et al., 2009) and Pakistan (Hussnain et al., 2011). A progeny of the cross of "CP62-374" and "CP63-588," the cultivar was developed in 1967 through cooperative research between the USDA-ARS, the University of Florida and the Florida Sugarcane Growers League (Miller, Tai, Glaz, Dean, & Kang, 1984; Rea et al., 1994). A full description for the cultivar is provided by Schuenneman et al. (2008).

CP72-2086 sugarcane is considered an early-maturing cultivar in Mexico (Milanes-Ramos et al., 2010), while in some countries, it is considered a middle- or late-maturing cultivar (Schuenneman et al., 2008). With a mean potential yield of 110–120 Mg/ha under dryland conditions and 135–140 Mg/ha under irrigated conditions in subhumid tropics (Alvarez-Cilva unpublished data, Bravo-Mosqueda et al., 2014), it has become the preferred cultivar of many Mexican farmers because of its high yield and early maturation. Growing this early cultivar makes it possible for farmers to avoid crop damage due to harsh winter conditions in some regions and to provide cane to the mills at the start of the harvest season. The lack of early-maturing Mexican varieties is another factor for its popularity (Aguilar & Debernardi, 2004).

2.3 | ALMANAC model

The study used the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model, which simulates processes of crop growth and soil water balance including light interception by leaves, dry matter production and partitioning of biomass into grain. Light interception is simulated by Beer's Law and considers total leaf area and height of the canopy (Kiniry et al., 1992). The water and nutrient balance subroutines are from the Erosion Productivity Impact Calculator (EPIC) model (Williams, Jones, & Dyke, 1984). Critical for yield simulation in water-limited conditions is the simulated water demand. Potential evaporation (E_o) is calculated first. Then, potential soil water evaporation (E_S) and potential plant water transpiration (E_P) are derived from potential evaporation and leaf area index (LAI).

In addition, the model calculates various environmental stresses. Temperature, soil moisture, plant nutrients (N and P), aeration, salinity, pH and soil compaction can limit plant growth in the model. The water-stress factor is calculated as the ratio of water use to water demand calculated from potential plant transpiration, and water use is a function of plant extractable water and root depth (Schilling & Kiniry, 2007). If available water in the current rooting zone is sufficient to meet demand, then water use equals $E_{p,}$ otherwise water use is restricted to the water available in the current rooting zone.

The ALMANAC model (Kiniry et al., 1992) has been used to simulate various crops grown in different parts of the world (Baez-Gonzalez et al., 2015; Meki, Snider, Kiniry, Raper, & Rocateli, 2013; Xie, Kiniry, Nedbalek, & Rosenthal, 2001), including sugarcane (Meki et al., 2015). It has also been used to study climatic change impact on native grasses (Behrman, Kiniry, Winchell, Juenger, & Keitt, 2013). A detailed description of the ALMANAC model can be found in Kiniry et al. (1992) and Kiniry (2006).

In preliminary studies, the model was parameterized to evaluate the performance of cultivar CP72 2086 in three regions of Mexico (Baez-Gonzalez et al., 2017). Field data from thirty dryland sugarcane locations in Northeastern Mexico, Gulf of Mexico and Pacific Mexico with distinct soil and climatic conditions were used to calibrate and validate the model. Calibration was carried out by adjusting crop parameters (Kiniry et al., 1992; Meki et al., 2015) in the model while minimizing the RMSE for yield. Statistical results of ALMANAC model validation are as follows: mean = 53.3 Mg/ha, RMSE = 3.8 Mg/ha and R^2 = .94.

2.4 | Baseline yield data

This study used information from the San Luis Potosi database that had been developed through interviews of sugarcane growers in the mill region of Ingenio Plan de Ayala (San Luis Potosi, Northeastern Mexico). The database contains climate, soil, management and socioeconomic data of farms in the area for the 2008–2009 and 2009–2010 growing seasons. The crop-management data, which are from planting to harvest, include preparation of the soil, planting period, planting density (quantity of seeds), planting method, distance between furrows, sugarcane variety, application of bud-sprouting promoters, fertilization (period, dosage, type of fertilizer), pest control (type of insecticide, dosage, number of applications, time of application), weed control (type of weed, control method, type of herbicide, dosage, period of application), disease control, date of harvesting and yields. For the climate change assessments, we randomly selected from the database five farm sites planted to the sugarcane cultivar CP

72-2086 that had not been used in an earlier study focusing on the parameterization and evaluation of the ALMANAC model (Table 2).

A second database for Jalisco (Pacific Sugarcane Region) included the following information from the Ingenio Jose Maria Morelos mill for two growing seasons (2007–2008 and 2008–2009): sugarcane variety, total harvested area, yields, date of harvest, fertilization date, soil type and crop age. Similarly, to assess climate change impacts on sugarcane production, we randomly selected eight farm sites planted to the sugarcane cultivar CP 72-2086 that had not been used in the parameterization and evaluation of the ALMANAC model (Table 2).

2.5 | Climate data for baseline and future climate change decadal periods

The baseline climatic data were from four weather stations distributed throughout the sugarcane areas of San Luis Potosi and Jalisco. These stations were selected because of their proximity (6.8 ± 2.2 km) to the farm sites under study and their record of at least 30 years of continuous daily weather measurements during the period 1961–2010.

Future climate for the periods 2021–2030, 2031–2040 and 2041–2050 was constructed with climatic values obtained from the Sistema de Información de Cambio Climático (Climate Change Information System) or SICC of INIFAP (Instituto Nacional de Forestales, Agricolas y Pecuarias; Appendix) This database has climate values based on downscaled outputs of an assembly model of ten global circulation models (GCMs) as described in Ruiz-Corral, Medina, Manriquez, and Ramirez (2010) and Medina-García, Ruiz-Corral, Ramírez-Legarreta, and Díaz (2011). For each decadal scenario, monthly average precipitation, monthly maximum temperature and monthly minimum temperature were input into the ALMANAC model weather database to reflect the predicted 10-year average under the A2 scenario. The values were added to the baseline data of each weather station. The wind variables were not changed.

TABLE 2 Farm sites used for simulating CP 72-2086 sugarcane yield under dryland conditions in the Northeastern and Pacific Sugarcane Regions of Mexico

Mill name and sugarcane region	Farm site location	Soil units and physical description[a]	Climate[b]	Average cane yield (Mg ha^{-1})[c]
Ingenio Plan de Ayala, San Luis Potosi, Northeastern Mexico				
1	Praxedis Guerrero 1, −99.06°, 22.59°,178 m asl	Vertisols, 36% clay, 34% silt, 1.86% OC, 8.5 PH	24.0°C, 1,202 mm, Aw2	52
2	Praxedis Guerrero 2, −99.07°, 22.61°, 156 m asl	Vertisols, 36% clay, 34% silt, 1.86% OC, 8.5 PH	24.1°C, 1,188 mm, AW2	62
3	La Coincidencia, −99.05°, 22.32°, 220 m asl	Vertisols, 36% clay, 20% Silt, 3.37% OC, 7.4 PH	23.5°C, 1,225 mm, AW2	72
4	Laguna El Mante 1, −99.08°, 22.51°, 241 m asl	Calcaric Regosols, 56% clay, 20% Silt, 3.37% OC, 7.4 PH	23.4°C, 1,193 mm, AW2	55
5	Laguna El Mante 2, −99.08°,22.50°, 240 m asl	Calcaric Regosols, 56% clay, 20% Silt, 3.3 7% OC, 7.4 PH	23.4°C, 11,941 mm, AW2	60
Ingenio Jose Maria Morelos, Jalisco Pacific Mexico				
1	El Saucillo, −104.44°, 19.62°, 324 m asl	Haplic Phaeozems, 40% clay, 36% silt, 1.4% OC, 8.5 PH	25.6°C, 1,549 mm, AW2	75
2	La Parota 1, −104.48°, 19.60°, 294 m asl	Haplic Phaeozems, 40% clay, 36% silt, 1.4% OC, 8.5 PH	25.7°C, 1,469 mm, AW2	60
3	Los Riegos, −104.44°, 19.59°, 319 m asl	Haplic Phaeozems, 40% clay, 36% silt, 1.4% OC, 8.5 PH	25.5°C, 1,581 mm, AW2	70
4	La Parota 2, −104.49°, 19.60°, 285 m asl	Haplic Phaeozems, 40% clay, 36% silt, 1.4% OC, 8.5 PH	25.7°C, 1,469 mm, AW2	70
5	Los Altillos 1, −104.47°, 19.56°, 290 m asl	Haplic Phaeozems, 40% clay, 36% silt, 1.4% OC, 8.5 PH	25.6°C, 1,441 mm, AW2	64
6	Los Altillos 2, −104.48°, 19.56°, 283 m asl	Haplic Phaeozems, 40% clay, 36% silt, 1.4% OC, 8.5 PH	25.7°C, 1,408 mm, AW2	62
7	Rancho Gudino 1, −104.50°, 19.51°, 291 m asl	Haplic Phaeozems, 44% clay, 28% silt, 2.21% OC, 6.3 PH	25.6°C, 1,358 mm, AW2	65
8	Rancho Gudino 2, −104.51°, 19.54°, 261 m asl	Haplic Phaeozems, 40% clay, 36% silt, 1.4% OC, 8.5 PH	25.7°C, 1,357 mm, AW2	63

[a]Soil units described by FAO-UNESCO-ISRIC (FAO 1988).
[b]Respectively: mean annual temperature, mean annual rainfall, Koppën classification modified by García (1973).
[c]Average cane yield for growth cycle 2009–2010 and 2010–2011 for sites in Ingenio Plan de Ayala, San Luis Potosi, Northeastern Mexico, and 2007–2008 and 2008–2009 for sites in Ingenio Jose Maria Morelos, Jalisco, Pacific Mexico, under dryland conditions.

2.6 | Model application to forecast climate change impact

First, to ensure that the model simulates accurately the two growing seasons considered in the baseline yield data, the model was run with the reported management conditions (Table 3) and soil type of each site (Table 2). The baseline climatic conditions of the two growing seasons for Jalisco and San Luis Potosi were also used. The model was run several times; each time, the planting date of each site was adjusted (this was necessary as our database contained the month of planting and harvesting but not the day) until we obtained the lowest difference between measured and simulated yield. This minimized the prediction error, which was measured by calculating the index of agreement (D), a standardized measure of the degree of model prediction error (Willmott, 1981), and applying the Fisher's paired t test to assess differences between measured and simulated sugarcane dry biomass.

Next, the model was rerun, using each of the decadal climate scenarios while keeping constant the management conditions and soil type of each site. A similar approach has been used in other climate impact studies (e.g. Knox, Rodriguez, Nixon, & Mkhwanazi, 2010; Lui et al., 2013; Jones and Thornton 2013).

The impact on sugarcane production was determined by calculating the difference between the simulated yield in each decadal climate scenario and the baseline simulated yield. To determine the climate-related factors with more influence on future sugarcane yield (dry matter), a multiple correlation analysis of climatic/weather variables was performed for each study area. For the variables that showed significant correlations, the tendency or linear regression (simple or multiple) was determined using the PROC REG procedure in SAS (SAS Institute, 2000), considering simulated dry matter yields for the decadal periods within 2021–2050 as the dependent variable and precipitation, evapotranspiration, potential evapotranspiration, and number of water and temperature stress days as independent variables.

3 | RESULT AND DISCUSSION

3.1 | Model accuracy

The model was considered adequate as a tool to forecast the climatic impact on sugarcane yield during 2021–2050. The simulated and measured dry matter yields of sugarcane cultivar (CP 72-2086) growing in the sugarcane regions of the Ingenio Plan de Ayala in San Luis Potosi (Northeastern Mexico) and Ingenio Jose Maria Morelos in Jalisco (Pacific Mexico) were not significantly different ($p \leq .05$), considering the calculated paired t test statistic of 0.79 and 0.007 with 15 and 9 degrees of freedom for both regions, respectively. Overall, the ALMANAC model was able to simulate dry matter yield with acceptable accuracy, with an agreement index of 0.89 and 0.53 and with a mean simulation error of −0.4 and 6 Mg/ha for San Luis Potosi and Jalisco, respectively.

3.2 | Climatic impact on sugarcane yield in Northeastern Mexico

The increases in temperature forecasted for the three decadal periods 2021–2030, 2031–2040 and 2041–2050 in the sugarcane mill region of Ingenio Plan de Ayala in the Northeastern Mexican state of San Luis Potosi have been estimated to be 0.8, 1.0 and 1.3°C, respectively (Medina-García et al., 2011; Ruiz-Corral et al., 2010). Based on the results of the present study, these temperature increases are expected to have a positive impact on sugarcane yields in the area (Table 4). The increases in dry matter yield, ranging from 1.2 to 9.0 Mg/ha, represent increments of 2%–10% during 2012–2030, 2%–10% during 2031–2040 and 2%–13% during 2041–2050. The largest increases were recorded at sites planted and harvested during the period September to January (sites 1, 2, 4 and 6). The lowest increase was in an area planted and harvested during October to April (Site 3). These results are similar to those reported by

TABLE 3 Management practices in two Mexican sugarcane regions planted to CP 72-2086 cultivar under dryland conditions (Harvest periods 2008–2009, 2009–2010)

Management practice	Ingenio Plan de Ayala, San Luis Potosi[a]. Northeastern Mexico	Ingenio Jose Maria Morelos, Jalisco[b]. Pacific Mexico
Land preparation	Subsoil: February, April or May	Subsoil: October, November and December
	First ripping: April	Ripping (3 times): October–November
	Second ripping and fallow: May	Fallow: October–December
	Herbicide application: June	Herbicide application: June–July
Planting period	September–November	October–December
Plant density	6–8 Mg of seed/ha	10–12 Mg of seed/ha
Planting method	Manual in inter-row furrows of 1.3 m	Manual in inter-row furrows of 1.4 m
Fertilization	First application: 23-22-10. Subsequent applications N: 100, P: 50, K: 100. Applied manually in moist soil	First application: Triple 16 (16-16-16) or 20-10-10. Subsequent applications urea or ammonium sulphate and organic compost (2 Mg/ha). Applied manually in moist soil
Harvesting	December–January	December–January
Other practices	Weed and pest control	Weed and pest control

Source of information: [a]farmer interviews and on-site surveys. [b]Alvarez-Cilva (unpublished research data).

TABLE 4 Forecasted yield (Mg Dry Matter ha^{-1}) for 2021–2050 of CP72-2086 sugarcane under dryland conditions in Ingenio Plan de Ayala mill region, San Luis Potosi (Northeastern Mexico) and the percentage of change compared to baseline yield

	Planting dates[a]	Baseline simulated yield	Forecasted yield during decadal periods and percentage of change compared to baseline		
			2021–2030	2031–2040	2041–2050
SITE 1	11/10	54.7	59.6 (8.2)	61.1 (10.5)	62.8 (12.9)
SITE 2	09/10	58.8	65.2 (9.8)	65.5 (10.2)	67.8 (13.2)
SITE 3	10/10	72.8	74.2 (1.9)	74.2 (1.9)	74.0 (1.6)
SITE 4	09/10	58.8	65.1 (9.7)	65.4 (10.1)	67.7 (13.1)
SITE 5	09/10	58.8	65.2 (9.8)	65.5 (10.2)	67.8 (13.2)

[a]Arvesting dates were 01/28 for all sites except Site 3 that was 04/28.

Da Silva et al. (2008), who forecasted increases of up to 13% in the production of sugarcane in Brazil and Australia under year 2070 scenarios. Singels, Jones, Marin, Ruane, and Thorburn (2014) similarly reported future yield increases of +9% in dryland sugarcane in Brazil and 20% in South Africa.

Canopy photosynthesis and partitioning to leaves, stems, roots and storage organs are important factors in biomass accumulation (Guo, Kang, Ouyang, Zhuang, & Yu, 2015). In crop production, the leaf area development is crucial for interception of solar radiation and accumulation of crop mass. The rate of leaf appearance is strongly dependent on air temperature (Sinclair et al., 2004). In this study, significant differences in leaf area index (LAI) were seen at the sites. Sites 1 and 2, which were planted in November and September, respectively, (Figure 2a,b) and harvested in January, showed high increases in yield (+13%) with future climate, while Site 3 (Figure 2c), which was planted in October and harvested in April, showed only a slight yield increase of 2%.

At sites 1 and 2 (Figure 2a,b), the simulated LAI for the baseline and the three scenarios had a logarithmic growing pattern until achieving a similar value, reaching a maximum value of 6.0 ± 0.1 in December. When comparing monthly LAI of each scenario relative to baseline (LAI baseline minus decadal LAI scenario), it can be observed in Figure 2 (a and b inset) that the biggest difference was in the month of May, with a mean 0.40 ± 0.1 and 0.6 ± 0.2 in three climate scenarios for sites 1 and 2, respectively. On the other hand, in Site 3, maximum LAI occurred in February for the baseline, in January for decades

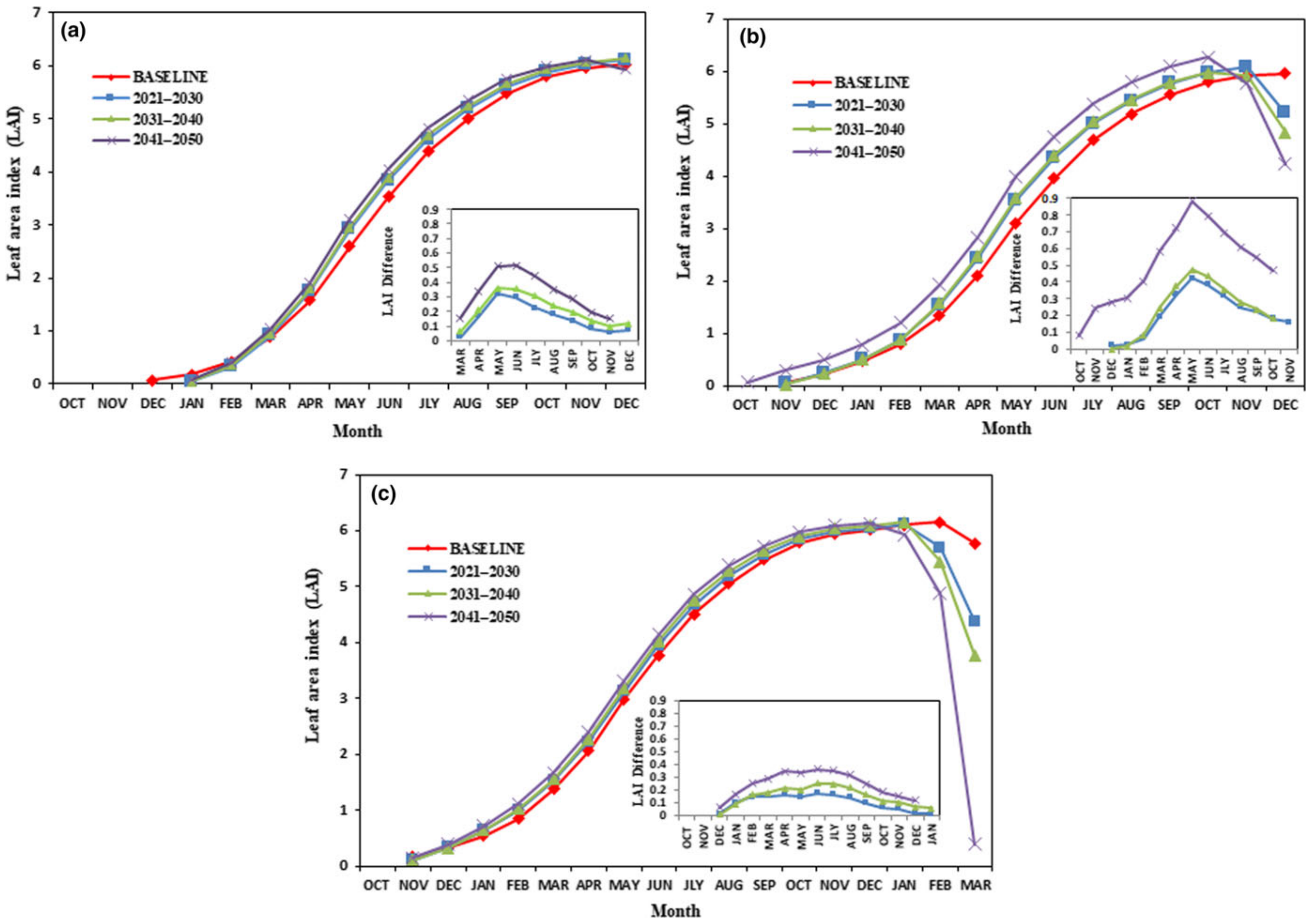

FIGURE 2 Leaf area index (LAI) of three farm sites planted to CP 72-2086 sugarcane under dryland conditions in the Ingenio Plan de Ayala mill region in San Luis Potosi (Northeastern Mexico) and monthly LAI difference (inset) between the decadal periods and baseline. Site 1 (a) and Site 2 (b) were planted in November and September, respectively, and harvested in January. Site 3 (c) was planted in October and harvested in April

2021–2030 and 2031–2040 and in December for 2041–2050 (Figure 2c). The highest mean monthly differences in LAI (0. 3 ± 0.1) were recorded in June in the three scenarios (Figure 2c, inset). The LAI decreased sharply from January. This may be a reason why yield increases at this site were less, compared to those at the site planted in September (Site 2), by 5.0, 5.3 and 7.8 Mg/ha during the decades 2021–2030, 2031–2040 and 2041–2050, respectively.

In sugarcane production, flowering is considered undesirable as it results in reduced sugar yields (Coleman, 1968; Rao, 1977). Moreno (2010) mentions that the CP72-2086 is a cultivar that flowers up to 95%; the early and heavy flowering (Milanes-Ramos et al., 2010) negatively affects sugarcane production. Rao (1977) reports a simple negative linear relationship between cane (and sugar) yield per plant and the proportion of canes that flowered. Floral initiation occurs when the day length is 12.5 hr (Coleman, 1968). In the present study, the monthly above-ground production reached the maximum soon after the maximum photoperiod (13.32 hr in the Northeastern Region) at sites 1 and 2, planted in November and September, respectively (Figure 3). The largest monthly increases in biomass (mean 12.7 Mg/ha) at both sites were recorded in the month of July, which had a photoperiod of 13.2 hr. On the other hand, the months of October and November, which had photoperiods of 11.6 and 11.0 hr, respectively, showed a mean reduction of 4 Mg/ha in the monthly rate of above-ground biomass production. If theoretically converted to sucrose loss, at 12.24% recovery rate (USDA, 2006), the reduction in biomass represents 0.49 Mg ha^{-1} month^{-1} of sucrose loss.

Considering these results, the planting of cane crops of the CP72 2096 cultivar in the region of Ingenio Plan de Ayala in San Luis Potosi, occurring from September to November, may continue under the current schedule, with the best time for planting in the month of September. However, the harvest period may be shortened by at least a month, that is concluding in November instead of December.

3.3 | Climatic impact on sugarcane yield in Pacific Mexico

The increases in temperature projected for Ingenio Jose Maria Morelos in Jalisco in the Pacific Sugarcane Region are 0.90, 1.1 and 1.4°C for decadal periods 2021–2030, 2031–2040 and 2041–2050, respectively (Medina-García et al., 2011; Ruiz-Corral et al., 2010). These increases are 0.1°C higher than in Ingenio Plan de Ayala in the Northeastern Region. The resulting simulated yield for 2021–2050 showed increases for most of the sites in the area (Table 5). All sites had the same soil type (Table 2). To facilitate discussion of the results, the sites were grouped according to the nearest meteorological station used to create the decadal climate scenarios.

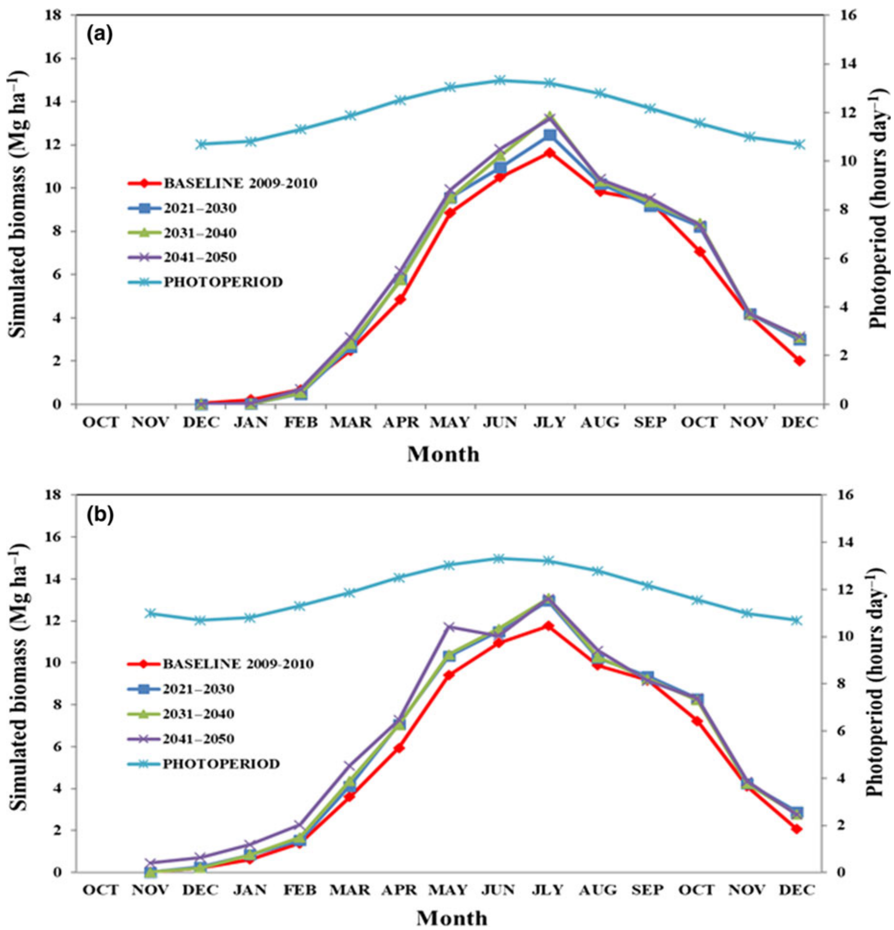

FIGURE 3 Biomass and photoperiod at sites 1 (a) and 2 (b) in San Luis Potosi (Northeastern Mexico) planted to CP72-2086 sugarcane under dryland conditions in November and September, respectively, and harvested in January

TABLE 5 Forecasted yield (Mg Dry Matter ha^{-1}) for 2021–2050 of CP72-2086 sugarcane under dryland conditions in Ingenio Jose Maria Morelos mill region, Jalisco (Pacific Mexico), and the percentage of change compared to baseline yield

	Farmer Site	Planting dates[a]	Baseline simulated yield	Forecasted yield during decadal periods and percentage of change compared to baseline		
				2021–2030	2031–2040	2041–2050
Group 1	1	10/15	68.2	68.1 (−0.1)	67.3 (−1.3)	68.8 (0.9)
	2	12/20	60.9	64.0 (5.1)	64.8 (6.4)	64.7 (6.2)
	3	10/01	68.5	67.7 (−1.2)	68.4 (−0.1)	66.7 (−2.6)
	4	11/25	64.5	66.6 (3.3)	67.2 (4.2)	67.1 (4.0)
	5	12/26	57.1	62.7 (9.8)	64.6 (13.1)	64.9 (13.7)
	6	11/21	65.7	66.5 (1.2)	67.6 (2.9)	66.6 (1.4)
Group 2	7	12/02	58.0	63.3 (9.1)	64.0 (10.3)	64.7 (11.5)
	8	12/25	55.0	59.5 (8.2)	61.1 (11.1)	61.6 (12.0)

[a]Harvest dates were 12/28 for all sites except Site 7, which was 12/25. Group I farm sites had the same soil type and weather stations; Group II farm sites had the same soil type but different weather stations.

Group 1 (farm sites 1–6) had increases in a range of 0.6–7.8 Mg/ha and decreases of 1.84–0.1 Mg/ha (Table 5). Planting date was the only difference among the sites of this group (Table 5). The sites planted during the period November and December (sites 2, 4, 5 and 6) showed increases in yield, while those planted in October (sites 1 and 3) showed decreases. Group 2 farm sites 7 and 8, both planted in December, showed almost the same yield increases in the range of 4.5–6.7 Mg/ha.

The observed LAI varied in sites 3, 4 and 5 (Figure 4). At Site 3 (planted in October), the maximum LAI value (6.1) was reached in September in the baseline and 1 month earlier (August) in the three

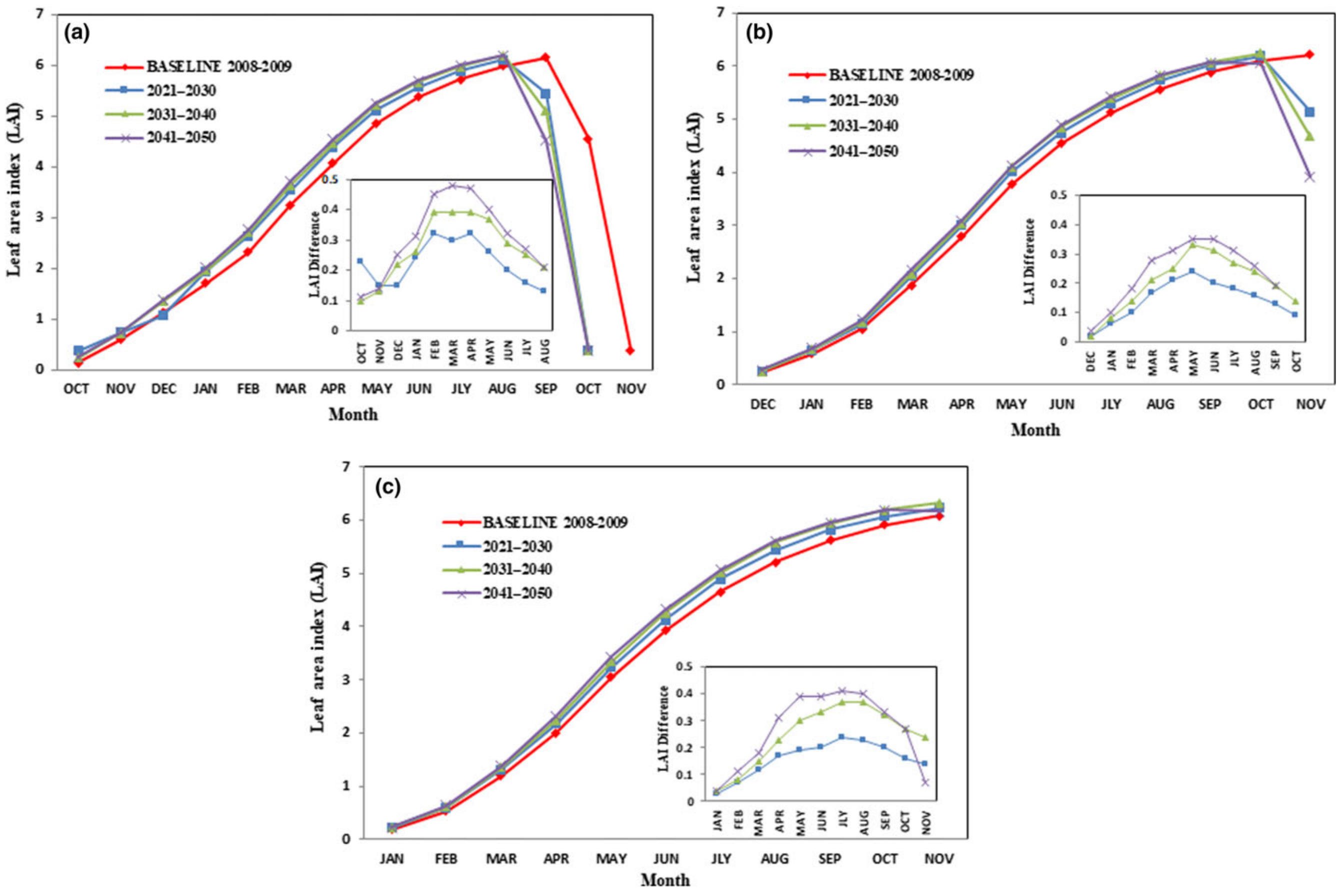

FIGURE 4 Leaf area index (LAI) of three farm sites planted to CP 72-2086 sugarcane under dryland conditions in the Ingenio Jose Maria Morelos mill region in Jalisco (Pacific Mexico) and monthly LAI difference (inset) between the decadal periods and baseline. Site 3 (a), Site 4 (b) and Site 5 (c) were planted in October, November and December, respectively, and harvested the following December

climate scenarios (Figure 4a). A similar behaviour was seen at Site 4 planted in November; maximum LAI (6.2) was reached in November in the baseline and 1 month earlier (October) in all three scenarios (Figure 4b). At Site 5 (planted in December), the maximum LAI (6.3) was in November for both the baseline and the three scenarios (Figure 4c.).

An analysis of the monthly differences in LAI of the baseline and the three scenarios (Figure 4 inset) shows large differences of up to 0.5 of LAI at sites planted in October (Figure 4a, inset) and up to 0.4 of LAI at the site planted in November (Figure 4b, inset). At the site planted in December (Figure 4c, inset), the difference was up to 0.7 during the 2041–2050 scenario, where more than 5 Mg/ha (13.7%) increases in yield are forecasted (Table 5).

A possible reason for the difference in forecasted yields is the behaviour of LAI once the maximum value has been reached. Sites 3 and 4 planted in October and November showed LAI reductions in the range of 0.7–4.2 and 0.1–2.4, respectively, while the site planted in December (Site 5) did not record any LAI reduction. As for the behaviour of the monthly increases in above-ground biomass at each site (Figure 5), the maximum biomass increase was in August at all three sites, coinciding with the maximum LAI and photoperiod of 12.7 hr. After August, a reduction in LAI is reflected in reduction in the rate of above-ground biomass production, with greater effect on the site that was planted early (Figure 5a).

It was possible to quantify the effect of floral initiation (due to the shortening of the photoperiod at all sites) on the rate of above-ground biomass production. For the months of October and November, whose photoperiods were 11.6 and 11.10, respectively, the rate of above-ground biomass production was reduced by 4 Mg/ha, with an estimated loss of 0.49 Mg/ha month of sucrose (12.24% recovery rate, USDA, 2006). These amounts are similar to those obtained for Northeastern Mexico, as previously discussed.

3.4 | Midsummer drought impact on sugarcane yield in Pacific Mexico

According to Marengo et al. (2014), in Central America and Mexico, warm days are likely to increase (cold days likely to decrease) and warm nights likely to increase (cold nights likely to decrease), and the region is expected to have more frequent, longer and more intense heat waves, warm spells in most of the region and an increase in dryness. In our study, it was possible to quantify the current and future impact of the phenomenon called midsummer drought (MSD) or "canicula" on the sugarcane crop (Figure 5). The MSD refers to the annual cycle of precipitation over the southern part of Mexico, upper Midwest of the United States and Central America, whose binomial distribution exhibits a maxima during June and September–October and a relative minimum during July and late August. It corresponds to a decrease in the amount of rain and not to an actual drought period. Highly variable in magnitude, its signal can also be detected in other climatic variables, such as minimum and maximum surface temperature (Magaña, Amador, & Medina,

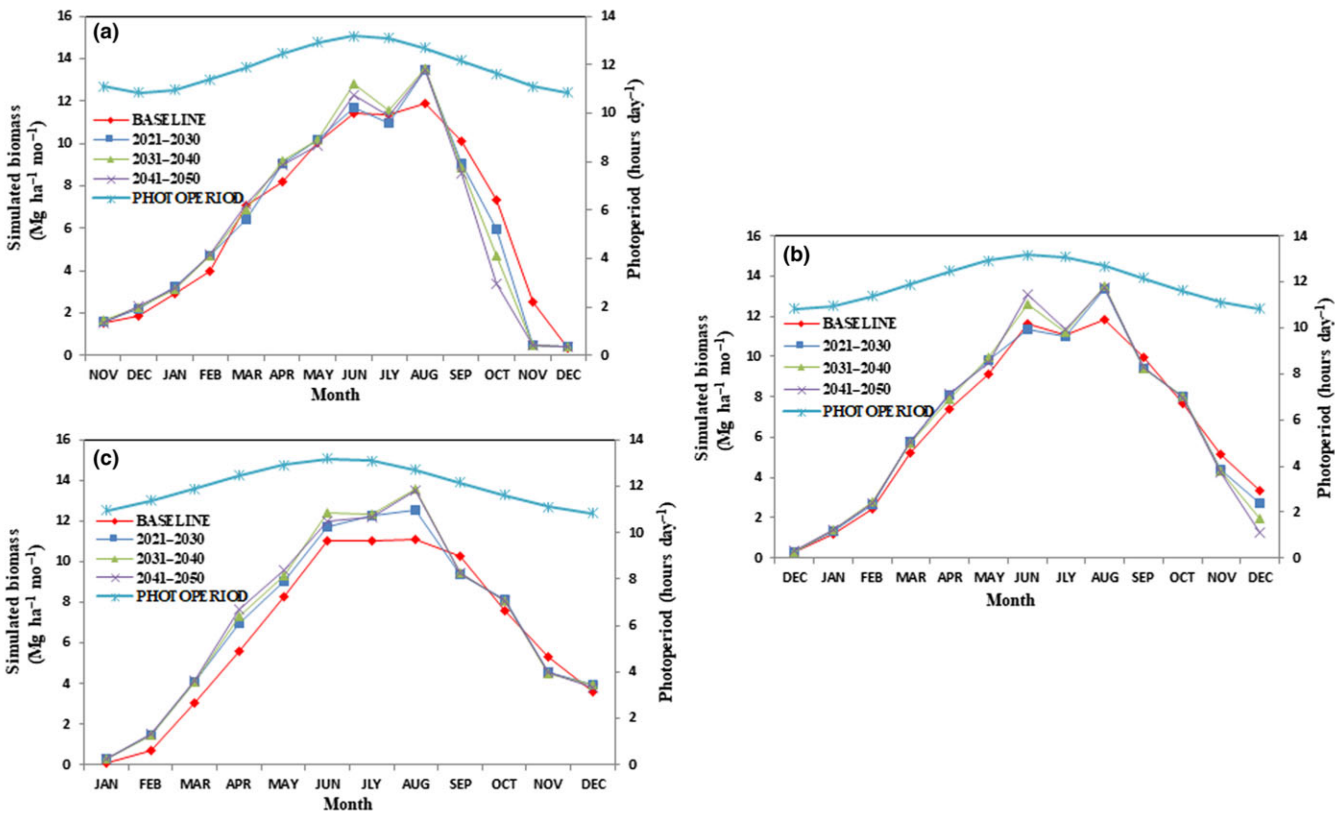

FIGURE 5 Biomass and photoperiod at sites 3 (a), 4 (b) and 5 (c) in Jalisco (Pacific Mexico) planted to CP 72-2086 sugarcane under dryland conditions in October, November and December, respectively, and harvested the following December

1999). The MSD recorded in the Mexican Pacific Region differentially affects the rate of above-ground biomass production during the July–August period at different sites (Figure 5).

Our study results show that in the sugarcane area of Ingenio Jose Maria Morelos in the Pacific Region, the MSD affects the monthly rate of above-ground biomass production in varying magnitude depending on the planting dates (Figure 5). For October planting (Site 3), MSD decreases the biomass production by 0.1 Mg/ha for the baseline and by 0.98 ± 0.3 Mg/ha for the mean in the three scenarios. Its greatest impact can be observed in 2031–2040, which shows a 1.3 Mg/ha reduction (Figure 5.).

For November planting (Site 4), the reduction in above-ground biomass is 0.5 Mg/ha for the baseline and 1.7 Mg/ha during 2041–2050, while for December planting (Site 5), a reduction of 0.1 Mg/ha resulting from MSD is observed during 2031–2040 (Figure 5c). The MSD is thus expected to have greater impacts in the coming decades, especially in 2041–2050.

As mentioned earlier, the MSD affects not only the amount of precipitation but also the surface maximum and minimum temperature. With precipitation decrease, maximum temperature rises in a short period of time (Magaña et al., 1999), and heat stress can occur abruptly. Even short episodes of high temperature can severely affect yields (Siebert et al., 2014). Heat stress in a C4 plant constrains biomass accumulation by limiting photosynthesis due to enzyme inhibition, which is more severe when the temperature increases rapidly rather than gradually (Crafts-Brandner & Salvucci, 2002). As the impacts in terms of reduced biomass accumulation may go unnoticed by producers and mill technicians, process-based crop models will be of help in quantifying the impact of heat and drought on crop yield (Siebert et al., 2014).

Deressa, Hassan, and Poonyth (2005) suggest that for adaptation strategies, special attention should be given to technologies and management regimes that enhance sugarcane tolerance to warmer temperatures. In the case of the studied areas, later planting (i.e. in December) in the Pacific Region is advantageous as seen in the case of sites 7 and 8 (Figure 6), which were planted in December (Table 5) along with sites 2 and 5 of Group 1. All these four sites showed the largest increases in yield (Table 5). Planting in December and harvesting during late October and early November are recommended to avoid negative impacts from midsummer drought and floral initiation. Conde, Ferrer, and Orozco (2006) also mention changing planting dates in their discussion of incremental strategies for maize (*Zea mays* L.) in dryland areas in three municipalities of Mexico, considering climatic extreme events such as El Nino (ENSO).

The results of the present study illustrate how planting date will be strategic to sugarcane in mitigating the adverse effects of future climate change (e.g. increasing intensity of the midsummer drought). At least for the next three decades (2021–2040), planting in December could be a technological option in sugarcane areas in Pacific Mexico. This region will need other agricultural technologies and practices to deal with such climate changes during the future decades after 2040. In their study of maize in sub-Saharan Africa, Folberth et al. (2014) mention that until the 2060s, crop management may be the main factor in obtaining yield targets and sustaining agroecosystems.

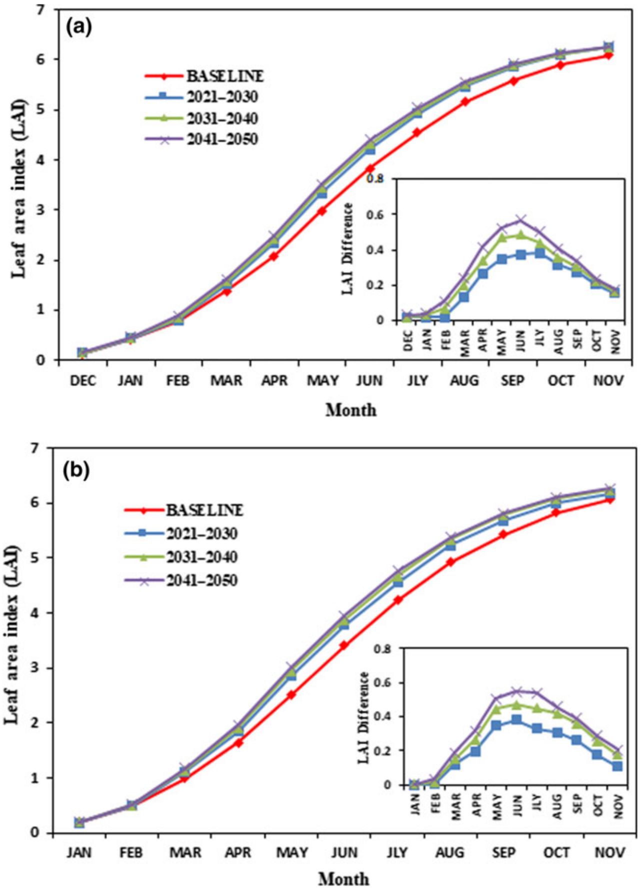

FIGURE 6 Leaf area index (LAI) of three farm sites planted to CP 72-2086 sugarcane under dryland conditions in the Ingenio Jose Maria Morelos mill region in Jalisco (Pacific Mexico) and monthly LAI difference (inset) between the decadal periods and baseline. Site 7 (a) and Site 8 (b) were planted in December and harvested the following December

3.5 | Influence of climate factors on predicted yields

Sugarcane's life cycle spans different seasons (rainy, winter and summer). Air temperature, solar radiation and moisture availability are generally considered the main climatic components controlling the growth, yield and quality of this crop (Marengo et al., 2014). In this study, we tried to determine the climatic-related factors likely to influence future sugarcane yield as this may help decision-makers plan the right type of practices or technology to be implemented during succeeding decades. Several climatic variables showed significant relationships with simulated sugarcane production in the Northeastern and Pacific Regions of Mexico for 2021–2050 (Table 6). Evapotranspiration showed the strongest single factor relationship to simulated production, explaining 93% of the yield variability in the

TABLE 6 Climatic variables with significant effect on the forecasted sugarcane yield for the decadal periods 2021–2050 under dryland conditions in the sugarcanes regions in Northeastern Mexico and Pacific Mexico

Sugarcane region	Variable	Regression model	Determination coefficient (R^2)	Level of significance of the regression model
Ingenio Plan de Ayala, San Luis Potosi (Northeastern Mexico)	Evapotranspiration	$Y = 0.01x + 31.59$	.93	0.001
	Number of water-stress days	$Y = -0.46x + 56.70$	.33	0.02
	Number of temperature stress days	$Y = -0.26x + 48.75$	.88	0.001
	Evapotranspiration and number of temperature stress days	$Y = 31.71 + 0.01x_1 - 0.08x_2$	.94	0.001
	Evapotranspiration, number of water and temperature stress days	$Y = 36.59 + 0.01x_1 - 0.03x_2 - 0.10x_2$	.97	0.001
Ingenio Jose Maria Morelos, Jalisco (Pacific Mexico)	Precipitation	$Y = 0.02x + 42.37$	.65	0.001
	Evapotranspiration	$Y = 0.01x + 28.22$	.77	0.001
	Potential evapotranspiration	$Y = 0.01x + 32.76$	.54	0.001
	Precipitation and evapotranspiration	$Y = 31.05 + 0.01x_1 + 0.01x_2$	.77	0.001
	Precipitation and potential evapotranspiration	$Y = 39.74 + 0.001x_1 + 0.01x_2$	.65	0.001

Northeastern Region and 77% in the Pacific Region. Evapotranspiration has been identified in other studies (e.g. Hanson, 1991) as the most significant component of the hydrologic budget. Long-term changes in evaporation and potential evapotranspiration are expected to greatly impact agricultural crop performance (Chattopadhyay & Hulme, 1997). Factors affecting evapotranspiration are weather parameters, crop factors and management and environmental conditions, such as salinity, poor land fertility, limited application of fertilizer, presence of hard or impenetrable soil horizons, the absence of control of diseases and pests and poor soil management (Allen et al., 1998).

Precipitation and evapotranspiration were highly significant in the Pacific Sugarcane Region, explaining 65% and 77%, respectively, of simulated sugarcane yield for 2021–2050. As previously discussed, the more intense midsummer drought will have greater impact on yield in the future in this sugarcane region. On the other hand, temperature and number of days with stress by temperature and water (simulated by the ALMANAC) showed significance only in the Northeastern Region of Mexico, accounting for 88% and 33%, respectively, of simulated yield (Table 6). These results agree with those of Gbetibouo and Hassan (2005) and Deressa et al. (2005), whose studies on effects of climate change on sugarcane in South Africa showed higher sensitivity to future increases in temperature than precipitation. Temperature has an impact on phenological development, causing temperature stress and damage when exceeding certain thresholds (Folberth et al., 2014). In this regard, farmers can help mitigate the adverse effects of climate change by implementing beneficial management practices that enhance the ability of sugarcane to cope with climate-related stresses. For instance, to reduce soil temperature and potential evapotranspiration, they can apply organic matter, such as compost material derived from the industrialization process in the sugarcane mills, and practice green manuring by sowing non-competing legume species or setting bean crop between rows of newly planted cane.

4 | CONCLUSIONS

In general, the increases in temperature projected for the next 50 years are expected to have a positive impact on sugarcane production in the Northeastern and Pacific Regions of Mexico, resulting in yield increases in areas planted to the sugarcane cultivar CP72 2086. Evapotranspiration is seen as the climate variable with the most influence on simulated regional yield in Pacific Mexico for 2021–2050, while in the Northeastern Region, the significant variables are evapotranspiration and the number of water-stress days and temperature stress days. The climate phenomenon "canicula" or midsummer drought will be more intense in 2021–2050 in the sugarcane regions near the Pacific, causing an estimated decrease of 0.5–1.7 Mg/ha in July–August. To mitigate this effect, sugarcane producers can modify crop management and avoid planting in the months of October and November. In addition, agricultural technologies and practices may be put in place, such as the use of heat- or drought-tolerant varieties and setting up of irrigation systems during periods of the year when heat and water stress are expected.

In both the Northeastern and Pacific Regions, harvest may be advanced by 1–2 months to achieve increases in yield and avoid early flowering that could negatively affect the cane production with sucrose loss of 0.49 Mg ha^{-1} $month^{-1}$.

The projected increases in sugarcane may help improve Mexico's capability to produce sugarcane for bioenergy without affecting sugar production for food for the domestic and export markets. However, it is necessary for the sugar sector to establish strategies that involve modifying the management regimes (e.g. planting and harvest dates) and accelerating research on short cycle varieties for replacing intermediate and late varieties currently established in Mexico to maximize the positive impacts of the forecasted climatic change on sugarcane in the decades to come.

This study has limitations relating to uncertainties associated with the use of downscaled outputs of global climate models (Lupo &

Kininmonth, 2013; Thornton et al., 2010) and to processes not taken into account in crop modelling (Rosenzweig et al., 2014). According to Rosenzweig et al. (2014), changes in the normal patterns of temperatures are likely to give rise to changes in the incidence of pests and diseases, which can affect production. It is thus necessary to find ways of integrating the predicted new scenarios with the incidence of primary and secondary pests affecting sugarcane.

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APPENDIX

FUTURE CHANGES IN THE MAXIMUM AND MINIMUM TEMPERATURES (°C) AND PRECIPITATIONS (MM) IN THE NORTHEASTERN AND PACIFIC SUGARCANE REGIONS OF MEXICO DURING THE PERIOD 2021–2050.

		Decadal period								
		2021–2030			2031–2040			2041–2050		
	Month	Tmax	Tmin	PPT	Tmax	Tmin	PPT	Tmax	Tmin	PPT
Jose Maria Morelos, Pacific Mexico	January	0.8	0.9	−3.1	1.1	1.2	−2.3	1.3	1.4	−3.7
	Feb	0.8	0.9	−1.0	1.1	1.1	−1.1	1.4	1.5	−1.1
	March	0.7	0.7	−0.8	1.0	1.0	−1.4	1.2	1.3	−1.4
	April	0.9	1.0	−1.0	1.3	1.3	−0.7	1.6	1.6	−0.5
	May	0.7	0.8	6.0	1.1	1.2	−8.1	1.4	1.4	−6.5
	June	1.0	1.0	1.7	1.3	1.4	−1.9	1.8	1.8	0.6
	July	0.9	0.9	−6.5	1.2	1.2	0.2	1.6	1.6	−8.8
	August	1.0	1.0	−15.3	1.3	1.3	−18.9	1.8	1.8	−8.9
	Sept	1.1	1.1	−24.7	1.3	1.3	−28.3	1.4	1.4	−25.3
	October	0.9	0.9	−15.3	1.1	1.1	−16.3	1.3	1.4	−19
	November	0.7	0.7	−0.6	0.7	0.8	−0.6	1	1.1	4
	December	0.6	0.7	−1.2	0.9	1.0	−1.2	1.3	1.3	−1.7
Plan de Ayala, Northeastern Mexico	January	0.9	0.8	−2.4	1.0	1.0	−2.9	1.2	1.2	−3.3
	Feb	0.8	0.8	−4.3	1.1	1.1	−4.1	1.4	1.4	−6
	March	0.6	0.6	0.2	0.9	0.9	−2.1	1.1	1.1	−3.3
	April	0.8	0.8	0.6	1.1	1.1	1.0	1.5	1.5	4.8
	May	0.8	0.8	−5.7	1.0	1.0	5.3	1.3	1.3	2
	June	0.8	0.8	10.2	1.0	1.0	4.8	1.4	1.4	7
	July	0.8	0.8	−8.2	1.1	1.1	−2.0	1.5	1.5	−13.6
	August	0.9	0.8	−2	1.1	1.1	1.8	1.4	1.4	−17.3
	Sept	1	0.9	−13.1	1.1	1.1	1.8	1.4	1.4	−24.6
	October	0.6	0.6	−13.9	0.8	0.8	−11.7	0.8	0.8	−20.6
	November	0.8	0.8	3.1	1.0	1.0	1.0	1.1	1.1	−3.2
	December	1.1	1.1	−3.7	1.0	1.0	−3.0	1.6	1.6	−5.1