Impact of climate change on rainfed sugarcane in Veracruz, Mexico

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ABSTRACT

Objective: To estimate the expected quantitative changes of the rainfed sugarcane yield in four sugar mills in the state of Veracruz using climate change scenarios for the end of the 21st century and considering that the same climate change could also affect soil fertility.

Design/methodology/approach: The data on the cultivated area with the rainfed sugarcane such as topography, principal properties of soil fertility, crop yields for the beginning of the 21st century, current climatic data from the meteorological stations and future ones based on existing climate change scenarios were analyzed. Then, by means of a physiological model of this crop based on biological, climatic and soil characteristics, proposed by IIASA/FAO, the current and future agricultural productivity of sugarcane was calculated. The actual productivity calculated with this model was compared with the observed data. Then, the productivity of this crop for the end of the 21st century was calculated. The comparative impact on the productivity of the expected changes in some climatic components and corresponding expected modification in soil fertility was assessed.

Results: The results of calculations indicate that if the CO_2 concentration in the atmosphere increases by 2 or 2.7 times at the end of the 21st century and the current varieties of sugarcane and their crop management will conserve, the yield of sugarcane will decrease up to 20% depending on the climate change scenario and location of the plot. The main climatic factor influencing the decrease in sugarcane productivity is the expected decrease in precipitation.

Limitations on study/implications: Monthly average climatic variables are used for both current and future productivity calculations since there are no estimates of daily data. There are also no predictions on the development of crop management technology as well as on the expected change in pests and diseases for the end of the 21st century.

Findings/conclusions: The IISA/FAO physiological model of sugarcane growth based on agroecological principles, considering even limited number of climatic variables, is useful for calculating of sugarcane productivity with correlations greater than 90% for calculated and observed data. This allowed us to estimate the expected impact of climate change in the productivity of rainfed sugarcane in Veracruz State of Mexico at the end of 21st century.

Keywords: calculation of agricultural crop yield, radiative index of dryness, integral soil fertility index, scenarios of the climate change.

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INTRODUCTION

Sugarcane (*Saccharum officinarum*) is an important crop for Mexico. SIAP (2022) reported that the country ranked eighth worldwide in annual production of 55 million tons of sugarcane and that the state of Veracruz ranked first in the country with a production of 21 million tons. About 50% of this crop in the state of Veracruz is produced under rainfed conditions.

Despite the importance of this crop and the existence of programs to support producers to increase the sugarcane production, there are few studies on the impact of the global climate change on this crop. Studies carried out in several countries around the world indicate that climate change can significantly affect the productivity of rainfed sugarcane (Srivastava and Mahendra, 2012; Marin *et al.*, 2013; Guerra and Hernández, 2014; Zhao and Li, 2015; Linnenluecke *et al.*, 2018). These studies used different approaches such as: analysis of observed statistical data on historical crop yields depending on climatic conditions, econometric regression models, simple models of crop development, etc. However, there are no studies based on physiological modeling of the sugarcane growth. In addition, the alteration of soil fertility depending on the climate change and its indirect impact on crop productivity have not been considered. Meanwhile this indirect impact can cause change up to 30% in the productivity of some agricultural crops (Castillo *et al.*, 2007).

Therefore, the purpose of this paper is to estimate the impact of the global climate change on the productivity of rainfed sugarcane in the state of Veracruz by the end of the 21st century using a physiological model of sugarcane growth (IIASA/FAO, 2012). This model considers the direct effect of climate on the crop yield. In addition, the alteration of soil fertility due to the same climate change can be considered. Unfortunately, it is still impossible to assess the change in pests and plant diseases depending on the climate change scenarios. The existing mathematical models to assess the impact of climate change on diseases and pests are empirical (CEPAL-FAO, 2013; Donatelli *et al.*, 2017). This means that the parameters of these models are applicable only to the geographic locations where they were assessed and cannot be used in arbitrary other locations without further justification. However, it can be assumed that plant protection practices will be improved in the future to avoid significant crop losses due to plant pests and diseases.

MATERIALS AND METHODS

The study was carried out for four sugar mills in the state of Veracruz: Coatotolapan, San Cristóbal, San Pedro and Tres Valles (Table 1).

The typical climatic conditions for the beginning of the 21st century were calculated using information from the meteorological stations located within the area of each sugar mill (CONAGUA, 2021). While the data on area, soil texture and typical nutrient content for each soil group in the sugarcane plot were obtained from the publications (INEGI, 1988; INEGI, 2004 and SIAP-COLPOS, 2009).

The climatic conditions for the end of the 21st century were assessed based on the climate change predictions for the atmospheric circulation models GFDL-CM3, HADGEM2-ES and MPI-ESM-LR considering two scenarios of change in CO_2 concentration in the

Table 1. Characteristics of the sugar mills in the state of Veracruz where the expected impact of the global climate change on the productivity of rainfed sugarcane has been assessed.

Sugar mills	Municipalities	Cultivated area (ha)	Codes of meteorological stations	Altitude range (masl)	Main soil groups
Coatotolapan	Hueyapan de Ocampo, Acayucan, San Andrés Tuxtla, Juan Rodríguez Clara, Santiago Tuxtla	47,417.25	30035 Cuatotolapan, 30185 Lauchapan, 30184 San Juanillo	10-200	Acrisols, Cambisols, Luvisols, Vertisols
San Cristobal	Carlos A. Carrillo, Cosamaloapan, José Azueta, Chacaltianguis, Ixmatlahuacan, Acula, Tlacojalpan, Amatitlan, Tuxtilla Isla, Tlacotalpan, Otatitlan	123,354.85	30152 Garro, 30117 Paraíso Novillero	0-50	Cambisols, Luvisols, Gleysols
San Pedro	Salta Barranca, Angel R. Cabada, Santiago Tuxtla	16,748.36	30015 Angel R. Cabada, 30143 Tres Zapotes	10-570	Vertisols, Cambisols, Litosoles
Tres Valles	Tres Valles, Cosamaloapan de Carpio, Tierra Blanca, Otatitlan, Tlacojalpan, San Miguel Soyaltepec	55, 104.12	20084 Papaloapan, 30045 Ciudad Aleman	10-50	Cambisols, Luvisols, Vertisols, Gleysols

atmosphere: scenario 4.5 (650 ppm CO_2) and 8.5 (1370 ppm CO_2) for the period 2075-2099 (Cavazos *et al.*, 2013; Fernández *et al.*, 2018).

Rainfed sugarcane (*Saccharum officinarum*) yields have been calculated for the beginning (2005 -2015) and end (2075-2099) of the 21st century with the equation proposed by IIASA/FAO (2012) and FAO (2018):

$$Y_{calc}^{j}=\frac{1}{1-\gamma}F_a^j\sum_i^j\left(Y_{pot}^{i}K_{hidr}^{i}\right) \qquad (1)$$

where: Y_{calc}^{j} is the agricultural productivity of the commercial raw mass of the crop (kg ha^{-1} year^{-1}), that is, the part of the biomass of the crop produced in the field, registered and used in the mills to produce sugar; Y_{pot}^{i} is the potential productivity of the commercial raw dry mass of sugarcane (kg ha^{-1}) in the absence of water and nutrient restrictions and free of pests or diseases, during month i of year j; K_{hidr}^{j} is the soil moisture coefficient that depends on the intensity of evapotranspiration of the crop and indirectly considers the soil moisture in month i of year j (dimensionless, varies from 0 to 1); F_a^j is the integral soil fertility index; γ is a coefficient that corresponds to the fraction of water content in commercial raw mass of the crop (dimensionless, less than 1).

The yields Y_{calc}^{j} for the beginning of the 21st century were calculated for each of the actual years from 2005 to 2015 and for the end of the century for an average climatic year for which there are climatic predictions at the monthly level, located in the period from 2075 to 2099 (Fernández *et al.*, 2018).

The relative change in sugarcane yield δY_{calc} by the end of the 21st century was determined as follows:

$$\delta Y_{calc} = \frac{Y_{calc}^{2100}}{Y_{calc}^{2000}} = \frac{Y_{pot}^{2100}}{Y_{pot}^{2000}} \frac{K_{hidr}^{2100}}{K_{hidr}^{2000}} \frac{F_a^{2100}}{F_a^{2000}} = \delta Y_{pot} * \delta K_{hidr} * \delta F_a \tag{2}$$

where: $Y_{pot} = \frac{Y_{pot}^{2100}}{Y_{pot}^{2000}}$; $\delta K_{hidr} = \frac{K_{hidr}^{2100}}{K_{hidr}^{2000}}$; $\delta F_a = \frac{F_a^{2100}}{F_a^{2000}}$; Y_{pot}^{2000} and Y_{pot}^{2100} are the potential yields of dry raw matter at the beginning (j=2000) and end (j=2100) of the 21st century; K_{hidr}^{2000} and K_{hidr}^{2100} are the crop water indices in these periods; F_a^{2000} and F_a^{2100} represent the soil fertility indices for the same period. The values of Y_{pot}^{2000}, Y_{pot}^{2100}, K_{hidr}^{2000}, K_{hidr}^{2100}, F_a^{2000} and F_a^{2100} are average annual values in the periods studied.

For the beginning of the 21st century, the values of Y_{calc}^{2000}, Y_{pot}^{2000} and K_{hidr}^{2000} were calculated as follows:

$$Y_{calc}^{2000} = \frac{1}{1-\gamma} \frac{\sum_{j=2005}^{2015} Y_{pot}^{j}}{11} * \frac{\sum_{j=2005}^{2015} K_{hidr}^{j}}{11} * F_a^{2000} = \frac{1}{1-\gamma} Y_{pot}^{2000} * K_{hidr}^{2000} * F_a^{2000} \tag{3}$$

where: $Y_{pot}^{2000} = \frac{\sum_{j=2005}^{2015} Y_{pot}^{j}}{11}$ y $K_{hidr}^{2000} = \frac{\sum_{j=2005}^{2015} K_{hidr}^{j}}{11}$.

The estimation of the potential yields Y_{pot}^{j} has been made with the formula of IIASA/FAO (2012):

$$Y_{pot}^{j} = H * \sum_i^j \frac{0.36 b_{gm} \beta K_{co_2}}{\frac{1}{N} + 0.25 C_t} \tag{4}$$

where: H is the harvest index or the fraction of the dry biomass of the crop produced in the field which is used to produce sugar (dimensionless, less than one); b_{gm} is the maximum possible intensity of increase in dry biomass (kg ha^{-1} day^{-1}) when the leaf area index *LAI* during the growing season reaches the value 5 (dimensionless); β is the dimensionless relationship between the maximum value of *LAI* in each consecutive month i and the value of $LAI=5$; K_{co_2} is the coefficient that considers the change in performance in the course of the 21st century with respect to its beginning based on the scenario of growth of the concentration of CO_2 in the atmosphere (dimensionless, greater than or equal to one); N is the duration of the crop season in each consecutive month i or its fraction (days); C_t is a coefficient dependent on the air temperature (day^{-1}).

The values of β and C_t are calculated as follows (IIASA/FAO, 2012):

$$\beta = 0.3424 + 0.9051 \ \mathrm{Log}_{10}(LAI) \text{ if } LAI < 5 \text{ and } \beta = 1 \text{ if } LAI \geq 5 \tag{5}$$

$$C_t = 0.0108\left(0.0044 + 0.019T + 0.001T^2\right) \quad (6)$$

where: T is the average air temperature (°C) in each consecutive month i or fraction of the month.

The b_{gm} values are assessed based on the maximum biomass production rate P_m (kg CH_2O ha^{-1} h^{-1}) and some parameters of the photosynthesis of the crop (IIASA/FAO, 2012):

If $P_m > 20$ kg ha^{-1} hour^{-1}

$$b_{gm} = \alpha\left(0.8 + 0.01P_m\right)b_0 + \left(1-\alpha\right)\left(0.5 + 0.025P_m\right)b_c \quad (7)$$

If $P_m < 20$ kg ha^{-1} hour^{-1}

$$b_{gm} = \alpha\left(0.5 + 0.025P_m\right)b_0 + \left(1-\alpha\right)\left(0.05P_m\right)b_c \quad (8)$$

$$\alpha = \left(A_c - 0.24R_g\right)/\left(0.8A_c\right) \quad (9)$$

where: P_m depends on the air temperature T, type of photosynthesis; b_0 and b_c are intensity of increase in gross dry biomass of the crop in cloudy and clear days, respectively (kg ha^{-1} day^{-1}); A_c is maximum active short-wave radiation on clear days (MJ m^{-2} day^{-1}); R_g is global radiation (MJ m^{-2} day^{-1}).

The values of γ, N, LAI, H, P_m and K_{co_2} for the sugarcane crop were obtained from IIASA/FAO (2012) and Allen *et al.* (2006), the values of A_c, b_0 and b_c —from Driessen and Konijn (1992).

The water coefficient K_{hidr}^{j} was determined as follows (IIASA/FAO, 2012; FAO, 2018):

$$K_{hidr}^{j} = 1 - k^{y}\left(1 - \frac{ET_a^{pl}}{ET_0^{pl}}\right) \quad (10)$$

where: k^{y} is the coefficient of sensitivity of the sugarcane crop to the deficiency of water in the soil (FAO, 2012); ET_a^{pl} refers to the actual intensity of crop evapotranspiration when soil moisture is equal to θ; ET_0^{pl} indicates the intensity of potential evapotranspiration in case of water deficiency in the soil.

The typical change in the value of $\left(ET_a^{pl}/ET_0^{pl}\right)$ as a function of soil moisture θ in the active root zone is expressed as follows:

$$\frac{ET_a^{pl}}{ET_0^{pl}} = \frac{\theta - PM}{CC - PM}, \text{ when } PM \leq \theta \leq CC \text{ and } \frac{ET_a^{pl}}{ET_0^{pl}} = 1, \text{ when } \theta \geq CC \quad (11)$$

where: θ - volumetric soil moisture content in the active root zone; *CC* and *PM* are the soil moisture values corresponding to field capacity and wilting point, respectively.

The determination of the K_{hidr}^{j} coefficient was carried out using the CROPWAT program (FAO, 2009).

In order to obtain the fertility index of agricultural F_a^j en sugarcane plots, the equation proposed by Pegov and Jomyakov (1991) was used:

$$F_a^j = 0.46\,\frac{OM}{OM_{max.}} + 0.28\sqrt{\frac{P}{P_{max.}}\frac{K}{K_{max.}}} + 0.26\,e^{-\left(\frac{pH-6}{2}\right)^2} \qquad (12)$$

where: F_a^j is the fertility index at the beginning (j=2000) and end (j=2100) of the 21st century. *OM*, *P*, *K* and *pH* are the modal values of organic matter, phosphorus and potassium content available for the crop and pH, respectively, in the 0-20 cm soil layer of the sugarcane plots at the beginning. (j=2000) and end (j=2100) of the 21st century. The F_a value is dimensionless and varies between 0 and 1, where 0 corresponds to a completely degraded or infertile soil and 1 to a soil with maximum fertility.

In order to calculate the sugarcane yields, the monthly climatic data at the beginning of the 21st century during the period 2005-2015 and the soil fertility factors mentioned in formula (12) have been analyzed. The calculated yields were compared with the productivity reported in publications (Aguilar-Rivera, 2014; Flores-Granados, 2017; SIAP, 2022).

The annual yields calculated for the period from 2005 to 2015 $\left(Y_{calc}^{2000}\right)$ for each of the sugar mills were compared with the observed yields $\left(Y_{obs}^{2000}\right)$. This comparison was realized between the normalized yields $Y_{calc}^{2000} / Y_{calc\,max}^{2000}$ and $Y_{obs}^{2000} / Y_{obs\,max}^{2000}$, where $Y_{calc\,max}^{2000}$ and $Y_{obs\,max}^{2000}$ are the maximum yields calculated and observed during the period from 2005 to 2015 in each sugar mill.

The objective of the comparison was to improve the fit between the calculated and observed crop yields, minimizing possible errors due to ignorance of some factors that influence the observed data, such as the possible mass loss of the harvested sugarcane during the burning process or transportation, or due to pests, diseases, etc. The parameters of the regression equation were established between the values $Y_{calc}^{2000} / Y_{calc\,max}^{2000}$ and $Y_{obs}^{2000} / Y_{obs\,max}^{2000}$ for each of the sugar mills.

Then, taking into account the parameters of the regression equation, the yields for the end of the 21st century $\left(Y_{calc}^{2100}\right)$ were calculated and the δY_{calc} values were estimated according to formula (2).

The alteration of the fertility of agricultural soils at the end of the 21st century due to the climate change was assessed using the methodology developed by Nikol'skii *et al.*

(2006) and Castillo *et al.* (2007). This methodology is based on the use of the quantitative relationship between the regional modal values of the integral fertility index of a virgin soil not used in agriculture F_{vrg}^{j} and a radiative index of dryness I_{vrg}^{j} regional mean annual established for the beginning of the 21st century, that is, for j=2000, for relatively flat terrain with surface slopes less than 3% in different climatic zones of Mexico (Nikol'skii *et al.*, 2006; Castillo *et al.*, 2007).

The climatic index I_{vgn}^{j} for virgin soils not used in agriculture is calculated as follows (Budyko, 1977; Koster and Suarez, 1999):

$$I_{vgn}^{j} = \frac{Rn_{vrg}^{j}}{\lambda Pr^{j}} \quad (13)$$

where: Rn_{vrg}^{j} and Pr^{j} are the mean annual measured values of net radiation (KJ m^{-2}) and precipitation (mm) typical for the virgin soils in the region of sugarcane production at the beginning (j=2000) and end (j=2100) of the XXI century; λ is the latent heat of evaporation equal to 2.51 KJ m^{-2} mm^{-1}.

In order to calculate the climatic index for the agricultural sugarcane lands I_{a}^{j} at the beginning and end of the 21st century, the mean annual value of net radiation Rn_{a}^{j} was determined using the following formula (Allen *et al.*, 2006):

$$Rn_{a}^{j} = (1-\alpha) Rg_{a}^{j} - Rb_{a}^{j} \quad (14)$$

where: α is the albedo of the sugarcane plot (α=0.15); Rg_{a}^{j} and Rb_{a}^{j} are global radiation (incoming radiation) and outgoing longwave radiation, respectively, in the year j (MJ m^{-2} day^{-1}). The Rg_{a}^{2000} and Rb_{a}^{2000} values for agricultural lands with sugarcane at the beginning of the 21st century were calculated with climatological data (CONAGUA, 2021); while the values of Rg_{a}^{2100} and Rb_{a}^{2100} were obtained from the publications by Cavazos *et al.* (2013) and Fernández *et al.* (2018).

The previously established graphs on changes in regional values of the integral fertility index of virgin soils F_{vrg}^{2000} and its components at the beginning of the 21st century depending on the climate index I_{vrg}^{2000} were used to assess the impact of the climate change on agricultural soil fertility in sugarcane lands $\left(F_{a}^{2100} / F_{a}^{2000}\right)$ at the end of 21st century. An example of such graphs is shown in Figure 1 (Nikol'skii *et al.*, 2010).

The methodology for obtaining similar graphs and their application to predict changes in some soil properties due to climate change was described in detail in several publications (Nikol'skii *et al.*, 2006; Castillo *et al.*, 2007; Terrazas-Mendoza *et al.*, 2010).

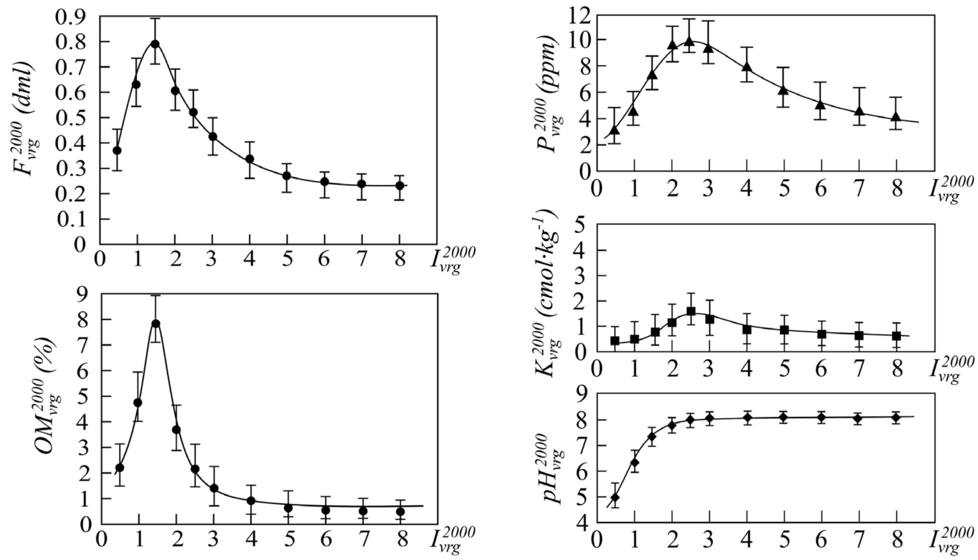

Figure 1. Dependence of the modal values of the integral virgin soil fertility index F_{vrg}^{2000} and its components MO_{vrg}^{2000}, P_{vrg}^{2000}, K_{vrg}^{2000} and pH_{vrg}^{2000} according to formula (12) at the beginning of the 21[st] century based on the climatic index I_{vrg}^{2000} typical for the land with slopes less than 3% and soils deeper than 1 m. Confidence intervals are shown. (Nikol'skii *et al.*, 2010).

In accordance with the Geographical Law of Soil Zonality and considering a relatively slow climate change at a mean annual level, the $F_{vrg}^{2000}\left(I_{vrg}^{2000}\right)$ relationship established for the beginning of the 21[st] century should be preserved at the end of the same century. Therefore, by knowing how the I_a^j index on agricultural land will change at the end of the century compared to its beginning, one can estimate the change of the agricultural soil fertility index due to climate change alone. For this, it is necessary to take the values of F_{vrg}^{2000} and F_{vrg}^{2100} from the relationship $F_{vrg}^{2000}\left(I_{vrg}^{2000}\right)$ corresponding to the climatic index of the sugarcane land I_a^{2000} and I_a^{2100} for the beginning and end of the 21[st] century. The regional ratio $F_{vrg}^{2100}/F_{vrg}^{2000}$ can be applied to the local ratio F_a^{2100}/F_a^{2000} for sugarcane lands as follows:

$$F_a^{2100} = F_a^{2000}\left(F_{vrg}^{2100}/F_{vrg}^{2000}\right) \quad (15)$$

where: F_a^{2000} and F_a^{2100} are the mean annual values of the integral soil fertility index of the sugarcane lands at the beginning and end of the 21[st] century, respectively. The F_a^{2000} values are determined with formula (12). F_{vrg}^{2000} and F_{vrg}^{2100} are the regional annual average values of the integral fertility index corresponding to virgin soils of the same region obtained from Figure 1 based on the known values of the climatic index I_a^{2000} and I_a^{2100}.

RESULTS AND DISCUSSION

Figure 2 shows the observed sugarcane yields $\left(Y_{obs}^{2000}\right)$ at the beginning of the 21st century in each of the selected sugar mills compared to the calculated yields $\left(Y_{calc}^{2000}\right)$. The observed yield data have been obtained from publications by Aguilar-Rivera (2014), Flores-Granados (2017) and SIAP (2022). The yields are presented in normalized form $\left(Y_{calc}^{2000}\,/\,Y_{calc\,max}^{2000}\right)$ and $\left(Y_{obs}^{2000}\,/\,Y_{obs\,max}^{2000}\right)$, where $Y_{calc\,max}^{2000}$ and $Y_{obs\,max}^{2000}$ are the maximum yields calculated and observed during the period from 2005 to 2015 in each sugar mill. The values of Y_{calc}^{2000}, $Y_{calc\,max}^{2000}$, Y_{obs}^{2000} and $Y_{obs\,max}^{2000}$ correspond to the commercial raw mass of the crop.

The figure shows two lines of adjustment as well. Continuous line is theoretical as a reference which corresponds to the case of complete coincidence between the calculated and observed yields: $Y_{calc}^{2000}\,/\,Y_{calc\,max}^{2000} = Y_{obs}^{2000}\,/\,Y_{obs\,max}^{2000}$. Dashed line is real and corresponds to the different regression equation: $Y_{calc}^{2000}\,/\,Y_{calc\,max}^{2000} = a\left(Y_{obs}^{2000}\,/\,Y_{obs\,max}^{2000}\right) + b$, where a and b are constants.

The regression equations of the calculated and observed yields are presented in the Table 2.

It was found that the linear relationship between the calculated maximum yield and the maximum real yield obtained with the fitted equations is statistically significant with a confidence level of 95%. In addition, a good fit is observed in all the obtained equations,

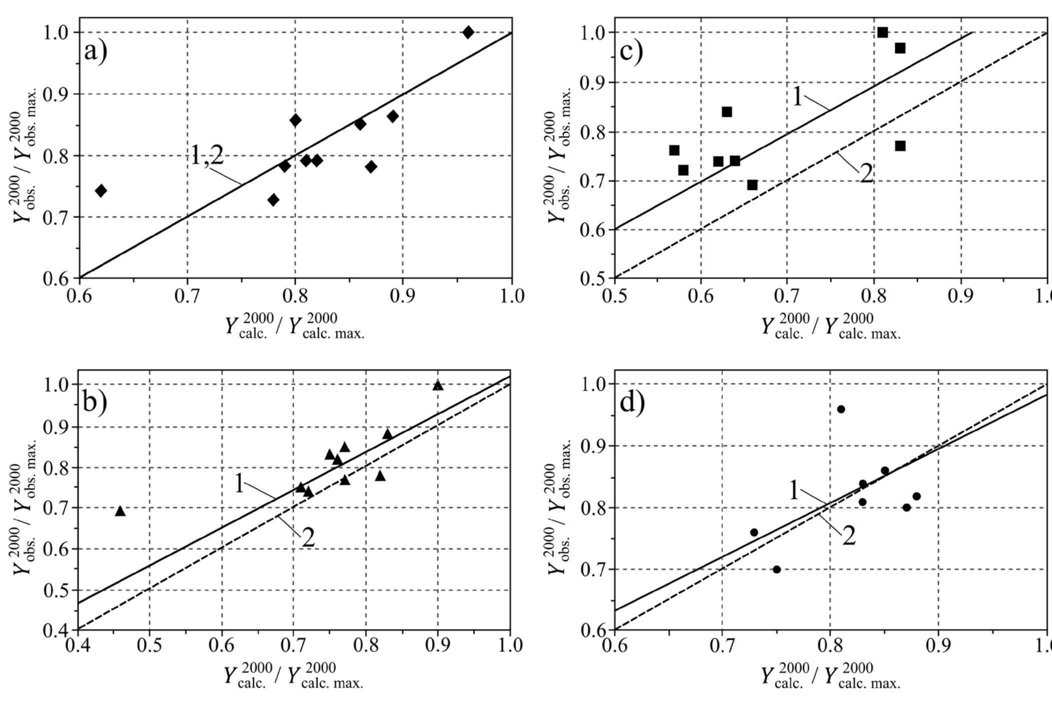

Figure 2. Graphs between the sugarcane yields calculated $\left(Y_{calc}^{2000}\,/\,Y_{calc\,max}^{2000}\right)$ and observed $\left(Y_{obs}^{2000}\,/\,Y_{obs\,max}^{2000}\right)$ in the sugar mills of the state of Veracruz at the beginning of the 21st century (a - Coatotolapan; b - San Cristobal; c - San Pedro; d - Tres Valles). 1 – theoretical adjustment; 2 – actual setting.

Table 2. Adjustment regression equations of calculated and observed sugarcane yields.

Sugar mill	Regression equation	R^2	$\sigma_{\bar{x}}$	$Y_{obs\ max}$ (t ha^{-1})	$Y_{calc\ max}$ (t ha^{-1})
Coatotolapan	$\frac{Y_{obs}^{2000}}{Y_{obs\,max}^{2000}} = 0.95\frac{Y_{calc}^{2000}}{Y_{calc\,max}^{2000}} + 0.04$	0.98	0.06	54.13	56.24
San Cristóbal	$\frac{Y_{obs}^{2000}}{Y_{obs\,max}^{2000}} = 0.93\frac{Y_{calc}^{2000}}{Y_{calc\,max}^{2000}} + 0.1$	0.95	0.08	56.26	58.68
San Pedro	$\frac{Y_{obs}^{2000}}{Y_{obs\,max}^{2000}} = 0.95\frac{Y_{calc}^{2000}}{Y_{calc\,max}^{2000}} + 0.12$	0.93	0.10	66.46	67.11
Tres Valles	$\frac{Y_{obs}^{2000}}{Y_{obs\,max}^{2000}} = 0.85\frac{Y_{calc}^{2000}}{Y_{calc\,max}^{2000}} + 0.13$	0.98	0.06	58.40	60.75

since in all cases we have a correlation coefficient greater than 0.9, the equation obtained for the San Pedro mill being the one with the lowest correlation. The difference in the quality of the fit possibly could be explained by the difference in the quality of the initial climatic and edaphic data.

Finally, Table 3 presents the results of the assessed impact of climate change at the end of the 21st century on the productivity of sugarcane in the state of Veracruz. This table estimates expected changes in relative yield $\delta Y_{calc} = Y_{calc}^{2100} / Y_{calc}^{2000}$ and its components δY_{pot}, δK_{hidr} y δF_a calculated with equation (2).

Analyzing the data in Table 3, it can be concluded that the three atmospheric circulation models (GFDL CM3, HADGEM2 and MPI ESM LR) recommended by Cavazos *et al.* (2013) show similar results of variation in change of sugarcane yield (δY_{calc}), although there is a small difference between its components (δY_{calc}).

The assessment of the impact of climate change on sugarcane indicates that in the case of a doubling of the concentration of CO_2 in the atmosphere at the end of the 21st century compared to the current one, the yields of the crop will be lower than the current ones of 8 to 15% in the sugar mills of Cuatotolapan, San Cristóbal and San Pedro. If the CO_2 concentration increases four times, the yields will be lower than the current ones of 11 to 20%. For the Tres Valles sugar mill, a conservation of the current yield is expected.

The expected increase in air temperature, photosynthetically active radiation and CO_2 concentration in the atmosphere will lead to a change in potential productivity (δY_{pot}) from a decrease of 12% to an increase of 13%, depending on location of sugar mill, model and scenario of CO_2 growth in the atmosphere. But most of the values of $\delta Y_{pot} = \delta Y_{pot}^{2100} / \delta Y_{pot}^{2000}$ are in the interval 0.95 to 1.05, which means that in both CO_2 growth scenarios, potential productivity will be practically unchanged.

It was found that the main factor for the decrease in the sugarcane productivity is a decrease of 4 to 22% of the soil moisture coefficient K_{hidr}^{j} mainly due to the decrease

Table 3. Change in the yield of sugarcane (*Saccharum officinarum*) (δY_{calc}), and its components (δY_{pot}, δK_{hidr} y δF_a) assessed with equations (1) and (2) in four sugar mills in the state of Veracruz for the end of the 21st century (2075-2099) corresponding to the GFDL CM3, HADGEM2 and MPI ESM LR climate models with two scenarios of the CO_2 concentration in the atmosphere growth (RCP): 4.5 (650 ppm CO_2) and 8.5 (1370 ppm CO_2).

Ingenio	Modelo	RCP 4.5				RCP 8.5			
		δY_{pot}	δK_{hidr}	δF_a	δY_{calc}	δY_{pot}	δK_{hidr}	δF_a	δY_{calc}
Coatotolapan	GFDL CM3	0.88	0.91	1.08	0.85	0.90	0.96	0.98	0.82
	HADGEM2	1.02	0.84	1.02	0.85	0.82	0.99	1.01	0.80
	MPI ESM LR	1.00	0.93	0.96	0.86	0.95	0.93	0.96	0.82
San Cristóbal	GFDL CM3	0.94	0.87	1.09	0.89	0.95	0.87	1.07	0.86
	HADGEM2	1.04	0.84	1.03	0.89	0.89	0.85	1.12	0.84
	MPI ESM LR	0.98	0.91	1.00	0.91	0.90	0.92	1.07	0.87
San Pedro	GFDL CM3	1.03	0.80	1.09	0.90	1.07	0.82	1.02	0.89
	HADGEM2	1.06	0.78	1.10	0.91	1.04	0.81	1.03	0.87
	MPI ESM LR	1.13	0.80	1.02	0.92	1.04	0.82	1.03	0.88
Tres Valles	GFDL CM3	1.01	0.96	1.04	1.01	0.93	0.98	1.08	0.99
	HADGEM2	1.05	0.89	1.08	1.01	1.11	0.86	1.04	0.99
	MPI ESM LR	0.97	0.96	1.08	1.01	1.06	0.90	1.04	1.00

in precipitation during the relatively dry season (from November to May) which causes a decrease in soil water reserves in the root zone during the crop cycle. The effect of an increase in air temperatures and solar radiation on an increase in evapotranspiration and a decrease in the K_{hidr}^{j} coefficient is insignificant.

Regarding the alteration of soil fertility due to climate change, no large changes are expected in the integral fertility index F_a in both scenarios of the growth of CO_2 concentration in the atmosphere. The typical variation of the value of $\delta F_a = F_a^{2100} / F_a^{2100}$ in the sugarcane lands is within the range of 1.00 to 1.05, except for the San Cristóbal mill, where δF_a varies in a slightly wider range, from 0.96 to 1.09 in the case of doubling of the CO_2 concentration and from 1.07 to 1.12 in case of four-fold growth of CO_2 concentration.

The results on the expected change in sugarcane productivity at the end of the 21st century is somewhat consistent with the results obtained by Marin *et al.* (2013). Although these authors use a different approach to the present one and conclude that sugarcane productivity will be increased insignificantly, they point out that this productivity may be limited by CO_2, temperature and solar radiation.

According to the information obtained in this study, we can point out that the main factor in the expected decrease in sugarcane productivity is due to the decrease in precipitation during the season with less precipitation (from November to May). It should be noted that the comments on the expected impact of climate change on the sugarcane productivity considers the case of application in future of current plant varieties and technologies of crop, soil and water management, although it should considered an improvement of crop varieties and the agricultural technology.

CONCLUSIONS

The assessment of impact of the climate change on the sugarcane productivity for four sugar mills in the state of Veracruz, carried out using the physiological model of crop development, proposed by IISA/FAO, indicates that at the end of the 21^{st} century there is a risk of loss of sugarcane production up to 20%, mainly due to the decrease in precipitation.

Sugarcane crop yield calculations for the beginning of the 21^{st} century indicate that there is a rather good coincidence between calculated and observed crop yields. The correlation coefficients between the calculated and observed yields are in a range of 0.93-0.98 with standard error between 0.06-0.10. This means that the IISA/FAO physiological model based on agroecological principles, and a limited number of climatic and edaphic variables can be used as a tool to estimate the impact of climate change on sugarcane productivity.

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