

Climate change and sugarcane yield at the Tres Valles sugar mill

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Abstract

The sugarcane agribusiness is important for food sovereignty in Mexico, but climate change affects its production and yield. This study analyzed how climatic variables and prices impact sucrose yield in fresh cane at the Tres Valles mill, Veracruz, from 1995 to 2022, using a model of two simultaneous equations. The objective was to analyze to what extent climatic variables and respective relevant prices affect the yield of sucrose in cane, expressed in its equivalent of fresh cane, in order to quantify the magnitude of this impact. The results show that thermal oscillation has the greatest positive impact (elasticity of 1.01), whereas solar radiation has the greatest negative impact (elasticity of -2.06). Carbon dioxide emissions have a moderate positive effect (elasticity of 0.78) and precipitation has a smaller positive impact (elasticity of 0.17). The index of prices of cane sugar shows a positive elasticity of 0.96, while the wholesale price of standard sugar has a negative elasticity of -0.2. It was concluded that this type of study provides valuable information on the sensitivity of sucrose yield to climatic and economic factors, useful for mitigating climate change.

Keywords:

climatological normals, distorted prices, Gauss-Markov theorem, sucrose in fresh cane.



Introduction

Climate change is a global phenomenon with primary manifestations in variations in meteorological normals (Arnell *et al.*, 2019). Its consequences include ecological, social, and economic impacts at the local and regional levels (Byg and Salick, 2009). Research shows that agricultural yields will decrease if climatological variables exceed certain thresholds (Habib-ur-Rahman *et al.*, 2022; Bibi and Rahman, 2023).

In Mexico, sugarcane is an important crop, economically and in terms of job creation. In 2023, it ranked third in agricultural production value with 5.8% of the total. Nevertheless, the sector faces challenges such as high sugar prices and increased imports, partly due to droughts. Models such as the DSSAT simulate crop growth under different scenarios, supporting decision-making (Everingham *et al.*, 2002). Nonetheless, these models focus on biophysical processes, making it difficult to incorporate complex economic analyses (Stern *et al.*, 2022). Although some incorporate basic economic analysis (Morris *et al.*, 2019), there is a gap between agroclimatic and economic models, as the former do not incorporate econometric structural analysis (McNunn *et al.*, 2019).

This research adopts a conventional econometric approach, modeling yield based on relevant variables, with the aim of estimating a simultaneous equation model to quantify the effects of climatic variables and prices on sucrose yield in cane.

Materials and methods

The study area of the research is the one delimited by the geographical coordinates of the four municipalities in which the supply area of the Tres Valles sugar mill is located. That is, between 18° 45' 00" and 18° 08' 00" north latitude and -96° 38' 0" and -95° 46' 00" west longitude. The study is carried out with data from the Tres Valles sugar mill, Veracruz, for the period from 1995 to 2022. The time series of temperature, precipitation, and solar radiation were obtained from NASA (2024). Data for sugarcane variables were obtained from the National Union of Sugarcane Growers of the National Confederation of Rural Owners for several years (UNC-CNPR, 2004; UNC-CNPR, 2014; UNC-CNPR, 2024).

Table 1 shows the variables that were used for the final run of the estimated empirical model.

Table 1

Definition of the variables used in the study.

Variable	Description	Units
Sacapa	Sucrose in cane expressed on a fresh cane basis	(t)
Taver	Average annual temperature	(°C)
Tosc	Thermal oscillation	(°C)
Rai	Average annual rainfall	(mm year-1)
SRad	Solar radiation	(MJ m-2 day-1)
CSPI	FAO cane sugar price index	Dimensionless and base (2014-2016= 100)
Wpri	Nominal price of standard sugar in the main supply centers	(\$ t-1)
CO2	Carbon dioxide	(ppm)

Variable	Description	Units
D1	Dichotomous variable for prevalence of the 'El Niño' or 'La Niña' phenomenon in a given year	0= La Niña, 1= El Niño

For Tosc, Rai, SRad, the source is NASA (2024); for Sacapa and WPri, it was the UNC-CNPR (2014, 2004 and 2024), the latter was deflated with the national producer price index (INPP, for its initialism in Spanish), thus obtaining the real price of standard sugar in the main supply centers (RWPri), which is the one finally used in the empirical model. The base year of the INPP was (2014-2016= 100) and the source of this index was Banco de México (2024). CO2 was obtained from NOAA (2024), and D1 from the SAS Institute (2024). Finally, the cane sugar price index (CSPI) was that from FAO (2024).

The empirical model to be estimated is the following system of two simultaneous equations.

1)

$$Sacapa = \beta_0 + \beta_1 Taver + \beta_2 Tosc + \beta_3 Rai + \beta_4 SRad + \beta_5 CSPI + \beta_6 RWPri + \beta_7 D1 + \varepsilon_1$$

$$Taver = \alpha_0 + \alpha_1 CO2 + \varepsilon_2$$

2). Where the β 's and α 's are the parameters of the respective equations. The parameters β_0 and α_0 correspond to the ordinate to the origin (intercept) of equations (1) and (2). The respective expected signs are the following: $\beta_1 > 0$, $\beta_2 \leq 0$, $\beta_3 > 0$, $\beta_4 \leq 0$, $\beta_5 > 0$, $\beta_6 > 0$, $\beta_7 \leq 0$ and $\alpha_1 > 0$. In addition, ε_1 and ε_2 are the statistical errors of the equation in question, with the property that they are normally distributed with mean μ and finite variance σ^2 .

It is important to note that, in the case of the parameter β_2 , which weights the thermal oscillation (Tosc), it is not possible to establish *a priori* the type of relationship it will have with the yield of sucrose in sugarcane (Sacapa) because, although in some studies such as that by Cardozo and Sentelhas (2013), it is mentioned that there is a positive correlation during the cane ripening phase, this is not always the case, as this relationship can vary depending on other factors, such as the variety of sugarcane, the age of the crop and fundamentally, the environmental conditions.

In the case of solar radiation (SRad), although a positive relationship with sucrose in cane would also be expected, under stress conditions; for example, drought, an excess of radiation could even have negative effects (Inman *et al.*, 2005). Regarding the parameters of the average temperature (β_1) and precipitation (β_3), they are expected to be positive in advance; however, if these are not in fact linear, the sign can be negative. It is important to note that when these variables are outside the optimal limits due to climatic variations, it can cause a decrease and even loss of sucrose in the cane (Inman *et al.*, 2005; Cardozo and Sentelhas, 2013).

In the case of the dummy variable (D1), a negative relationship would be expected since both 'El Niño' and 'La Niña' cause stress in sugarcane, especially in the phenological stage of ripening (de Souza *et al.*, 2015). In the case of the parameter α_1 , a positive relationship between the mean temperature (Taver) and carbon dioxide (CO2) is expected. Lacis *et al.* (2010) have established the causal relationship between temperature increase and carbon dioxide emissions.

In the first equation of the system, the FAO cane sugar price index (CSPI) is introduced as a proxy economic variable that explains the sucrose yield in cane expressed in tonnes of fresh cane. The CSPI is a global indicator that reflects trends in the international sugar market, which can have an impact on production decisions and management in sugarcane crops at the local level and influence producers' management practices, potentially affecting sucrose yield (Cheavegatti *et al.*, 2011).

Finally, the introduction of the real average price of standard sugar in the main supply centers of Mexico (RWPri) is due to the fact that it is used by CONADESUC (2010) to determine the reference price that serves to determine the liquidation price for sugarcane producers. It is assumed that a higher reference price incentivizes producers to increase the planted area and production of sugarcane, but more importantly, the reference price in Mexico is based partly on sucrose content because this incentivizes sugarcane producers to focus not only on volume, but also on the quality of the cane in terms of its sugar content.

For the identification of the empirical model and following Gujarati and Porter (2009); Wooldridge (2016), the order and rank conditions were applied and for the estimation of the structural and reduced models, the SAS/ETS 9.4 system was used. Lastly, it is necessary to mention that the calculation of the elasticities evaluated at one point was carried out as indicated in Tomek and Kaiser (2014).

Results and discussion

The empirical model that was used consists of two simultaneous equations that are composed of seven exogenous or predetermined variables and two endogenous variables. It was found that the first equation of the system (Sacapa) is exactly identified, whereas the second equation (Taver) is over-identified; therefore, the model as a whole is identified and it is possible to estimate the structural parameters. Table 2 shows the descriptive statistics of the variables used in the model.

Table 2. Descriptive statistics of the variables used in the research.

Variable	Mean	Standard	Maximum value	Minimum value
Sacapa	255 708	54 150	341 227	156 899
Taver	23.7	0.4	24.5	23.1
Tosc	23.6	1.2	26.6	20.3
Rai	1 659.1	242.6	2 104.5	1 229.4
SRad	17.8	0.5	18.9	16.8
CSPI	388	17.7	418.5	3 610
RWPri	92.8	43.1	170.6	24.9
CO2	278.2	40.6	365.2	201.1
D1	0.5	0.5	1	0

Table 3 shows the structural parameters of equation (1) of the estimated model.

Table 3. Structural parameters of the first equation of the estimated empirical model.

Variable	Estimated parameter	Standard error	t- value	Pr > t	Value of the statistic	VIF
Intercept	-606216	825830.6	-0.73	0.4719	F, 11.71	0
Taver	50109.29	39018.69	1.28	0.2145	R ² adjusted, 0.74	2.102
Tosc	10984.02	4517.723	2.43	0.0251	DW, 1.97	1.08
Rai	25.57816	22.70002	1.13	0.2739		1.142
SRad	-29592.5	12828	-2.31	0.0325		1.42
CSPI	629.605	293.8182	2.14	0.0453		2.61
RWPri	-554.624	175.23	-3.17	0.0051		1.843
D1	-8822.63	13359.91	-0.66	0.5169		1.475

DW= Durbin-Watson; VIF= Variance inflation factor. Prepared based on the output of SAS 9.4.

As observed in column six, the value of 11.7 of the *F* statistic with 7 degrees of freedom indicates that, statistically, the model as a whole is highly significant; there is strong evidence to reject the null hypothesis that all coefficients of the independent variables are simultaneously equal to zero. Additionally, given that the adjusted coefficient of determination (*R*²adjusted) is 0.74, this model explains approximately 74% of the variability in the dependent variable (Sacapa).

Additionally, the Durbin-Watson (DW) statistic has a value of 1.97 (very close to 2), so it can be stated that there is no significant first-order autocorrelation in the model residuals, which suggests that the model is well specified in terms of its temporal structure and that important variables that could cause dependence on errors have not been omitted (Gujarati and Porter, 2009). Finally, in the

case of the variance inflation factor (VIF), it indicates that there are no problems of multicollinearity. Although in the case of the cane sugar price index, it has a VIF of 2.6, it can be considered as a mild to moderate multicollinearity that does not cause problems (Hair *et al.*, 2019).

Table 4 shows the results of the second equation of the empirical model.

Table 4. Structural parameters of the second equation of the estimated empirical model.

Variable	Estimated parameter	Standard error	t- value	Pr > t	Statistic	Value	VIF
Intercept	18.1153	1.212693	14.94	<0.0001	F	21.33	0
CO2	0.014385	0.003115	4.62	0.0001	R ² adjusted	0.46	1
					DW	1.67	

DW= Durbin-Watson; VIF= variance inflation factor. Prepared based on the output of SAS 9.4.

The interpretation of the statistics *F*, *R*²adjusted and *DW* is analogous to the previous case and therefore, the estimated parameters of the empirical model are unbiased, consistent, and efficient. Nevertheless, the analysis of the marginal effects of the covariates on the response variable can be confusing if it is carried out in terms of absolute values due to the physical units of the variables. To avoid this situation, in economics, it is more common to perform sensitivity analysis in relative terms, free of physical units, that is, through the analysis of elasticities evaluated at a point, which are shown in Table 5.

Table 5. Elasticities of the reduced form of the estimated empirical model.

Variable	Tosc	Rai	SRad	CO2	CSPI	WPri	D1
Sacapa	1.01	0.17	-2.06	0.78	0.96	-0.2	-0.02
Taver				0.17			

In general, it can be assumed that the sensitivity analysis in relative terms of the results of the reduced model through elasticities considers taking a 1% change in the exogenous or predetermined variables, and the respective estimated parameter will be the percentage change that will occur in the endogenous or response variable. Thus, a 1% change in the thermal oscillation (Tosc) will increase the sucrose in cane by 1.01%, but expressed in terms of fresh cane (Sacapa), a 1% increase in precipitation (Rai) will increase the yield of the Sacapa by 0.17%; a 1% increase in solar radiation (SRad) will cause the yield of the Sacapa to decrease by 2.06%; in the event of a 1% increase in CO2 emissions, the Sacapa will increase by 0.78%, which is due to the so-called fertilization effect of this greenhouse gas on sugarcane.

The elasticity of the average temperature (Taver) with respect to the Sacapa, which is obtained from the structural model since both variables are endogenous, was 4.64. This implies that if the Taver increases by 1%, the Sacapa will increase by 4.64%. On the other hand, if the cane sugar price index (CSPI) increases by 1%, the Sacapa will increase by 0.96%. In the case of the real wholesale price of standard sugar (RWPri) as an exogenous variable of the Sacapa yield, it did not present the expected sign, since a 1% increase would cause a decrease in the Sacapa, which is, apparently, an economic irrationality on the part of the producer .

However, a possible explanation for this fact is that the sugarcane market is one of the most distorted, since; for example, local sugarcane leaders continuously promote social movements that can affect the prices of sugarcane as a fundamental input of the sugar industry; likewise, the price of sugarcane is a controlled price, as it is set by the government and not by the market (Aguilar *et al.*, 2011) . Finally, in the case of the dummy variable D1, coded as 0 for the prevalence of 'La Niña' in the respective year and as 1 for the prevalence of 'El Niño' in that year, the corresponding parameter had a value of -0.02; its interpretation is as follows: on average, the Sacapa is 0.02% lower during the years of prevalence of 'El Niño' compared to the years of prevalence of 'La Niña', keeping all other variables in the model constant.

Discussion

The research revealed complex relationships between climatic and economic variables and the yield of sucrose in cane (Sacapo). The mean temperature (Taver) showed a direct relationship with Sacapo, with a 1% increase in Taver increasing Sacapo by 4.64%. This contrasts with Chandio *et al.* (2020) findings in China, where there was a negative effect of temperature on agricultural production in the long term. Precipitation showed a positive impact, with a 1% increase causing Sacapo to grow by 0.17%. This result differs from what was reported in Chandio *et al.* (2020) in China, but is consistent with Habib *et al.* (2022), who found a positive impact of precipitation on agricultural production.

Solar radiation (SRad) presented a negative effect, with a 1% increase decreasing Sacapo by 2.06%. This could be explained by the nonlinear relationship between solar radiation and sucrose accumulation in sugarcane, a C4 plant with high photosynthetic efficiency, as mentioned in Cardozo and Sentelhas (2013); Arnell *et al.* (2019). The thermal oscillation (Tosc) showed a positive impact, with a 1% variation causing Sacapo to increase by 1.01%. This is in line with studies in Guatemala that associate greater thermal amplitudes with greater accumulation of sugar in sugarcane, as noted in Castro *et al.* (2010). A 1% increase in CO2 concentration increased Sacapo by 0.78%.

The FAO cane sugar price index (CSPI) was statistically significant ($t = 2.14$) as an explanatory variable for Sacapo. The real wholesale price of standard sugar (RWPri) was used as a proxy for the liquidation price of sugarcane (RLPri), as the latter was not statistically significant. This may be because the price of sugarcane is controlled by the government via the 2005 Sugarcane Law, which distorts the price and affects the allocation of resources and the producer's decisions.

Conclusions

The study reveals that climate change negatively influences sugarcane production and yield, affecting Mexico's food security. A simultaneous equation model was adopted to quantify the effect of climate variables and prices through elasticities. The main findings include the following: thermal oscillation has a significant positive effect on sucrose yield, solar radiation shows a negative impact on yield, and international sugar prices play a relevant role in cane yield. This approach integrates economic analysis with climatic variables, providing a more comprehensive assessment than previous studies focused primarily on biophysical aspects. The proposed model offers a more comprehensive understanding of the interrelationship between climatic and economic factors in sugarcane production.

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