

TOTAL PRODUCTIVITY OF FACTORS IN THE SUGARCANE AGROINDUSTRY BY STATE IN MEXICO, 2010/2011-2019/2020 HARVESTS

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ABSTRACT

In Mexico, in the period 2011/2020, the net production of ground sugarcane grew by 1.1%, the industrialized surface by 1.5%, the field yield decreased -0.4% and the factory efficiency -0.2%. Sugarcane production has grown due to the increase in surface area and not due to technological change. The objective of this study was to verify empirically whether technological change and technical efficiency have come to a halt or whether there has been a technological regression at the level of the 15 producing states for the period 2011/2020. The methodology used was the Malmquist Index, which can be broken down into several indicators. The results show that the assertion that the sustained increase in sugarcane production and standard sugar is due exclusively to the extensive growth based on surface area is not entirely correct. The findings show that on average, between periods, technical efficiency grew by 0.1%, technological change by 2.0%, and total factor productivity by 2.1%. As panel data, the average for all states is of the same magnitude. At the state level, the analysis allowed detecting that, in Colima, the three indicators are 0.0%, being at a complete halt. In Sinaloa, technological change was 12.5%, which reflects a true incorporation of technological innovations and improvements. Tabasco is the only state where there were improvements in efficiency (2.0%), technological change (2.4%), and total factor productivity (4.4%).

Keywords: data envelopment analysis, Malmquist index, technical efficiency, technological change.

INTRODUCTION

Sugarcane (*Saccharum officinarum* L.) belongs to the grass family, the group of plants of greatest economic importance in the world (Pérez, 2022). It is produced in diverse regions of the world and, in 2023, it was cultivated in 96 countries; the main producing nations were Brazil and India with 37% and 23% of total production. For its part, Mexico produced 2.63%, occupying seventh place globally (FAO-Food and Agriculture Organization, 2025). Sugarcane is the third most important crop in Mexico in terms of production value, preceded only by grain corn and avocado, and it represents about 7% of the total value of national production (SIAP-Servicio de Información Agroindustrial y Pesquera, 2025). According to the Ministry of Agriculture

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and Rural Development (SADER, 2021), in Mexico, there are more than 800 thousand hectares cultivated with sugarcane, in more than 267 municipalities in 15 states of the Mexican Republic. The main producing states in 2023 were Veracruz, Jalisco, San Luis Potosí, Oaxaca and Chiapas with 32, 14, 10, 8 and 6% of national production, respectively; these states produce about 70% of the total production in Mexico. It should be noted that the state with the highest yield was Puebla, with nearly 106 tons/ha; on the contrary, Tamaulipas has the lowest yield with 49 tons/ha (SIAP, 2025).

Sugarcane cultivation in Mexico has four main uses: sugar production, fodder, fruit, and to produce piloncillo (Castillo *et al.*, 2018). The presence of sugar mills has allowed the transformation, processing, and refining of the crop (Alvarado-Silva and Bustamante-Lara, 2022). Sugar production in the mills, as part of the cane transformation process, begins with the reception of the cane (which is cut manually or mechanically in the field), cleaning, milling, clarification, evaporation, crystallization, centrifugation, refining, and storage (Hernández-Cázares, 2014).

In Mexico, the production of standard sugar has grown at an average annual rate of 1.7% in the last decade (2011-2020), while the production of industrialized sugarcane has grown by 10.7% (Comité Nacional para el Desarrollo Sustentable de la Caña de Azúcar-CONADESUCA, 2020a). This has made it possible to guarantee the self-sufficiency of this basic good that is consumed as a sweetener by the entire population, whether high or low income, and is also important as an intermediate input for the soft drink and baking industries, among others. Currently, at the state level, Veracruz has 18 of the 50 sugar mills that operated in the 2019/2020 harvest and the largest harvested area of industrialized cane in the same harvest (CONADESUCA, 2020b). The harvest season is the time when the process by which the cane is harvested and sugar is produced takes place, and it begins in November and ends in July (Castillo *et al.*, 2018).

CONADESUCA (2020a) points out that during the 2007-2018 period, the harvested and industrialized surface of sugarcane had an average annual growth rate of 1.5%, while the field yield and factory efficiency practically remained stagnant, which implies that sugar production grew extensively and not due to an increase in the productivity of the sugarcane field or sugar mills.

The objective of the study is to analyze the evolution of technical efficiency, technological change and total productivity of factors in sugarcane cultivation for the harvest period 2010/2011 to 2019/2020, in the 15 states where sugarcane is grown in Mexico. As a hypothesis, it was proposed that the sustained increase of standard sugar can be attributed to extensive growth, rather than to the incorporation of technological improvements and better management of inputs in the links of the production process involved in obtaining said sweetener.

THEORETICAL FRAMEWORK

The neoclassical school focuses its attention on the optimization and efficient allocation of production factors, since productive resources are scarce, while the needs of society are unlimited. In the production process, enterprises transform the factors of production into products, and these factors are commonly classified as labor, raw materials and capital (Pindyck and Rubinfeld, 2009); they use different combinations of factors that will depend on the level of technology they have (Varian, 2010). The relationship between the factors of production and the resulting production can be described with a production function, which shows the maximum level of production (q) that the enterprise can obtain with each specific combination of factors (Pindyck and Rubinfeld, 2009); in a simplified way, they are commonly classified as labor (L) and capital (K).

Therefore, the production function can be expressed as follows:

$$q = f(K, L)$$

Varian (2010) assumes that there is a single factor measured by x , and a single product measured by y . Therefore, a more simplified production function results:

$$y = f(x)$$

This last production function will be useful later to illustrate the concepts of productivity, efficiency and technological change. The productivity of a given production unit is defined as the relationship between the results it obtains, and the resources involved in its production (Katharaki and Katharakis, 2010). Fontalvo *et al.* (2018), in addition to the company's internal resources or factors that are controllable, also mention that productivity depends on external factors that cannot be controlled, such as economic and demographic changes, natural resources and public policies.

To analyse productivity, two approaches are identified: partial productivity and total factor productivity (TFP). The first approach compares changes in the total product associated with changes in specific productive factors, such as capital or labor, thus considering individual productivities, while the TFP approach compares changes in total product associated with changes in all productive factors (Candia *et al.*, 2016).

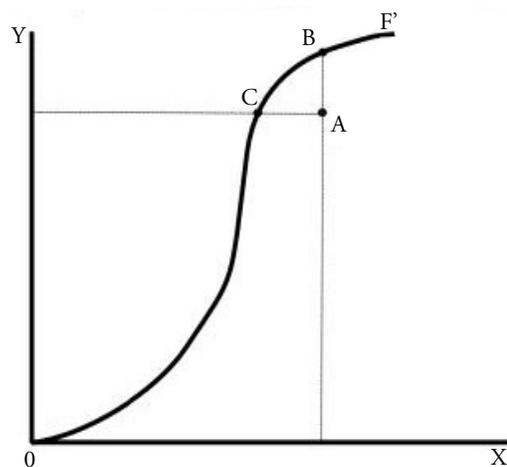
The TFP, measured by the Malmquist index, is redefined as the net effect of changes in technical efficiency (or movements relative to the existing frontier) and changes in the production frontier (or technological change) between two time periods, under the multiple input-multiple output framework (Cooper

et al., 2007). The terms technical efficiency and technological change are explained below.

Efficiency is related to the proportion of the production value compared to the value of the input or productive factor (Heyne, 1998). According to Silvestre and Chamú (2015), efficiency has been approached from two points of view: the economic and the technical. The first of these is related to the quotient between the economic results obtained and the financial resources invested in obtaining them; and the second, with the quotient between the production of a period and the use of the necessary productive factors; generally, this measure is not calculated in monetary units, but rather in physical units.

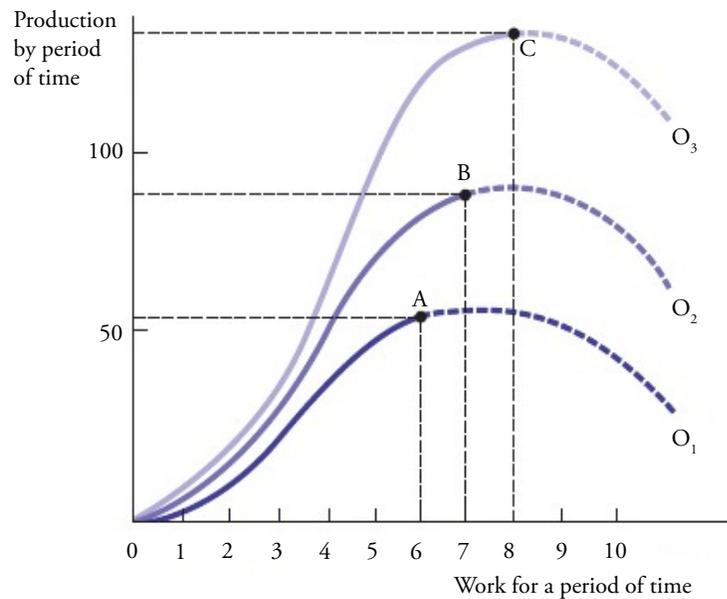
Technical efficiency is graphically shown in Figure 1. The line OF represents a production frontier, which indicates the maximum product obtainable for each level of input. The firm operates on the production frontier if it is technically efficient (points B and C), or below it if it is technically inefficient (point A). The firm operating at point A is inefficient because it could increase the level of output associated with point B without requiring additional amounts of input.

For its part, technological change is necessarily observed in a dynamic context, and this implies that the relationship between the use of inputs and the output generated changes over time. The usual way to represent technological change consists of a shift in the production function, assuming that there is a stable relationship between output, input and time (Lema and Brescia, 2001). Figure 2 shows this change; initially, the production curve is given by O_1 , but improvements in technology can allow it to shift upwards, first to O_2 and then to O_3 (Pindyck and Rubinfeld, 2009).



Source: Coelli *et al.* (2005).

Figure 1. Production and Efficiency Frontier Technique.



Source: Pindyck and Rubinfeld (2009).

Figure 2. The effect of technological improvement.

In agricultural production, there are three types of factors that influence its performance, which are: agronomic management, environmental conditions of the cultivation region, and genetic characteristics of the seed used (Hatfield and Walthall, 2015). In addition to this, Galván (2022) identifies two aspects for the increase of agricultural productivity. One of them focuses on increasing the production volume, implementing technologies and innovations that enable the units to achieve economies of scale, which allow them to participate in export markets, increasing their profitability, accessing better prices, and increasing the profit margin. The second is implementing sustainable practices that reduce production costs and increase the profitability of national products. Castelán-Estrada *et al.* (2016) present an induction to the High Profitability Model for sugarcane (HPM), which includes the diagnosis of soil, water, drainage; tillage system and soil preparation, high density and ideal planting date, selection of suitable varieties and seeds, balanced fertilization, water and drainage management, integrated pest management, including weeds; preparation for harvest and mechanized green harvest. For their part, Aquino *et al.* (2018) identified the main variables that influence the yield of sugarcane in Mexico. Among the environmental factors, two were frost and the presence of coffee rust. In management variables, it was found that the renewal of sugarcane fields, despite being rainfed, favors yield. In the genetic factors, the surface harvested with the MY 55-14 variety was significant; this variety is

of early to intermediate maturing, and a yield of over 180 tons/ha has been achieved in experimental fields. At the same time, the sugarcane agroindustry has had a series of inefficiencies and technological delays, which have impacted its profitability and probably influenced the closure of 22% of the existing mills in a period of 19 years (Valdivia, 2022). Likewise, CONADESUCA (2024) states that, in some factories, the processes and inputs used to transform sugarcane are the same as those used for many years, and the application of new technologies is still incipient. Modern and efficient mills coexist with old and inefficient mills. Hernández-Cázares (2014) mentions that, in order to increase technical efficiency in the sugar agroindustry, a range from innovations in primary production to the adoption of new technologies must be included.

Therefore, it is of interest to quantitatively estimate the technical efficiency and technological change in each of the sugarcane producing states in Mexico. The methodology used to quantify total factor productivity is the Malmquist index method, procedure that was based on Färe *et al.* (1994), Coelli *et al.* (2005), and Coelli and Prasada (2005). The Malmquist index approach is based on data envelopment analysis (DEA) to construct a piecewise production frontier for each year of the data set. The DEA is based on linear programming, which uses input and output quantity data, in this case from a group of 15 states, to construct a piecewise linear surface over the data points. This frontier surface is constructed by solving a sequence of linear programming problems for each state in the sample period 2010/2011 – 2019/2020. The degree of technical inefficiency of each state, the distance between the observed data point, and the frontier are produced as a byproduct of the frontier construction procedure (Coelli and Prasada, 2005).

The DEA can be input-oriented or output-oriented. In the first case, the DEA method seeks the maximum proportional increase, keeping the levels of products for each state constant. In the case of the output-oriented DEA, the maximum proportional increase in the elaboration of products is sought with constant input levels. Both measures provide the same technical efficiency scores when a technology with constant returns to scale (CRS) is applied, but they are different when variable returns to scale (VRS) are assumed (Coelli *et al.*, 2005; Coelli and Prasada, 2005). In this study, constant returns to scale are assumed and the output-oriented DEA has been chosen, because it is considered that, in agriculture, there is usually the attempt to maximize the product, given a set of inputs rather than the opposite case.

MATERIALS AND METHODS

The information used in this research was obtained mainly from CONADESUCA (2020a), CONADESUCA (2020b), the Agri-Food and Fisheries Information Service (SIAP, 2021) and the Mexican Sugar Manual Publishing Company

(CEMA, 2017). The software used to estimate the Malmquist indices was CRAN-R 4.0. The data set used to run the DEA linear programming models, from which the total factor productivity (TFP) indices for each Decision-Making Unit (DMU) are obtained, is a balanced panel data set. Its temporal dimension corresponds to 10 periods ranging from the 2010/2011 harvest to the 2019/2020 harvest, while its cross-sectional dimension corresponds to the 15 states (DMU) where sugarcane is grown in Mexico. Table 1 presents the definition of the variables used in the study, their units, and whether they correspond to a product or an input.

The units of the variables used correspond to those defined in CONADESUCA (2020), except for the variable total energy consumed (ENTOCO). In the case of the variable ENTOCO, the variables of net bagasse produced (tons), total oil consumed (liters), and electrical energy acquired from the Federal Electricity Commission (*Comisión Federal de Electricidad*, CFE) were added, in order to express in a single variable the energy sources used to operate the heaters and physical equipment related to sugarcane milling. It is assumed that all net bagasse is used as fuel in sugarcane milling.

The procedure for the aggregation was as follows. To convert bagasse to electrical energy, the bagasse obtained per hectare was taken and multiplied by the total harvested surface, in order to obtain the total bagasse per state. The bagasse packed and sold was subtracted from the total bagasse to obtain the total net bagasse. According to the Ministry of Energy (*Secretaría de Energía*, SENER) (2017), one ton of bagasse is equivalent to 1,684,990 kilocalories (kcal), which, in turn, is equivalent to 7,054.7161 megajoules (MJ). Therefore, when the amount of bagasse is multiplied by this amount, the equivalence of tons of bagasse in MJ is obtained. Since it is known that one MJ is equivalent to

Table 1. Variables used in the study.

Variable	Description	Units	Type
PTABEST	Total standard sugar produced	Tons	Product
GELECT	Electric power generation	MW h ⁻¹	Product
GEVAP	Steam generation	Tons	Product
VACARRE	Transport vehicles	Truck	Input
CORTAD	Cutters	People	Input
ENTOCO	Total energy consumed	MW h ⁻¹	Input
KARBET	Theoretical kilos of recoverable standard sugar	kg/tCB	Input
CAMOLBR	Gross milled sugarcane	Tons	Input
SUPCIND	Industrialized cane surface	Hectares	Input
TINETZA	Net harvest time	Hours	Input

Notes: MW h⁻¹: Megawatt-hours; kg/tCB: kilograms of sugar per ton of raw cane.
 Source: prepared by the authors based on CONADESUCA (2020).

0.277778 kilowatt-hours (kWh), the equivalence of bagasse burned in electrical energy was obtained by performing the respective multiplication. In the case of oil, SENER (2017) indicates that a barrel of oil is equivalent to 158.9872 liters, so the total oil consumed in each state during the respective harvest was converted to barrels of oil. Similarly, SENER (2017) indicates that a barrel of oil of 158.9872 liters is equivalent to 1,469,600 kcal, so they converted the barrels of oil consumed to kcal. Since the conversion factor of a kcal to MJ is 0.0042, converting kcal to MJ, similarly the bagasse was converted from MJ to kWh. Finally, to facilitate the interpretation of the variables total energy consumed and electric energy generated, they were expressed in megawatt hours (MW-h). Regarding the variable called recoverable kilos of standard sugar (KARBE), it is a variable used by CONADESUCA to define the reference price per ton of sugarcane. In the Center for Studies for Sustainable Rural Development and Food Sovereignty (CEDERSSA, 2019), a broader explanation is given of how KARBE is used to define such a reference price paid to the sugarcane producer, while in CONADESUCA (2016), the technical formula to obtain KARBE is explained in detail.

The methodology used to quantify the total factor productivity was the Malmquist Index method.

In this way, given the data of N states in a particular period of time, then the linear programming problem that must be solved for the i -th state under the output-oriented DEA is set out as follows:

$$\begin{aligned} & \max_{\phi, \lambda} \phi \\ & \text{Sujeto a } -\phi y_i + Y\lambda \geq 0 \\ & \quad x_i - X\lambda \geq 0 \\ & \quad \lambda \geq 0 \end{aligned}$$

Where y_i : is a $M \times 1$ vector of product quantities for the i -th state; x_i : is a $K \times 1$ vector of input quantities for the i -th state; Y : is a $N \times M$ matrix of product quantities for all N states; X : is a $N \times K$ matrix of input quantities for all N states; λ : is a $N \times 1$ vector of weights and ϕ : is a scalar.

In this ϕ linear programming problem, a value greater than or equal to one and $(\phi-1)$ is the proportional increase in product that could be obtained by the i -th state, if all input quantities are held constant. It can also be seen that the relationship $1/\phi$, defines a technical efficiency score that ranges between zero and one. This linear programming problem is solved N times, that is, once for each country in the sample period. The solution to each linear programming problem produces a vector of values for ϕ and λ . The ϕ vector of parameters provides information on the technical efficiency score for the i -th state, and

the λ vector provides information on the comparison countries for the i -th inefficient state. The states that serve as comparison are the efficient states, which help define the efficient frontier against which the i -th inefficient country is projected (Coelli and Prasada, 2005).

Having said that, the Malmquist index of total factor productivity is defined using distance functions. Distance functions describe a multi-product, multi-input production technology without the need to specify a behavioral objective, such as cost minimization or profit maximization. Both types of functions can be defined as follows. An input distance function characterizes the production technology by seeking a minimum contraction of the input vector given the product vector. The product distance function considers a maximum proportional expansion given the input vector (Coelli and Prasada, 2005).

A product distance function can be characterized as follows: A production technology can be defined using a product set $P(x)$, which represents the group of all product vectors y , which can be produced using the input vector x . That is,

$$P(x) = \{y : x \text{ can produce } y\}$$

The input distance function is defined on the set of inputs, $P(x)$, as:

$$d_o(x, y) = \min \{ \delta : (y / \delta) \in P(x) \}$$

According to Coelli and Prasada (2005), the distance function, $d_o(x, y)$, will take a value less than or equal to one, if the product vector y , is an element of the production set $P(x)$. Additionally, the distance function will take a value of one, if y is located on the outer edge of the feasible production set, and will take a value greater than one if y is located outside, but above, the feasible production set. The DEA method is commonly used to calculate such distance measures, which are briefly described next.

The Malmquist total factor productivity index measures the change in TFP between two data points, for example, those of a particular country in two adjacent time periods, by calculating the ratio of the distances of each data point relative to a common technology. According to Fare *et al.* (1994), the Malmquist (product-oriented) index of change in TFP between period s (the base period) and period t is given by:

$$m_o(y_s, x_s, y_t, x_t) = \left[\frac{d_o^s(y_t, x_t)}{d_o^s(y_s, x_s)} \times \frac{d_o^t(y_t, x_t)}{d_o^t(y_s, x_s)} \right]^{1/2}$$

where the notation $d_o^s(x_t, y_t)$ represents the distance from the observation of period t to the technology of period s . A value m_o greater than 1 will indicate a

positive growth of TFP from period s to period t , while a value of less than one indicates a decline in TFP. It is important to note that the above expression, in practice, is the geometric mean of two TFP indices. The first index is evaluated in relation to the technology of period s and the second index is evaluated in relation to the technology of period t (Coelli and Prasada, 2005).

An equivalent way of expressing the Malmquist Index of the TFP is:

$$m_o(y_s, x_s, y_t, x_t) = \frac{d_o^t(y_t, x_t)}{d_o^s(y_s, x_s)} \left[\frac{d_o^s(y_t, x_t)}{d_o^t(y_t, x_t)} x \frac{d_o^s(y_s, x_s)}{d_o^t(y_s, x_s)} \right]^{1/2}$$

where the ratio that multiplies the expression in brackets measures the change in Farrell's (1957) product-oriented measure of technical efficiency between periods s and t . That is, the change in efficiency is equivalent to the ratio of the technical efficiency in period t and the efficiency in period s . The part in brackets is a measure of the technical change, which is also the geometric mean of the change in technology between the two periods, assessed at x_t and also at x_s .

However, in Coelli and Prasada (2005), who cite Färe *et al.* (1994) and given that this study uses panel data, the distance measures for the Malmquist Index of the TFP are calculated using linear programs similar to DEA models: for the i -th state, four distance functions are calculated, with the aim of measuring the change in TFP between two periods, s and t . This requires solving four linear programming problems. These linear programming problems are:

<p>(1)</p> $\left[d_o^t(y_t, x_t) \right]^{-1} = \max_{\phi, \lambda} \phi$ <p>Sujeto a</p> $-\phi y_{it} + Y_t \lambda \geq 0$ $x_{it} - X_t \lambda \geq 0$ $\lambda \geq 0$	<p>(2)</p> $\left[d_o^s(y_s, x_s) \right]^{-1} = \max_{\phi, \lambda} \phi$ <p>Sujeto a</p> $-\phi y_{is} + Y_s \geq 0$ $x_{is} - X_s \lambda \geq 0$ $\lambda \geq 0$
<p>(3)</p> $\left[d_o^s(y_s, x_s) \right]^{-1} = \max_{\phi, \lambda} \phi$ <p>Sujeto a</p> $-\phi y_{is} + Y_s \lambda \geq 0$ $x_{is} - X_s \lambda \geq 0$ $\lambda \geq 0$	<p>(4)</p> $\left[d_o^t(y_t, x_t) \right]^{-1} = \max_{\phi, \lambda} \phi$ <p>Sujeto a</p> $-\phi y_{it} + X_s \lambda \geq 0$ $x_{it} - X_s \lambda \geq 0$ $\lambda \geq 0$

As can be seen in (3) and (4), where production points are compared with technologies from different time periods, it is not necessary for the parameter ϕ to be greater than or equal to 1, as it must be when calculating standard product-oriented technical efficiencies. The data points may be above the production frontier, which is more likely to occur, in the linear programming problem (4), where a production point from period t is compared with the technology in a previous period, s . If technical progress has occurred, then a value of ϕ less than one is possible. It should also be noted that it could happen in model (3), if technological regression occurs, which is less likely.

Now, an important topic is that of the properties of the returns to scale of the technology, which are very important in the measurement of the TFP. First, in this study, constant returns to scale were used, because aggregate data at the state level are used in most cases, except in Campeche, Colima and Quintana Roo, where only one sugar mill operated during the study period and, therefore, the data of the respective mill correspond to the state data. Second, constant returns to scale were used, since this assumption is applicable both at the company level and to aggregate data (Coelli and Prasada, 2005).

RESULTS

The results obtained from the balanced panel data set for the 2010/2011-2019/2020 harvests, for the 15 states where sugarcane is produced, for the production of sugar as a sweetener, are presented below, as well as the descriptive statistics of the variables used in the research (Table 2).

Since this is a balanced data set, the total number of observations is 150 for 15 cross-sectional units (N) and 10 time periods (T). The cross-sectional units correspond to the 15 states where sugarcane is grown and the 10 time periods correspond to the 10 harvests of the study; that is, from the 2010/2011 harvest to the 2019/2020 harvest. Therefore, Table 2 shows three different types of descriptive statistics: the "Total" statistics, based on the 150 observations; the "Between" statistics, which are the summary statistics of the variables of the 15 states; and the "Within" statistics, which represent the measurements of the 10 time periods. However, since the "Within" descriptive statistics sometimes have negative average values, they are not included in the table. This normally occurs in panel data and not because the calculation procedure is wrong, but for the present study these statistics are not of interest.

Now, the Malmquist Index can be broken down into several indicators: the indicator of change in technical efficiency, the indicator of technological change (or change in the efficient production frontier), and the indicator of total factor productivity. These three indicators can be calculated both for the change between periods (between harvests) and for each year, for each of the decision-making units, which in this case correspond to the 15 states where sugar cane is grown.

Table 2. Descriptive statistics of the study panel variables.

Variable		Average	Standard dev .	Minimum value	Maximum value
PTABEST	Total	394,341	527,877	25,799	2,628,598
	Between		537,419	66,392	2,216,537
GELECT	Total	69.4	111.0	5.4	652.3
	Between		109.0	14.2	449.6
GEVAP	Total	1,866,331	2,666,168	133,641	13,500,000
	Between		2,722,152	381,758	11,300,000
VACARRE	Total	1,089	1,705	84	7,735
	Between		1,736	191	7,204
CORTAD	Total	4,857	8,319	13	37,597
	Between		8,508	876	34,888
ENTOCO	Total	297,000,000	902,000,000	419,474	4,180,000,000
	Between		919,000,000	5,679,461	3,600,000,000
KARBET	Total	112.920	10.953	83.694	139.091
	Between		10.437	94.940	136.176
CAMOLBR	Total	3,505,829	4,790,749	264,043	23,700,000
	Between		4,884,633	719,076	20,200,000
SUPCIND	Total	51,065	73,725	2,984	332,186
	Between		75,763	9,505	312,950
TINETZA	Total	278,604	335,737	36,416	1,796,221
	Between		342,785	68,991	1,444,790

Source: prepared by the authors based on the CRAN-R output.

The results of the percentage change between periods were obtained for the three indicators into which the Malmquist Index breaks down: change in technical efficiency, technological change, and change in total factor productivity (Table 3). If the percentage change measure turns out to be positive, it represents an advance in technical efficiency, a technological advance or else an increase in total factor productivity. Otherwise, if the percentage change measure turns out to be a negative value, it means a regression in these indicators.

The average change in technical efficiency between periods was 0.1%, in technological change it was 2.0%, and in total factor productivity it was 2.1%. Technical efficiency showed its greatest regression between the 2011/12 harvest and the 2012/13 harvest, with a change of -0.7%; it also showed regression in the 2015/16-2016/17 and 2018/19-2019/20 harvests, with -0.2%. The 2010/11-2011/12 and 2012/13-2013/14 harvests had the greatest increase in technical efficiency, with 0.9%. The 2014/15-2015/16 and 2017/18-2018/19 harvests did not show changes in technical efficiency.

In the case of technological change, although the greatest changes were observed, for example with the change between the 2014/15 harvest and the 2015/16 harvest, which was 12.2%, there are also technological regressions, as observed, for example, between the 2018/19 and 2019/20 harvests, where the

Table 3. Change between periods of the Malmquist Index .

Change between harvests	Change in technical efficiency (%)	Technological change (%)	Change in total factor productivity (%)
2010/11-2011/12	0.9	4.5	5.5
2011/12-2012/13	-0.7	7.4	6.7
2012/13-2013/14	0.9	-3.6	-2.7
2013/14-2014/15	0.1	7.1	7.2
2014/15-2015/16	0.0	12.2	12.2
2015/16-2016/17	-0.2	-3.1	-3.3
2016/17-2017/18	0.2	-5.5	-5.3
2017/18-2018/19	0.0	6.2	6.2
2018/19-2019/20	-0.2	-5.8	-5.9
Average	0.1	2.0	2.1

Source: prepared by the authors based on the CRAN-R output.

technological reversal was -5.8%.

During the study period, the 2012/13-2013/14, 2015/16-2016/17, 2016/17-2017/18 and 2018/19-2019/20 harvests showed a regression in total factor productivity, with the 2018/19-2019/20 harvest showing the greatest negative change with -5.9%. On the contrary, the 2010/11-2011/12, 2011/12-2012/13, 2013/14-2014/15, 2014/15-2015/16 and 2017/18-2018/19 harvests had an increase in total factor productivity, the greatest advance occurred in the 2014/15-2015/16 harvest, with 12.2%.

This period-by-period analysis of the indices of change in technical efficiency and technological change shows that in the 2011/12-2012/13, 2012/13-2013/14, 2016/17-2017/18 harvests, these indices move in opposite directions; that is, in the same period, there may be an improvement in efficiency, but at the same time, a technological regression or vice versa.

Similarly, the results of the percentage change were obtained for the three indicators into which the Malmquist Index breaks down: change in technical efficiency, technological change, and change in total factor productivity by state (Table 4). If the percentage change measure is positive, it represents an advance in technical efficiency, a technological advance, or an increase in total factor productivity. Otherwise, if the percentage change measure is negative, it means a regression in these indicators.

As can be seen in Table 4, unlike the average annual growth rate, which only allows productivity to be viewed for each variable at a time, the indicators into which the Malmquist Index is broken down allow synthesizing into a single percentage the technical efficiency, technological change, and total factor productivity for ten variables, of which three are considered as products and seven as inputs.

The change indicator in technical efficiency shows that, in general, during the 2010/11–2019/20 period, it was halted in 13 of the 15 states where sugarcane is grown, with a value in these states of 0.0%. In Oaxaca, this indicator even showed a regression. The state of Tabasco is striking, where technical efficiency grew by 2.0%.

In the case of the indicator of technological change, it shows that in 12 of the 15 states where sugarcane is grown, there was an increase in technological improvements and innovations. Sinaloa with 12.5%, Jalisco 3.3%, Campeche 3.0%, Tabasco 2.4%, Veracruz 2.4% and Nayarit 2.1%. The states of Chiapas, Morelos, Oaxaca, Puebla, San Luis Potosí and Tamaulipas had technological advances, although below the national average (2%). However, in the study period, two states showed a technological regression: Michoacán and Quintana Roo, where the technological change indicator was -0.3% and -1.0%, respectively. Colima did not present changes.

Regarding total factor productivity, positive changes were observed in the states of Sinaloa with 12.5%, Tabasco with 4.4%, Jalisco with 3.3%, Campeche with 3.0%, Veracruz with 2.4%, and Nayarit with 2.1%. The states of Chiapas, Morelos, Oaxaca, Puebla, San Luis Potosí and Tamaulipas also showed progress in total factor productivity, although below the national average (2.1%). Colima was the only state that did not show changes in either technical or technological efficiency, therefore, it did not show changes in total factor productivity either. The states of Michoacán and Quintana Roo showed a

Table 4. Malmquist index by federal entity.

Decision-making unit	Change in technical efficiency (%)	Technological change (%)	Change in total factor productivity (%)
Campeche	0.0	3.0	3.0
Chiapas	0.0	1.7	1.7
Colima	0.0	0.0	0.0
Jalisco	0.0	3.3	3.3
Michoacán	0.0	-0.3	-0.3
Morelos	0.0	0.2	0.2
Nayarit	0.0	2.1	2.1
Oaxaca	-0.3	1.2	0.9
Puebla	0.0	1.5	1.5
Quintana Roo	0.0	-1.0	-1.0
San Luis Potosí	0.0	0.4	0.4
Sinaloa	0.0	12.5	12.5
Tabasco	2.0	2.4	4.4
Tamaulipas	0.0	1.1	1.1
Veracruz	0.0	2.4	2.4
National	0.1	2.0	2.1

Source: prepared by the authors based on the CRAN-R output.

decline with -0.3 and -1.0% respectively, which corresponds to a technological decline and by not having a change in technical efficiency, this value represents a regression in total factor productivity.

DISCUSSION

Table 5 shows the preliminary analysis of the average annual growth rates of some of the most common productivity indicators, in the evaluation of the performance of the sugarcane agroindustry at the state level, in the 2010/2011-2019/2020 harvest period.

In Table 5, the following facts can be observed at the national level during the study period. The industrialized sugarcane surface grew steadily by 1.52%, in contrast with the field yield, which decreased by -0.41%. The growth rates of the production of raw milled cane and standard sugar also grew by 1.108% and 0.166%, respectively. Two of the partial productivity indicators considered most important had a negative growth rate: factory efficiency decreased by -0.152% while factory yield decreased by -0.917%. Three decimal places were considered for these indicators, due to how sensitive they are for the analysis of productivity performance in the sugarcane agroindustry.

By state, Veracruz confirms what is indicated in CONADESUCA (2020b): sugarcane production, and consequently the production of standard granulated sugar, has grown steadily, at least for the period 2011 to 2020 in an extensive manner. That is, its growth has been based on the planted

Table 5. Productivity growth rates of some variables of the sugarcane agroindustry by state.

Entity	Industrialized surface (%)	Field performance (%)	Gross milled sugarcane (%)	Standard sugar (%)	Efficiency in factory (%)	Factory performance (%)
Campeche	8.46	1.69	10.29	8.45	-0.194	-1.639
Chiapas	0.79	0.86	1.66	1.12	-0.169	-0.497
Colima	2.66	0.29	2.96	3.51	0.233	0.536
Jalisco	2.16	2.08	4.28	4.31	0.009	0.026
Michoacán	2.31	-0.18	2.13	1.70	-0.018	-0.428
Morelos	1.15	-0.10	1.06	1.38	0.468	0.313
Nayarit	0.77	1.16	1.94	1.17	-0.005	-0.749
Oaxaca	1.16	0.58	1.75	-0.28	-0.419	-1.978
Puebla	1.04	-0.09	0.95	0.54	0.187	-0.361
Quintana Roo	2.28	-7.01	-4.89	-6.90	-1.184	-2.025
San Luis Potosí	0.14	-4.68	-4.55	-5.98	-0.279	-1.497
Sinaloa	-9.28	-1.17	-10.34	-10.51	-0.089	-0.123
Tabasco	2.56	2.70	5.34	4.33	0.189	-0.929
Tamaulipas	1.02	-3.13	-2.14	-3.16	-0.555	-1.023
Veracruz	1.85	-0.54	1.30	-0.10	-0.284	-1.370
National	1.52	-0.41	1.11	0.17	-0.152	-0.917

Source: prepared by authors based on CONADESUCA (2020b).

surface and, therefore, the harvested area. The indicators of innovations and technological change have even registered a decrease; for example, also in Veracruz, the sugarcane field yield has decreased by -0.54% on average per year. Sinaloa is an extreme case, since all its indicators have decreased in the study period. This reflects the fact that in that state, during the study period, two sugar mills ceased to operate: the Los Mochis mill ceased to operate in the 2014/2015 harvest and the Avance Regional (La Primavera) mill ceased to operate in the 2013/2014 harvest. Finally, Campeche stands out because the growth rate of the industrialized sugarcane surface increased by 8.46% each year.

Regarding the indicator used in the previous analysis, it is worth mentioning that the average annual growth rate allows us to see whether the respective variable grew or decreased in terms of productivity, but it does not allow us to separate the performance of the decision-making unit in a single measure; in this case, the respective state, in terms of technical efficiency and technological change, this situation was overcome by using data envelopment analysis applied to panel data. Regarding technical efficiency, it was found that, in the study period, it came to a halt in 13 of the 15 states where sugarcane is grown, its value being 0.0% in those states. This result is consistent with statements by SADER (2021), which states that, in the last ten years, although the harvested and industrialized sugarcane area showed an annual growth rate of 1.4%, although the yield in the field and the efficiency in the factory remained practically stagnant, which means that sugar production increased extensively and not due to an increase in the productivity of the sugarcane field or the sugar mills.

On the other hand, 12 of the 15 states where sugarcane is grown showed an increase in technological improvements and innovations; however, Sinaloa was the only state that showed a significant change, contrary to the preliminary analysis of the average annual growth rates. Although the Los Mochis and Primavera sugar mills ceased to operate in that state, the data envelopment analysis applied to panel data obtained a positive value in technological change. SADER (2021) states that 34% of the sugarcane field is planted with the CP 72-2086 variety, which makes the crop vulnerable to biotic and abiotic stress, pests and diseases, so it is necessary to diversify the mosaic of varieties in the Mexican sugarcane farmland. Aquino *et al.* (2018) identified that with the MY 55-14 variety, in experimental fields, a yield above 180 tons/ha has been achieved, since this variety is of early to intermediate maturation.

On the other hand, in some of the factories, the processes and inputs used to transform sugarcane are the same as those used for many years, and the application of new technologies is still incipient. This is consistent with the results obtained in the case of the technological change indicator, at the national

level, during the study period, where an average of only 2% was obtained. Below is a comparison of the Malmquist indices of the sugar industry in Mexico with other producing countries (Table 6).

An assessment of the change in productivity, technical efficiency and technological change carried out for the sugar agro-industry in China, in the 2004-2013 period, showed a decrease in the tendency of sugarcane productivity during 2004-2013, with a total factor productivity index score of 0.894, a slight increase in the level of technical efficiency, with a score of 1.002, and a decrease in technological innovation, with a score of 0.880 (Yet *et al.*, 2016). For its part, in a study of the sugar agro-industry in India, for the period 2004/05-2013/14, the results showed that the average value of the total factor productivity index was 0.993, which indicates that during that period, productivity decreased by 0.70% annually, reaching the conclusion that this decrease is largely due to a technological regression, since technical efficiency showed a moderate growth rate during the study period (Singh, 2016).

Raheman *et al.* (2009), in their study of the sugar industry in Pakistan for the 1999-2007 period, found that the total factor productivity index decreased by -0.1%, which was explained by a decrease in technical efficiency of -0.8% and a technical growth rate of 0.8% per year.

When comparing the indices obtained in Mexico and the indices of other countries, it can be seen that Mexico's technical efficiency index is lower than that of China, India and Pakistan; however, Mexico's technological change index is higher than those obtained by these same countries. Therefore, it is important to highlight the need to conduct a thorough study of Sinaloa, Jalisco and Campeche, which obtained the highest indices of technological change, in order to replicate their production processes and technological improvements in less-favored mills.

CONCLUSIONS

The analysis of technical efficiency, technological change and total factor productivity through panel data and estimates using the non-parametric method of data envelopment analysis, allowed us to understand how these

Table 6. Change between periods of the Malmquist Index for the sugar industry in different countries.

Country	Change in technical efficiency (%)	Technological change (%)	Change in total factor productivity (%)	Period
China	1.002	0.880	0.894	2004-2013
India	1.005	0.988	0.993	2004/05-2023/14
Mexico	0.1	2.0	2.1	2010/11-2019/20
Pakistan	0.992	1.008	0.999	1998-2007

indicators change over time and for decision-making units in this period, for many inputs and for many products.

The claim that the sustained growth of sugarcane has been due exclusively to (extensive) growth in surface area, and that technological change in the field and in factories, has become stagnant, is not entirely correct. Three of the indicators of the Malmquist Index have allowed us to locate in which period between harvests, technical efficiency, technological change and total factor productivity have grown, declined or stagnated.

The methodology has allowed us to detect which states have had improvements in technical efficiency, technological improvements and innovations, and growth in total factor productivity. At the state level, technical efficiency was halted for almost all states and even showed regression in Oaxaca. In nearly all the states, there was technological change and the incorporation of innovations into production processes, except in Michoacán and Quintana Roo, where there was a technological regression of -0.1 and -0.3%, respectively. In terms of the three indicators, Colima was the only state where there was stagnation, since the indices are equal to zero. Sinaloa, although it did not have improvements in its technical efficiency, shows a great incorporation of technology and innovations, since its index of technological change in the study period was 12.5%.

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