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Analysis of water productivity and social impact on forage sorghum (*Sorghum bicolor* (L.) and maize (*Zea mays* L.) in the Comarca Lagunera, Mexico

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ABSTRACT

Objective: The purpose of the study was to compare the profitability, efficiency, and productivity indexes of water in forage sorghum (*Sorghum bicolor* (L.) Moench) and maize (*Zea mays* L.) production in the Comarca Lagunera in 2019.

Design/methodology/approach: Mathematical models were used to estimate the efficiency and productivity indexes of water used in sorghum and maize production. Data used in the mathematical models was obtained from official statistical sources.

Results: The water efficiency and physical productivity results were 226 L kg^{-1} and 4.42 kg m^{-3} and 221 L kg^{-1} and 4.52 kg m^{-3} for sorghum and maize, respectively. The efficiency and economic productivity indexes of water were 82.87 and 49.96 m^{3} per USD profit and \$12,067 and \$20,018 USD profit per hm^{3}. Nevertheless, social efficiency was higher in maize (7.7 employments hm^{-3}) than sorghum (7.1 employments hm^{-3}), which required 8% more water to produce an employment unit.

Study Limitations/Implications: Models should be used to compare different productivity indexes of sorghum and maize in the Comarca Lagunera which has a shortage of water resources.

Findings/Conclusions: In the case of the Comarca Lagunera, maize was more productive and efficient than sorghum in physical, economic and social terms (employment creation); however, further research must take into consideration dynamic models.

Keywords: Water footprint, Forage production, Water, Efficiency, Productivity.

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INTRODUCTION

The scarcity of water resources impacts agricultural activities, reducing the crop yield potential (Reyes-González *et al.*, 2020). Maize is the most important crop in Mexico: it is the main food source for humans, but it is also an excellent livestock forage. In 2019,

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the domestic production of forage maize reached 15,569,846.80 tons (t), generating an economic revenue of approximately \$10.2 billion Mexican pesos (\$10,198,617,458.29 pesos). Meanwhile, the production sorghum amounted to 3.3 million tons, reaching a domestic production value of 1.2 billion pesos (SADER, 2019). According to SIAP (2019), the Comarca Lagunera produced 12.53 and 25.34% of the total forage sorghum and maize production in the country (37,860.24 ha, 76.36% of which was used for forage maize and 23.63%, for forage sorghum). As a whole, the production amounted to 1.5 million tons of forage (9.73% of the domestic production), generating an overall economic revenue of more than \$1.18 million pesos —79.3 and 20.87% was obtained from maize and sorghum, respectively (SIAP, 2019).

Agriculture —as the activity that consumes most water resources— demands strategic actions promoting increased efficiency in the use of water during the input-output transformation (Mancosu *et al.*, 2015). Conventional methodologies have failed to identify the problem: how to assess the water footprint with specific data. However, the use of mathematical models based on physical, economic, and social water footprints provides certainty about the origin of the data to be processed. An output that can be replicated in different settings is obtained (Ríos-Flores and Navarrete-Molina, 2019; Ríos-Flores *et al.*, 2018). Optimization models provide solutions to problems involving the maximization or minimization of an objective function with a system of strictly delimited equations (Ramírez-Barraza *et al.*, 2019).

Agricultural production should focus on improving yield per unit area (Perales-García *et al.*, 2019). Physical and monetary productivity indexes that can be used as eco-efficiency, yield, and environmental pressure indexes are useful tools for producers or decision-makers (Ríos-Flores *et al.*, 2014).

The Comarca Lagunera shows a high rate of productivity. However, since the water resource supply does not satisfy the demand, the region also suffers water scarcity, representing an allocation conflict between different users (Ramírez-Barraza *et al.*, 2019). It is estimated that more than 683.15 hm^3 are extracted from the subsoil in this area, while the average annual recharge only amounts to 534.10 hm^3 (Tovar-Triana, 2021). The purpose of this study was to compare the profitability, efficiency, and productivity indexes of the water used in the production of forage sorghum (*Sorghum bicolor* (L.) Moench) and maize (*Zea mays* L.) crops with groundwater irrigation, using pumping and gravity irrigation, in the Comarca Lagunera during 2019. This comparison would be used to selected the most efficient crop.

MATERIALS AND METHODS

Geographical location of the study area

The Comarca Lagunera study area is located between 26° 00' and 26° 10' N and 104° 10' and 103° 20' W, at an altitude of 1,119 m (Acevedo- Peralta *et al.*, 2017). According to García (2004), the Comarca Lagunera has a desertic climate with low atmospheric humidity and an annual rainfall of 260 mm.

Official statistical sources used

RF_i=Physical yield of the *i*-th crop (t ha^{-1}). Where $RF=VBP/P$; the sources of the *VBP* (Gross Value of Production), P=Annual physical production during the 2019 agricultural closure according to SIAP-SADER (2021).

LR_i=Irrigation sheet of the *i*-th crop (m^3) (INIFAP-CENID-RASPA, 2006).

EC_i=Hydraulic conductivity efficiency of the *i*-th crop ($0<EC<1$).

Where *EC* is the Hydraulic conductivity efficiency (INIFAP-CENID-RASPA, 2006).

The weighted price for the aggregation level of both forages (overall forage production for both crops) is provided by the following equation, in which "Q_i" is the production and "P_i" is the price per ton:

$$Weighted\ price = \frac{\sum_{i=1}^{n} Q_i * P_i}{1\sum_{i=1}^{n} Q_i}$$

P_i=Price of the *i*-th crop product (in MX\$ t^{-1}), for which $p=VBP/P$, where the *VBP* sources (gross value of production) and P=annual physical production (t) (SIAP-SADER, 2021).

PC=Exchange rate in Mexican pesos (MX\$) per each USD (\$20.50 MXN) (Banco Mundial-XE, 2021).

Mathematical models used

The following equation was used to determine the weighted cost per hectare:

$$Weighted\ cost = \frac{\sum_{i=1}^{n} S_i * C_i}{1\sum_{i=1}^{n} S_i}$$

C_i=Production cost per hectare of the *i*-th crop (MX\$ ha^{-1}) (FIRA, 2019).

S_i=Harvested area of the *i*-th crop (ha) (SIAP-SADER, 2021).

$g_i=U_i$=Profit per hectare of the *i*-th crop (USD\$ ha^{-1})$=RF_i\,(p_i/PC)-(C_i/PC)$.

The following equation was used to estimate the weighted profit per hectare of maize and sorghum crops:

$$Weighted\ profit = \frac{\sum_{i=1}^{n} S_i * g_i}{1\sum_{i=1}^{n} S_i} = \frac{\frac{1}{PC}\sum_{i=1}^{n}\left[S_i * RF\left(P_i-\left(C_i / RF_i\right)\right)\right]}{\sum_{i=1}^{n} S_i}$$

J_i=Number of daily wages invested per hectare in the *i*-th crop (FIRA, 2019).

Table 1. Mathematical models used to determine productivity.

Variable	Model for an individual crop
PFA (L kg^{-1})	$Y = 10^4 * LRi * (RFi * ECi)^{-1}$
EFA (kg m^3)	$Y = 10^{-1} * RFi * ECi * LRi^{-1}$
EEA (m^3 USD^{-1})	$y = \frac{10^4 \left(LR_i / EC_i \right)}{RFi\left(P_i / PC \right) - \left(C_i / PC \right)}$
PEA (Thousands of USD earned per hm^{-3} of water)	$y = 10^2 g_i EC_i \left(LR_i \right)^{-1}$
PSA (Jobs hm^{-3})	$y = \frac{25}{72} \frac{J_i}{\left(LR_i / EC_i \right)}$
ESA (m^3 $Jobs^{-1}$)	$y = \frac{2.88 * 10^6 LR_i}{J_i EC_i}$

PFA=Physical Productivity; PEA=Economic Productivity; PSA=Social Productivity; EFA=Physical Efficiency; EEA=Economic Efficiency; and ESA=Social Efficiency. All these values are related to the water used in the individual crop production or for crop aggregates designed by Ríos-Flores & Navarrete-Molina (2019) and Ríos-Flores *et al.* (2020).

i=i-th crop under a specific irrigation system (groundwater and gravity irrigation) (FIRA, 2019).

Number of working days per year per worker=6 days per week times 48 weeks per year=288=1 equivalent employment (FIRA, 2019).

RESULTS AND DISCUSSION

Productivity efficiency of forage sorghum and maize

Table 2 shows the total harvest of both crops: forage sorghum and maize (37,860.24). In 2019, over 100 thousand hectares were planted in the Comarca Lagunera; two out of every five hectares (almost 40%) were planted with these forages.

The cost-benefit ratios (RB/C) for sorghum and maize were 1.09 and 1.13, respectively. For every dollar invested in forage, sorghum obtained a 9% profit, while maize obtained a higher profit (13%). Although profits are reported in this study, Ríos-Flores *et al.* (2016) reported a loss of −23.4 million pesos in their study of *Triticum vulgare* in the Mexicali Valley, despite the large volume of water invested in irrigation (low yield m 3 kg^{-1}).

Social efficiency of forage sorghum and maize

An investment of 18.13 daily wages (145.04 working hours) was required to produce one sorghum commercial hectare, while 19.62 daily wages (156.96 working hours) were required to produce one maize commercial hectare. The number of daily wages (J) invested per sorghum and per maize hectare generated the equivalent of 493.58 employments to harvest forage sorghum in 8,948.74 and 1,473.57 employments to harvest forage maize in 28,911.5 ha. Overall, a total of 1,967.15 employments were created.

Table 2. Macroeconomic statistical indicators of forage maize and sorghum crops irrigated with groundwater by pumping and gravity irrigation (Comarca Lagunera, 2019).

Macroeconomic Variable	Forage sorghum	Forage Maize
Harvested area (ha)	8,948.74	28911.5
Annual production (t)	351,334.99	1161998.78
Gross value production (millions of USD)	$ 12.05	$ 47.70
Yield (Green forage; t ha^{-1})	39.26	40.19
Price (USD t^{-1})	$ 34.30	$ 39.3
Incomes (USD ha^{-1})	$ 1,347	$ 1,581
Costs (USD ha^{-1})	$ 1,239.39	$ 1,403
Exchange rate (MX per USD)	$ 20.5 MXN per 1 USD	
Profits (USD ha^{-1})	$ 107	$ 178
Cost-Benefit ratios	1.09	1.13
M^3 of water used per ha	8,888.90	8,888.90
Daily wages per ha (J)	18.13	19.62
Irrigation cost ha^{-1} (USD)	$ 149	$163

Developed using SIAP data (2019).

The social water efficiency (ESA) reported for sorghum was 141,203 m^3 employment^{-1}. Meanwhile, forage maize required a smaller volume of water resource to generate one employment (130,479 m^3 employment^{-1}). Sorghum cultivation generated 7.1 employments hm^{-3}, as a result of the use of a greater water volume; on its part, according to the PSA, maize cultivation generated 7.7 employments hm^{-3} surpassing sorghum. Maize was more efficient, since sorghum required 8% more water to produce an employment unit. These results surpass the values recorded in the Comarca Lagunera by Ríos-Flores *et al.* (2015) for alfalfa (0.037), forage oats (0.68), rye grass (0.76 employments hm^{-3}). García-García *et al.* (2013) and others reported the generation of 24 to 62 employments hm^{-3} in the vegetable and fruit production, while in greenhouses more employments were created (190 employments hm^{-3}).

Water efficiency of forage sorghum and maize

According to SADER (2020), forage sorghum and maize used 8,888.9 m^3 ha^{-1} of water. The area sown with both crops amounted to 37,860.24 ha (8,948.74 hectares of sorghum and 28,911.55 hectares of maize). If we multiply 37,860.24 ha by the total number of m^3 used (8,888.9 m^3), we find that both crops used 336.53 hm^3. On the one hand, sorghum producers invested $0.017 USD in water per m^3, while maize producers invested $0.018 USD (SADER, 2020). On the other hand, in Spain the cost ranged from 0.59 to 0.17 € m^{-3} j (García-García *et al.*, 2013), while, in California, the productivity of water amounted to 0.20 € m^{-3}, €0.70 m^{-3}, and €5.00 m^{-3} for maize, almonds, and strawberries, respectively (Fereres, Goldhamer, & Parsons, 2003).

Forage sorghum used 226 L kg^{-1} and forage maize 221 L kg^{-1}, suggesting that forage maize was more efficient than sorghum, since it can produce the same biomass kg using only 97.78 % of the water volume used by forage sorghum (Table 3). We obtained less efficient results than those reported by Pedroza-Sandoval *et al.* (2014) (175 L kg^{-1} for maize). Values for dryland (875 to 710 L kg^{-1}) and for irrigation (586 to 671 L kg^{-1}) were reported by Alvarez *et al.* (2016). This improved use of water in the Comarca Lagunera can be attributed to the varieties used.

The production of forage sorghum and maize amounted to 4.42 kg m^{-3} and 4.52 kg m^{-3}, respectively (PFA) (0.98; Table 4). Similar values (3.60 kg m^{-3} to 2.18 kg m^{-3}) were reported by Garcia-Garcia *et al.* (2013) in Spain for artichoke using three different irrigation options. In the study about *Triticum vulgare* by Ríos-Flores *et al.* (2016), lower values (0.321 kg m^{-3}, 0.668 kg m^{-3} and 0.667 kg m^{-3}) were obtained in Ensenada, Mexicali Valley, and Baja California. Lower values were likewise reported in the province of Punjab, Pakistan, regarding wheat (0.43 kg m^{-3}) and cotton (1.12 kg m^{-3}) (Shabbir *et al.*, 2012), as well as regarding wheat in China (0.9 kg m^{-3}) and the United States of America (1.3 kg m^{-3}) (Brauman, Siebert, & Foley, 2013).

Producing one dollar of profit requires 82.87 m^3 of water in the case of sorghum, while forage maize requires almost half the water (49.96 m^3) and the index was equal to 1.66 (Table 3). Water-wise, forage sorghum was less efficient, since it required almost double the amount of water (177 %) than maize to produce the same amount of profit. Sorghum economic productivity reached $12,067 USD of profit, while forage maize had a higher revenue ($20,018 USD), using the same volume of water. Compared with the indexes reported by Ríos-Flores *et al.* (2015) —70,000 USD hm^{-3} (sorghum) and 40,000 USD hm^{-3} (maize) PEA indexes— This study has values far below the ones reported in 2015. The above statement is also reported by Pedroza-Sandoval *et al.* (2014) with a $32,683 USD index for forage maize. The variation in the efficiency of the crops can be attributed to the high temperature that influences the photosynthesis rate of crops; forage sorghum is more sensitive to different types of stress (Chadalavada, Kumari, & Kumar, 2021).

Table 3. Efficiency and productivity indexes of water, capital, and labor of forage sorghum and maize crops using groundwater (Comarca Lagunera, 2019).

Index	Units	A: Forage Sorghum	B: Forage Maize	c=a/b
EFA	m^3 kg^{-1}	0.226	0.221	1.02
EFA	L kg^{-1}	226	221	1.02
PFA	kg m^{-3}	4.42	4.52	0.98
EEA	m^3 of water used for each USD of profit (m^3 USD^{-1})	82.87	49.96	0.94
PEA	USD profit per hm^3 of water in production	$ 12,067	$ 20,018	0.60
ESA	m^3 of water used per each job generated	141,203	130,479	1.08
PSA	Jobs generated per hm^3 (Jobs hm^3)	7.1	7.7	0.92
Price of water	USD per hm of water used	$ 16,765	$18,336	0.91
PEA/Price of water	Dimensionless	0.72	1.09	

PFA=Physical Productivity; PEA=Economic Productivity; PSA=Social Productivity; EFA=Physical Efficiency; EEA=Economic Efficiency; and ESA=Social Efficiency. All these values are related to the water used in the individual crop production or for crop aggregates designed by Ríos-Flores & Navarrete-Molina (2019) and Ríos-Flores *et al.* (2020).

CONCLUSIONS

Mathematical models can be indicative of the sustainability assessment of natural resources; consequently, a more comprehensive analysis of the said resources can be carried out. Production- and water-wise, forage maize was more efficient than forage sorghum, which would benefit the Comarca Lagunera by saving water resources. Further research must take into consideration dynamic models that cover environmental variables, in order to obtain a better explanation of the crop productive behavior.

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