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Not all ruminants were created equal: Environmental and socio-economic sustainability of goats under a marginal-extensive production system

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ABSTRACT

Globally, while the livestock sector contributes significantly to the environmental impact (EI), it faces some key challenges such as to increase production to cover increased demand, to adapt to highly variable natural and economic scenarios, and to enhance its eco-environmental performance. Such complex scenarios require a comprehensive evaluation of the EI considering the carbon footprint (CF), the blue water footprint (BWF), the socio-economic sustainability (SES) and their interactions. Hence, the economic value (EV) made by the goat production system (GPS) in the Comarca Lagunera (CL), northern-arid Mexico was quantified to compare it with its EI and SES (1994–2018). Response variables included the EV of the CF and BWF and the SES of the EV-GPS. The value of each of the variables was adjusted to 2011 euros while indicating the value in United States Dollars (USD) between parentheses. The CL recorded annual averages of 390,427 goats, 64.34 million liters of milk and 3,316.12 tons of meat. When contrasting the EV-GPS [M€ 18.17 (MUSD 23.47)] with the EV-CF [M€ 3.61 (MUSD 4.67); 84.29 kg $CO_{2\text{-eq}}$ kg milk-meat protein^{-1}, MMP^{-1}] + EV-BWF [M€ 2.48 (MUSD 3.20); 462.99 l H_2O kg MMP^{-1})], a positive balance was observed. The accumulated GPS-CL economic spillover effect was M€ 454.23 (MUSD 586.83), 5.79 million minimum wages (MW) yearly and close to 400,000 MW during the studied period. The GPS is highly eco-efficient considering both the CF and the transformation of the BWF into animal protein (milk-meat) with an undisputable biological value. Besides, the greater the economic and productive efficiency of the GPS, the better the socio-economic conditions of the producer and his family, with concomitant decreases in both the index and degree of marginalization of families and municipalities where goat production develops.

1. Introduction

Human population growth has increased demand for goods and services, resulting in overexploitation of the world's resources at an ever-greater economic and environmental cost (Cardoso, 2012). Globally, the livestock sector contributes significantly to the environmental impact (EI) (Steinfeld et al., 2013). Hence, this sector has a triple challenge: 1) to increase production to cover increased demand, 2) to adapt to highly variable natural and economic scenarios, and 3) to enhance its eco-environmental performance (Opio et al., 2013). Such complex scenarios require a comprehensive evaluation of the EI, mainly related to the carbon footprint (CF), the water footprint, and their interactions (Ridoutt and Pfister, 2013).

In this respect, goat production has been scarcely studied and mainly focused on evaluating the CF (Leip et al., 2010; Michael, 2011; Opio et al., 2013; Robertson et al., 2015; Weiss and Leip, 2012). Besides being limited, most studies have not comprehensively evaluated the EI of most goat production systems (GPS). This

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is probably because most GPS are mainly in marginal environments, mostly under arid and semi-arid conditions, and linked to underfunded financial support, common in emergent economies (Gonzalez-Bulnes et al., 2011; Meza-Herrera and Tena-Sempere, 2012). This is despite the numerous advantages of the *Capra* genus, which lives under extreme climatic conditions, displays a higher ability to convert different food resources into milk and meat with a higher biological value than other domestic ruminants. Certainly, distinctive characteristics of goats, from a sustainable point of view, that contribute to these being listed as the best ruminant species are: 1. Use of natural vegetation without competition with humans, 2. A more efficient use of water, 3. Maintenance of biodiversity, 4. Low use of non-renewable energy, 5. High potentials for positive impacts in new market niches, 6. Goats and their permanence-resilience-sustainability ability, 7. Maintenance of ancestral traditions, abilities and knowledge, and 8. Promotion of cultural activities under organic schemes of community social importance, under clean, green and ethical management schemes (Peacock and Sherman, 2010). Besides, as stated by Koluman and Silanikove (2018), goats disperse lower methane emissions. On this respect, it has been estimated that Africa produces 10–13% of all global methane emissions from livestock, and cattle produce 84% of it and sheep and goats only 16%. Other investigations reported that cattle emit 25–118 kg CH4 per head, while sheep and goats emit only 5–18 kg CH4 per head (IPCC, 1995). In this same context, and regarding annual emissions in Turkey, cattle produce 76.53%, sheep 20.49% and goats only produce 2.98% of annual methane emissions. Interestingly, since the most extreme climate change scenarios will significantly affect the global dairy industry, the importance of goat production will proportionally rise as global warming increases. Undeniably, goats will accomplish a strategic role in the future of the dairy industry, predominantly under harsh climatic conditions as well as in tropical, subtropical, dry-arid and Mediterranean contexts (Silanikove and Koluman, 2015).

While the intertropical area of Asia and Africa has the largest human population, it possesses the lowest bovine inventory while concentrating around 80% of the world's goat population, suggesting that, globally, more people consume milk or milk products derived from goats than other ruminants (Silanikove et al., 2010). In the Americas, Mexico ranks third in goat milk production, generating 162,323 tons, almost 25% of the continent's total production continent, just below Brazil and, unexpectedly, Jamaica (FAO, 2019). In Mexico, goat production is mainly associated with the low-income rural stratum, with more than 80% of the national census managed by the social sector (i.e. low-income smallholders, peasants who own neither the croplands nor the rangelands) (Isidro-Requejo et al., 2019). In Mexico, the Comarca Lagunera (CL) agro-ecological region in the semi-arid north has one of the largest goat populations in the Americas and ranks first in goat milk production, generating income for more than 2,800 families under a production scheme mainly oriented to organic goat milk production, favoring the economic, social and biotic environment of goat keepers, under a clean, green and ethical production scheme (Isidro-Requejo et al., 2019). In 2018, the CL had a goat inventory of 240,462, with a production herd close to 50% which generated 55.34 million liters of milk and 2,460 tons of meat, equivalent to 36% and 6% of national production, respectively, representing an economic value of M€ 24.08 (MUSD 31.11) (SIAP, 2019). Recent studies by our group demonstrated a significant EI by the dairy (Navarrete-Molina et al., 2019a) and the beef (Navarrete-Molina et al., 2019b) cattle industry in the CL. Consequently, based on the aforementioned attributes of goats, we hypothesized that the EI, considering the economic value (EV) of both the carbon (CF) and the blue water (BWF) footprints generated by the goat production system (GPS) in the CL, would be less than the EV generated by goat production in this region.

2. Methods

2.1. Location, environmental information on the study area and data bases

The Comarca Lagunera (102° 22′, 104° 47 ′ WL; 24° 22′, 26° 23′ NL, at 1,139 m.a.s.l.) is located in a semi-arid ecotype, with an average temperature of 22 °C, lows of 0 °C (winter) and highs of 40 °C (summer). While the rainy season extends from June to October, the mean annual rainfall and temperature are 225 mm and 24 °C, respectively. Relative humidity fluctuates from 26.1 to 60.6% and the photoperiod ranges from 13 h, 41 min (summer solstice, June) to 10 h, 19 min (winter solstice, December). The CL is an interesting agro-ecosystem; it has an agricultural component with large spaces devoted to forage production (i.e. alfalfa, sorghum forage, corn forage) with a large availability of agricultural by-products and crop residues. The other component of this complex agro-ecosystem is the rangeland, comprising a large area with vegetation characterized as Chihuahuan desert rangeland, previously described by Meza-Herrera et al. (2017). Briefly, although creosotebush (Larrea tridentata (DC. Cov)) dominates the grazing area, other important species include lechuguilla (Agave lechuguilla Torr), mesquite (Prosopis glandulosa v. glandulosa) and blue gramma (Bouteloua gracilis (Wild). Ex Kunth Lag. Ex Griffiths). Goats graze-browse mostly on rangelands though they have access to crop residues such as corn, sorghum, cotton, and alfalfa. Goats walk approximately 5 km daily from the corral to different rangeland sites, so grazing-browsing constraints can be considered negligible (Mellado, 2016). During the spring-summer, goats graze-browse the rangeland driven by a herdsman 9 h daily (1000–1900 h) and are then penned from 1900 to 1000 h. Goats spend the night in an unroofed corral where they have free access to water and a commercial mineral-mix. As stated, the GPS is based on diurnal extensive grazing-browsing and night-time corral confinement; importantly, the largest portion of the goat's diet is directly harvested from the rangeland, yet goats may have sporadic access to crop residues (i.e. alfalfa, cotton). Most of the GPS, almost 92%, is managed under this daily feeding pattern on the rangeland without nutritional supplementation while only 8% receives sporadic supplementation during the lactation period; intensive systems in the region are minor (Salinas-González et al., 2016).

In the development of the study, information generated by the Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food's was considered (SIAP, 2019). Additionally, calculus relative to goat supplementation considered the average obtained from a sample of 50 interviewed producers who supplement their milking goats for 112 days (Nov–Feb). Supplement was offered daily and includes alfalfa hay (163 g), oat hay (163 g), corn silage (813 g) and wheat bran (163 g), equivalent to 601 g dry matter, 1.34% of the goat live weight. Based on such information, the requested amount of commercial fertilizer to produce this supplement was estimated as previously outlined (Figueroa-Viramontes et al., 2011). The study also used data bases already published as well as those generated *ex-profeso* in the study; each response variable (i.e. EV, CF and BWF) was adjusted to a 2011-euro reference value, indicating the value in United States Dollars (USD) between parentheses.

2.2. Methods for estimating the economic value of the goat production system (EVGPS) and greenhouse gas emissions (GHGE)

The annual EVGPS was calculated as the total volume of milk and meat produced yearly multiplied by the average payment per liter of milk and kg of meat received by the producers. The EV of goat meat moved from M€ 3.36 (MUSD 4.33) in 1994 to M€ 23.33 (MUSD 30.14) in 2018, representing a global increase close to 700% during this period. Besides, GHGE assessments included various factors and indices recommended by the Intergovernmental Panel on Climate Change (IPCC) in 2016. Such emission factors (EF) reflect the fact that virtually all manure is managed through “dry management systems”, including the rangeland, pastures, dry feeding corrals and daily distribution throughout the rangeland (Hongmin et al., 2006). The IPCC-proposed global warming potential values were used: 1 unit of methane (CH_4) = 25 units of CO_2 ($CO_{2\text{-eq}}$) and 1 unit of nitrous oxide (N_2O) = 296 of $CO_{2\text{-eq}}$. The EV-GHGE considered an international carbon emission price of 15.75 € t^{-1} of $CO_{2\text{-eq}}$ (USD 20.35) (Environmental Finance, 2011; Thompson Reuters, 2011). According to the IPCC, the quantification of GHGE (CH_4 and N_2O) in the agricultural sector includes the categories of livestock and agriculture (i.e. forage production for supplementation) (Hongmin et al., 2006).

a) Goat milk-meat subsector

Emissions of CH_4 generated from enteric fermentation were quantified considering the equation outlined by Hongmin et al. (2006), and following the description made by Navarrete-Molina et al. (2019a,b). In this estimate, the emission factor (EF) considered was 5 kg CH_4 $head^{-1}$ y^{-1}, corresponding to the goat category for developing countries (Hongmin et al., 2006). In addition, quantification of CH_4 emissions for manure management were based in the Tier 1 methodology proposed by Hongmin et al. (2006) as described by Navarrete-Molina et al. (2019a,b). The EF used was 0.22 kg $head^{-1}$ y^{-1}, corresponding to goats managed in developing countries with a hot climate with temperature averages above 25 °C.

The emissions of N_2O produced during manure management was quantified considering both feces and urine produced by goats under extensive conditions, and were measured based on the methodology outlined by Hongmin et al. (2006) and adjusted by Navarrete-Molina et al. (2019a,b).

b) Agriculture subcategory

Those direct N_2O emissions from agricultural areas devoted to forage production for supplementation purposes were estimated. Nitrogen inputs from synthetic fertilizers were considered; such estimations were based in the equation outlined by Hongmin et al. (2006) as described by Navarrete-Molina et al. (2019a,b). To estimate the amount of nitrogen, the fertilizer used in forage production for supplementing goats in the CL was considered. The level of nitrogen fertilizer extracted from soils by different forage crops (corn and oats) was quantified, as suggested by Figueroa-Viramontes et al. (2011).

2.3. Method for estimating the blue water footprint (BWF)

The basis for calculating the BWF was the mathematical methodology proposed by Mekonnen and Hoekstra (2010) as outlined by Navarrete-Molina et al. (2019a,b). Thereafter, it was then calculated as a stress-weighed BWF value, which results from multiplying the BWF value by a water stress index (WSI) as suggested by Ridoutt and Pfister (2010) adjusted according to Navarrete-Molina et al. (2019a,b).

For quantification purposes, a conservative approach was adopted and additional water resources derived from agricultural land use (green water footprint) were not considered. The last because the green water consumption *per se* does not contribute to water scarcity until it is transformed to blue water (Ridoutt and Pfister, 2010). Certainly, green water does not contribute to the environmental flows required for the health of freshwater ecosystems, nor is it accessible for other human uses. For quantifying the BWF’s economic costs, the international average price of water per m^3 in some European Union countries (Denmark, Germany, the Netherlands, Belgium, and France, among others), as reported by Kjellsson and Liu (2012) [3.5 € m^{-3} (USD 4.52)], was considered. Besides, in order to make the analyses as representative as possible, besides euros, the economic value in United States dollars (USD) was also included.

2.4. Method for estimating the social impact (SI) of goat production

To determine the EVGPS-CL social impact, the minimum wage for the geographic “C” area which belongs to the study area, published by the National Commission for Minimum Wages and adjusted at 2011, was considered. Besides, the information generated by the National Household Expenditure Survey-2012 was also considered (INEGI, 2013). Since this national survey is not annually performed, we used the information generated in 2012 because of its chronological approximation to our 2011-year based adjustments. Moreover, the Absolute Municipal Marginalization Index (AMMI), based on the methodology proposed by the National Population Council (CONAPO, 2013), was calculated. The value considered for the variables used for the AMMI calculation was published by CONAPO (2019), considering the years 1995, 2000, 2005, 2010 and 2015. The variables included for the AMMI calculation were: 1) percentage of population up to 15 years’ old that is illiterate, 2) percentage of inhabitants in a house with no electricity, 3) percentage of inhabitants in a house with no running water and 4) percentage of inhabitants of a private house with no drainage or exclusive lavatory. According to CONAPO (2013), the AMMI is directly obtained from the percentages of the recorded deficiencies for each municipality, using the same adjustment for each socioeconomic indicator; since each of the four components is adjusted by a 0.25 value, it is possible to compare them among different years; the AMMI was calculated as:

$$AMMI_i = \frac{\sum_{j=1}^{4} I_{ij}}{4}$$

Where:

$AMMI_i$: = refers to the value of the absolute margination index of a municipality i,
I_{ij}: = refers to the value of the j-th indicator of the municipality i.

This methodologic option is similar to that used to calculate the first component from the Principal Component Analysis. The method used in the AMMI calculation is a mathematical methodology which transforms a set of variables or indicators into a new set, then, with a reduced number of variables remakes a simpler interpretation of the original phenomenon (CONAPO, 2013). A correlation analysis was carried out among the AMMI for each municipality during the mentioned periods with respect to the economic efficiency variables; EV of milk production (thousands of €), EV of meat production (thousands of €), EV per liter of milk (€ l^{-1}), EV per kg of meat (€ kg^{-1}) with the correspondent productive efficiency (l $head^{-1}$ and kg $head^{-1}$). The municipalities included in this study should have covered the following characteristics: 1) an average goat inventory greater than 10,000 head, since a reduced census will rank the GPS as a municipality with decreased goat importance, and 2) a total population of less than 200,000 inhabitants, since a larger population would represent an industrialized municipality.

2.5. Statistical analysis and equivalencies

When required, the original information was transformed into kg of milk-meat protein (MMP). Therefore, all information generated by other studies that have required such a transformation, for comparison purposes, will be shown with numbers in ***italics and bold***. These transformations were performed using the equivalences shown in Table 1, based on the equation proposed by Robertson et al. (2015), to calculate the fat and protein corrected milk (FPCM) for the standard goat milk. Also, the average values for the percentage of fat and protein in goat milk for the CL considered those reported by Isidro-Requejo et al. (2019), as well as those proposed by Urieta et al. (2001) for the meat calculations. During the analyzed period, linear regressions were estimated for CH_4 emissions, the EV for both the GHGE and the milk-meat production, setting 1994 as the intercept throughout the REG procedure of SAS; the correlation procedures among the response variables and the AMMI also considered the SAS procedures (SAS Inst., Cary CC, version 9.4). The Minitab (Minitab Inc., State College, Pensilvania) and Mathworks (Natick, Massachusetts) programs were used for data management and calculations.

3. Results

3.1. What we obtained regarding the goat inventory and production?

The goat inventory and total milk-meat production are shown in Table 2. While a reduction in the goat inventory was observed (−54.31%), a significant increase in milk production per goat, from 168 to 482 l milk goat^{-1} y^{-1}, equivalent to a 187% increase, occurred during the studied period (1994–2018). Goat meat production, on the other hand, only rose 3% during the analyzed period, but the average meat amount produced per goat was 4.12 kg goat^{-1} in 1994, with an interesting increase to 10.23 kg of meat goat^{-1} in 2018. Yet, when dividing the annual meat goat regarding the milking goats, that is, those goats that kidded, this figure increases up to 19.68 kg of meat goat^{-1} in 2018, generating a significant increase from 1994 to 2018 of close to 500%, regarding kid meat production.

3.2. Quantification of the carbon footprint (CF)

The observed values for methane emissions during the evaluated period showed a downward trend across the years (Fig. 1). Likewise, the CH_4 emissions reported as $CO_{2\text{-eq}}$ per kg MMP also showed a decreasing trend from 1997 to 2015 (Fig. 2). Moreover, a total reduction of 60% occurred from 1994 to 2018, with an average annual reduction of 761 g of $CO_{2\text{-eq}}$ per kg MMP.

The N_2O emissions, in gigagrams of $CO_{2\text{-eq}}$, are directly proportional to the CH_4 emissions, depicting the same trend across time; the largest N_2O reduction (20.20%) occurred between 1994 and 1995 (Table 2). Fig. 3 depicts the EV trend of both MMP and GHGE. From 1994 to 2018, EV-MMP increased M€ 1.03 year^{-1} (MUSD 1.33) while the EV-GHGE as $CO_{2\text{-eq}}$ decreased M€ 0.10 year^{-1} (MUSD 0.12).

The $CO_{2\text{-eq}}$ emissions generated by the forage production used for supplementing the milking goats during the dry season fell from 17.81 Gg $CO_{2\text{-eq}}$ in 1994 to 8.14 Gg $CO_{2\text{-eq}}$ in 2018, mainly due to the reduction in the goat inventory across years. The three main forages produced were alfalfa, corn and oats; according to the methodology proposed by the IPCC, only corn (85.66%) and oats (14.34%) contributed to the GHGE. Fig. 4 concentrates the annual EV-GHGE and the GHGE kg MMP^{-1}, considering both milking goats or the total herd, either with or without supplementation. The annual average EV-GHGE of milking goats was M€ 1.55 (MUSD 2.00), with 36.65 kg $CO_{2\text{-eq}}$ kg MMP^{-1}. These values increased up to M€ 3.61 (MUSD 4.67) and 84.29 kg $CO_{2\text{-eq}}$ kg MMP^{-1} when considering both the whole herd and the forage production for supplementation in such quantification. Interestingly, in 1994, when considering the whole herd + supplementation, the observed values were M€ 4.87 (MUSD 6.29) and 149.04 kg $CO_{2\text{-eq}}$ kg MMP^{-1}.

3.3. Quantification of the blue water footprint (BWF)

The evolution of both the goat inventory and the BWF generated by the GPS-CL (1994–2018) is shown in Table 2. The BWF volumetric value used by the GPS-CL was 1.93 m^3 million in 1994, representing a 57% reduction compared to 2018, equivalent to 3.40 m^3 goat^{-1} and 462.99 l of water kg MMP^{-1}. Fig. 5 shows the annual average for the BWF under four different scenarios A: Milking goats, B: Milking goats + supplementation, C: Total goat herd and D: Total goat herd + supplementation, during 1994–2018.

According to the information presented for the CL by CONAGUA (2015), the WSI was 0.97, categorized as extreme according to the following classification: <0.1 low; $0.1 \leq$ & <0.5 moderate; $0.5 \leq$ & <0.9 severe, and >0.9 extreme (Pfister et al., 2009). The last one generates a stress-adjusted water footprint of 1.27 Mm^3 y^{-1} of H_2O-equivalents ($H_2O_{\text{-eq}}$), equal to 3.30 m^3 $H_2O_{\text{-eq}}$ head^{-1}, and 449.10 l $H_2O_{\text{-eq}}$ kg MMP^{-1}. Based in our evaluations, the production of one kg of MMP produced in the GPS-CL theoretically contributes to fresh water scarcity which corresponds to the drinking of 449.1 l of water of an average person worldwide. This impact refers to the use of the blue water for drinking and services in the goat herd. Fig. 6 displays the contrast between the average annual EV-GHGE and the BWF with regard to the annual average of the EV of goat milk and meat. Considering the total herd with supplementation, the environmental cost represented 33.52% of the VE-GPS.

3.4. Quantification of the socioeconomic impact (SEI) of the goat production system

As mentioned, the CL is formed by municipalities in two States: Coahuila and Durango. To quantify the socio-economic impact (SEI), three municipalities in Durango (Lerdo, Mapimí and Tlahualilo; CL-DGO) and four in Coahuila (Francisco I Madero, Matamoros, San Pedro and Viesca; CL-COAH) were considered. These municipalities concentrated an annual average of 289,279 head, equivalent to 73% of the goat herd in the CL. Regarding the value of milk-meat production, these municipalities contributed with an annual average of 8.67 M€ (11.20 MUSD) and 4.01 M€ (5.18 MUSD), corresponding to 76% and 70% of the milk and meat produced in the CL, respectively. These figures are equivalent to 73% of the total economic value of the GPS-CL.

Interestingly, the correlation analyses showed that all the relationships between the AMMI and the productive and economic response variables were significant at 95% probability. Very interesting results were obtained from this evaluation; considering the CL's total goat herd, it was found that the GPS-CL generated

Table 1
Equivalencies used to transform the original milk-meat goat data.

1 kg of goat meat protein	= 5.31 kg of meat
1 kg of goat milk protein	= 30.30 kg of milk
1 kg of goat milk	= 0.96 l of milk
1 kg of fat & protein corrected milk	= 3.24 kg of milk

Table 2
Inventory of goats, milk-meat production, methane emissions (CH_4) and nitric oxide (N_2O) emissions, and blue water footprint, (BWF; millions of m[c]) generated by the goat production system in the Comarca Lagunera, Mexico, across time (1994–2018).

Year	Census (head)	Production			CH_4 emissions (Gg)			N_2O emissions (Gg)			BWF (Mm[c])
		Milk (million l)	Meat (t)	MMP[a] (t)	Enteric-F [b]	Manure-M [c]	TE[d] $CO_{2\text{-eq}}$	N_2O–N	N_2O	TE $CO_{2\text{-eq}}$	
1994	576,317	47.52	2,377	2,074	2.63	0.12	68.68	0.48	0.75	222.58	1.93
1998	442,233	48.01	2,917	2,192	2.21	0.10	57.71	0.40	0.63	187.01	1.49
2002	459,589	71.75	5,444	3,480	2.30	0.10	59.98	0.42	0.66	194.36	1.55
2006	463,317	80.90	4,165	3,553	2.32	0.10	60.46	0.42	0.66	195.94	1.40
2010	444,831	76.52	3,804	3,335	2.22	0.10	58.05	0.40	0.64	188.12	1.24
2014	280,183	61.68	3,111	2,696	1.40	0.06	36.56	0.25	0.40	118.49	1.04
2018	240,462	55.34	2,460	2,357	1.20	0.05	31.38	0.22	0.34	101.69	0.83

[a] MMP: Milk-Meat Protein.
[b] Enteric-F = Enteric Fermentation.
[c] Manure-M = Manure Management.
[d] TE = Total Emissions.

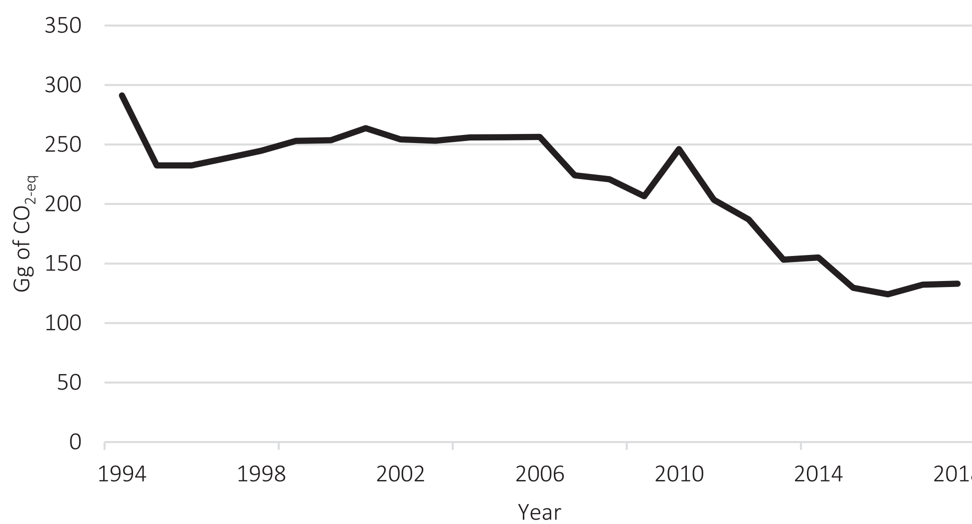

Fig. 1. Dynamic of total methane emissions (CH_4) (Gg of $CO_{2\text{-eq}}$) generated by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018).

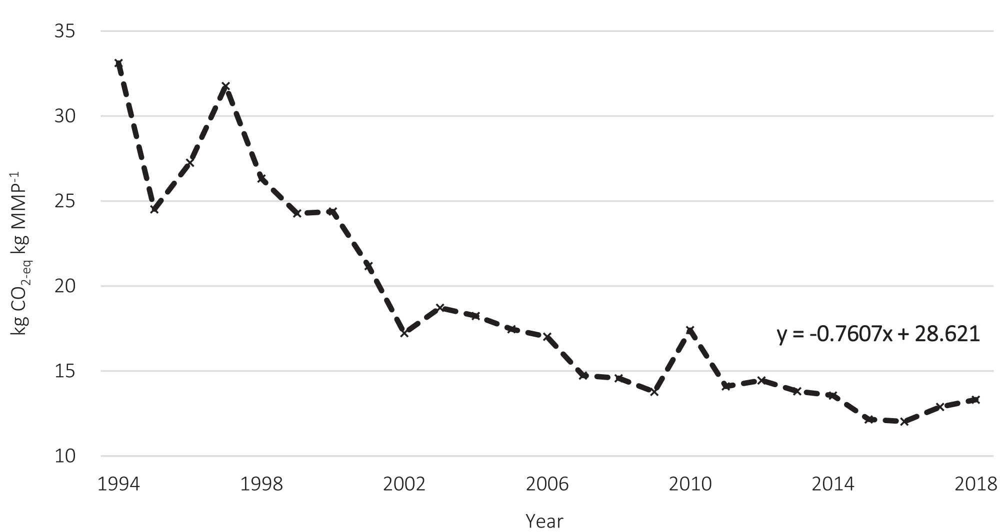

Fig. 2. Total methane emissions (CH_4) in kg $CO_{2\text{-eq}}$ per kg milk-meat protein (kg $CO_{2\text{-eq}}$ kg MMP^{-1}) generated by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018).

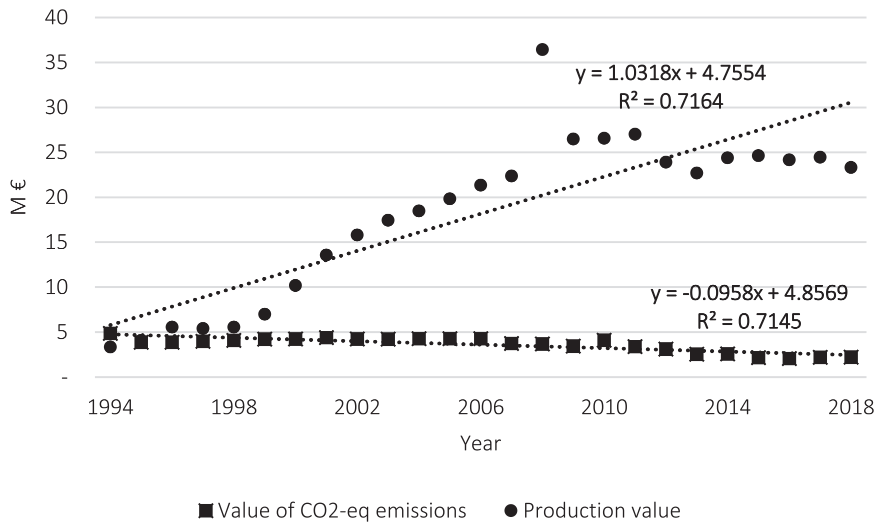

Fig. 3. Comparative analyses between the economic value of milk-meat production and the economic value of greenhouse gas emissions as $CO_{2\text{-eq}}$, generated by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018).

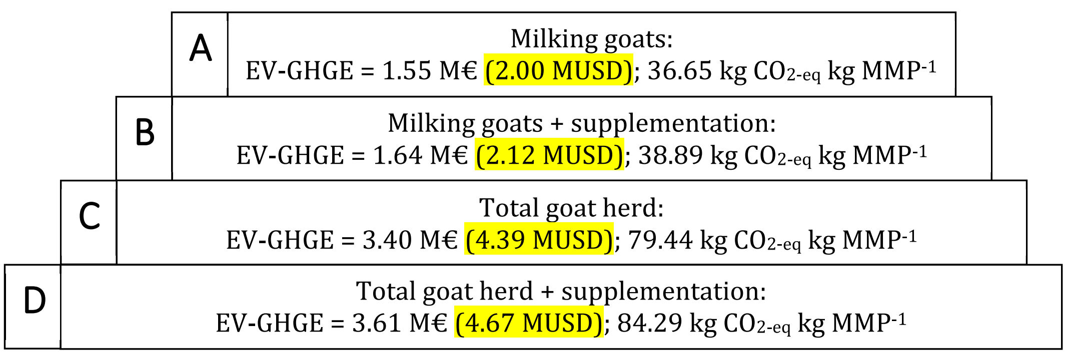

Fig. 4. Average economic value of greenhouse gas emissions [EV-GHGE; M€ (MUSD)] and GHGE per kilogram of milk-meat protein (kg $CO_{2\text{-eq}}$ kg MMP^{-1}) generated by A: Milking goats, B: Milking goats + supplementation, C: Total goat herd, and D: Total goat herd + supplementation by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018). Note: The annual average value of the goat production system was 18.17 M€ (23.47 MUSD). The EV-GHGE considered the estimated price of 15.75 € $tCO_{2\text{-eq}}^{-1}$ (USD 20.35) as proposed by Environmental Finance (2011), Thompson Reuters (2011).

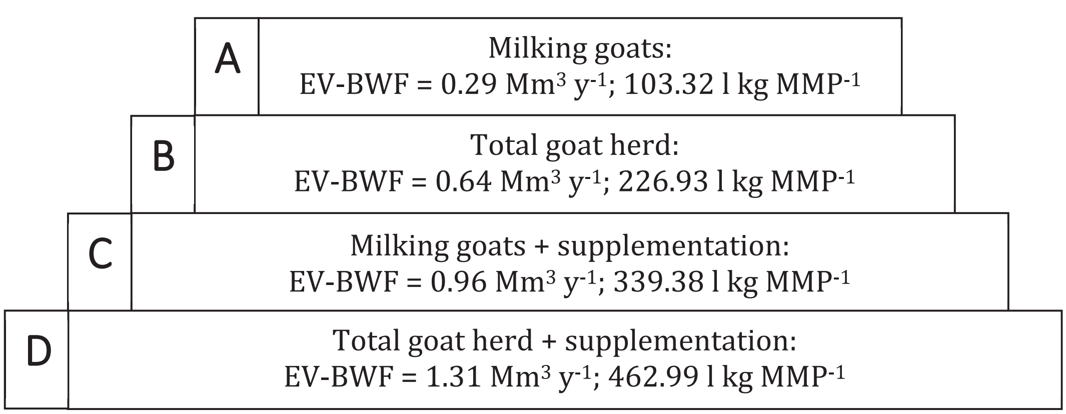

Fig. 5. Annual average value of the blue water footprint (EV-BWF; Mm^3 y^{-1}) and liters per kg of milk-meat protein (l kg MMP^{-1}) generated by A: Milking goats, B: Milking goats + supplementation, C: Total goat herd, and D: Total goat herd + supplementation by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018).

15,854.86 annual minimum wages (AMW), equivalent to the average income of 3,863 families in the rural stratum. Certainly, during the 1994–2018 period, increases were observed not only in the AMW which rose from 2,938 to 20,360 but also in the number of families that can be supported by such increases, moving from 713 to 4,960 rural families in this period. Moreover, during the

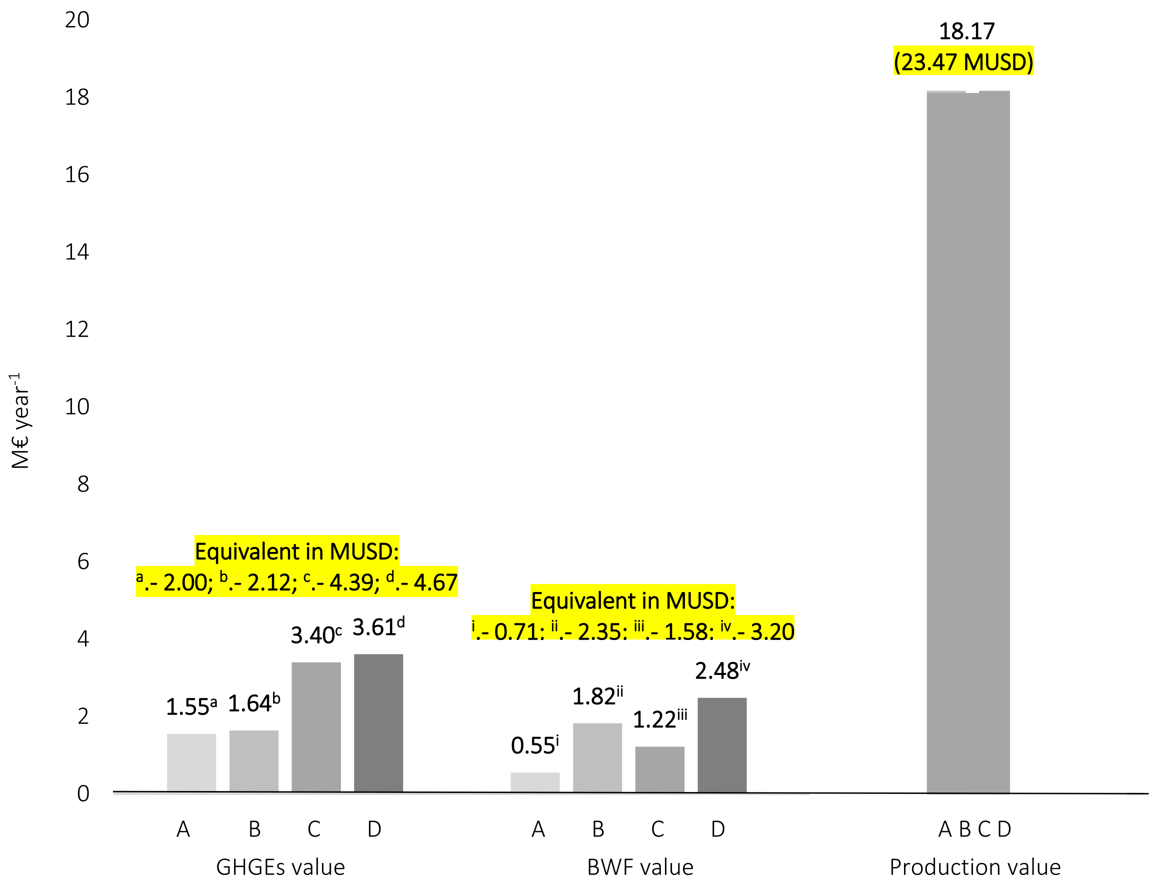

Fig. 6. Annual average economic value of greenhouse gas emissions (GHGE), blue water footprint (BWF) and milk-meat production (M€ $year^{-1}$) generated by A: Milking goats, B: Milking goats + supplementation, C: Total goat herd and D: Total goat herd + supplementation by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

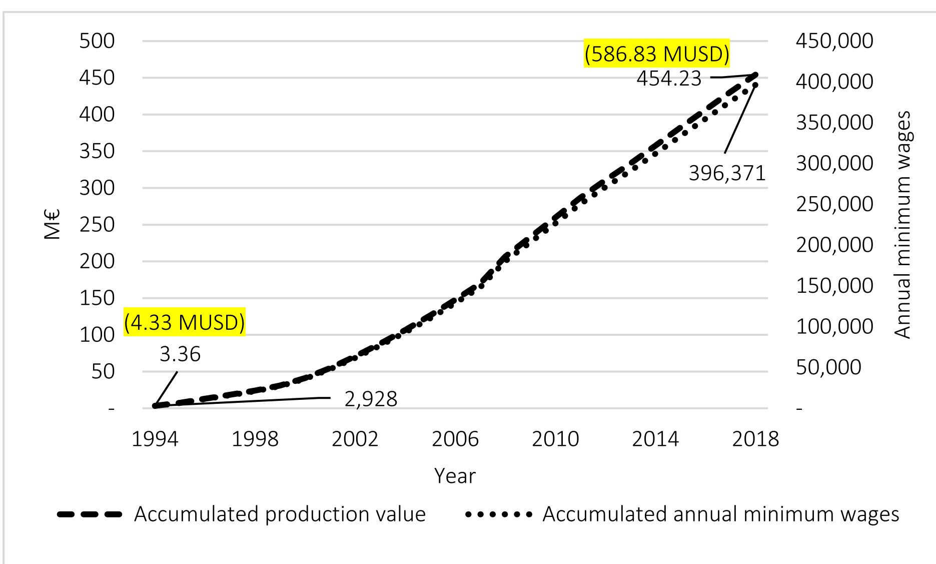

Fig. 7. Accumulated value of milk-meat production, million euros and accumulated annual minimum wages, generated by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018). Note: This GPS-value of production and this amount of annual minimum wages represent the income of 96,576 families from the rural stratum.

analyzed period, there was an accumulated economic spillover effect by the GPS-CL of M€ 454.23 (MUSD 586.83), representing the income of 96,576 families, equivalent to 396,371 accumulated AMW adjusted to the 2011 euro value (Fig. 7). Additionally, the correlation matrix between the Absolute Municipal Marginalization Index and the economic and productive calculated variables is presented in Table 3.

When evaluating the municipalities considered in the socio-economic analyses, across the period 1995–2015, a 449% global increase occurred in the EV-GPS, with growths from 3.15 M€ (4.07 MUSD) in 1995 up to 17.30 M€ (22.35 MUSD) in 2015. Moreover, a significant decrease of 536% in the AMMI was observed in the selected municipalities when contrasting an average value of 17.66% in 1995 down to 2.78% in 2015 (Fig. 8).

As an improvement in the quality of life of rural families is observed, a parallel decrease in the AMMI occurred. The AMMI is represented by a numerical scale, but it can also be expressed alphabetically in a range that goes from very low to very high, known as degree of marginalization (DOM). Table 4 shows the evolution of the AMMI and the DOM of the municipalities considered herein.

4. Discussion

4.1. What we learned from these results and how they compare to other studies?

The main outcomes of our study reveal that the environmental and economic impact of the CF and BWF generated by the GPS-CL is less than the economic value generated by this activity in the region during the analyzed period; based in such findings our working hypothesis is not rejected. Certainly, the EV-GPS showed a higher increase regarding the EV-CF and the EV-BWF (Fig. 6). The main factors explaining this difference include: 1) the BWF is totally negligible in comparison with other production systems (e.g. dairy cattle and beef cattle), 2) an uninterrupted increase in productivity, mainly in liters of milk goat^{-1}, occurred, 3) an increase in the price paid to producers per liter of milk and kilogram of meat produced was recorded, and 4) a long-term downward trend in greenhouse gas emissions was observed (Fig. 2). Moreover, the EV-CF and the EV-BWF represented only 33.52% of the EV-GPS-CL, even when considering the total goat herd + supplementation of 10% of the milking goats for a four-month period (Fig. 6). These outcomes highlight a remarkable positive performance by the GPS, especially considering the semiarid agro-ecological context in CL. In Mexico, 250,000 families in rural areas live off goat production and most of the milk produced is marketed through collection centers for the cheese and candy industry, observing a low consumption of fluid milk (Santos-Lavalle et al., 2018). However, in the face of population growth, climate change and reduced natural resources, it is feasible to predict increased demand for goat fluid milk in the coming years.

4.2. Some comparisons regarding greenhouse gas emissions

Global atmospheric concentrations of CH_4 and N_2O have increased considerably over the last 250 years. The main sources of these emissions can be directly or indirectly attributed to ruminants, including dairy cattle, goats, sheep and buffaloes (Opio et al., 2013). This represents a challenge for the goat sector's growth and development. Consequently, accurate GHGE estimates are crucial to designing effective mitigation strategies; however, while analyses of CF in dairy cattle are abundant, in goats they are scarce.

The obtained GHGE per kg MMP in this study is comparable to that described in other countries or regions in the world (Table 5). The greater value of the GHGE by the GPS-CL compared to other regions of the world is indicative of the possibility of implementing substantive measures to reduce these emissions and of the opportunities to improve goat production efficiency.

The CH_4 emissions in kg MMP^{-1} decreased from 33.12 kg $CO_{2\text{-eq}}$ in 1994 to 13.32 kg $CO_{2\text{-eq}}$ in 2018, suggesting greater efficacy by the GPS-CL regarding the use of food harvested in the rangeland and its subsequent transformation to milk-meat with high biological value, observing in parallel a lower energy loss because of the methane production. The average value of the total GHGE during 1994–2018 was 84.29 kg $CO_{2\text{-eq}}$ kg MMP^{-1}, being less than the world average value (134.73 kg $CO_{2\text{-eq}}$ kg MMP^{-1}) reported for goat production, with diverse differentials with respect to Africa (182.81 kg $CO_{2\text{-eq}}$ kg MMP^{-1}); Latin America and the Caribbean (135.62 kg $CO_{2\text{-eq}}$ kg MMP^{-1}); Asia (131.24 kg $CO_{2\text{-eq}}$ kg MMP^{-1}) and Oceania (109.79 kg $CO_{2\text{-eq}}$ kg MMP^{-1}). However, the value obtained in this study is higher than that reported for North America (72.27 kg $CO_{2\text{-eq}}$ kg MMP^{-1}), Europe (49.51 kg $CO_{2\text{-eq}}$ kg MMP^{-1}) and the Russian Federation (44.73 kg $CO_{2\text{-eq}}$ kg MMP^{-1}) (FAO, 2017). The observed results during the same period and study area generated by the dairy cattle and beef cattle systems were ***259.36*** kg $CO_{2\text{-eq}}$ kg MMP^{-1}, a value 207.70% higher than that found in the present study in goats (Navarrete-Molina et al., 2019a). These results confirm our working hypothesis that GPS-CL is more efficient from a clean, green and ethical perspective, heightening the opportunity for greater sustainability.

4.3. What significance does the water footprint hold?

From a global perspective, the availability of freshwater availability is quite reduced since it only represents 2.5% of total water resources (Tiu and Cruz, 2017). Besides, as stated by Thornton (2010), 40% of the world's population depends on groundwater to

Table 3
The correlation matrix between the absolute municipal marginalization index (AMMI) and some economic and productive variables calculated from key-goat producing municipalities in the Comarca Lagunera, Mexico, across years (1995–2015).

			AMMI	Economic value				Efficiency	
				(m€)		(€ per unit of product)		(production per head)	
				Milk	Meat	Milk (€ l^{-1})	Meat (€ kg^{-1})	Milk (l head^{-1})	Meat (kg head^{-1})
Absolute municipal marginalization index			1	−0.428	−0.339	−0.814	−0.815	−0.355	−0.599
				0.010	0.047	0.000	0.000	0.036	0.000
Economic value	(m€)	Milk		1	0.929	0.532	0.495	0.467	0.556
					0.000	0.001	0.003	0.005	0.001
		Meat			1	0.413	0.408	0.441	0.614
						0.014	0.015	0.008	0.000
	(€ per unit of product)	Milk (€ l^{-1})				1	0.975	0.565	0.757
							0.000	0.000	0.000
		Meat (€ kg^{-1})					1	0.449	0.746
								0.007	0.000
Efficiency	(production per head)	Milk (l head^{-1})						1	0.625
									0.000
		Meat (kg head^{-1})							1

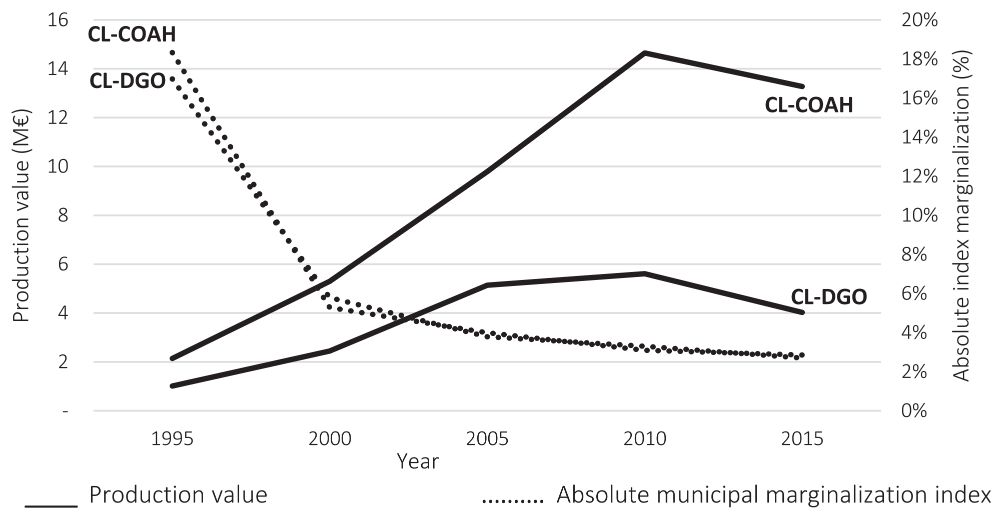

Fig. 8. Average value of goat production (M€) and absolute municipal marginalization index (%) of some municipalities of the Comarca Lagunera of Durango (Lerdo, Mapimi and Tlahualilo) (CL-DGO) and Comarca Lagunera of Coahuila (Francisco I Madero, Matamoros, San Pedro, Viesca) (CL-COAH), Mexico, observed across year (1995–2015).

Table 4
Evolution of Absolute Municipality Marginalization Index (AMMI, %) and the Degree of Municipal Marginalization (DMM) of some municipalities of the Comarca Lagunera of Coahuila (Francisco I Madero, Matamoros, San Pedro and Viesca; CL-COAH) and Comarca Lagunera of Durango (Lerdo, Mapimi and Tlahualilo; CL-DGO), Mexico, across years 1995–2015.

Comarca Lagunera	Municipality	AMMI (%)/DMM					AMMI Decrease (%)
		1995	2000	2005	2010	2015	
CL-COAH	F. I. Madero	15.8% - HI	3.9% - VL	3.5% - VL	2.1% - VL	2.0% - VL	13.78%
	Matamoros	18.2% - HI	4.2% - VL	3.4% - VL	2.1% - VL	1.6% - VL	16.58%
	San Pedro	15.5% - HI	5.1% - LO	4.0% - VL	3.5% - VL	3.1% - VL	12.38%
	Viesca	23.6% - VH	7.7% - LO	4.9% - VL	4.4% - VL	4.4% - VL	19.17%
CL-DGO	Lerdo	10.5% - ME	4.3% - ME	2.7% - VL	1.9% - VL	1.7% - VL	8.83%
	Mapimí	19.8% - HI	7.7% - LO	5.1% - LO	4.5% - VL	3.3% - VL	16.45%
	Tlahualilo	20.5% - VH	5.3% - LO	3.4% - VL	3.4% - VL	2.9% - VL	17.58%

VH= Very high, HI= High, ME = Medium, LO = Low, VL= Very low.
Source: Author-made with information from CONAPO, 2019.

Table 5
Greenhouse gas emission average (GHGE; kg $CO_{2\text{-eq}}$ kg milk-meat protein^{-1}) generated by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018) as compared to other studies.

Source	GHGE (kg $CO_{2\text{-eq}}$ kg MMP^{-1})	Product – Country – Region
This study	84.29	Milk-meat; Comarca Lagunera, México
Weiss and Leip (2012)	***89.86–136.49***	Milk-meat; European Union
Michael (2011)	***52.50***	Milk; Australia
Kanyarushoki et al.	***11.90***	Milk; France
Opio et al. (2013)	***134.58***	Milk-meat; World average
Leip et al. (2010)	***97.86***	Milk-meat; European Union
Robertson et al. (2015)	***7.58–9.64***	Milk; New Zealand

drink, while a noteworthy deficit between groundwater extraction and recharge has augmented in a significant fashion in diverse regions worldwide. The use of potable water for domestic livestock species is close to 2180 km^3 year^{-1}, so it is fundamental to evaluate the relationships between livestock production and human water consumption (Herrero et al., 2009). In these relationships, it is important to consider the value of water, because in most of the world it is not adequately valued, being considered a low-cost or more often free resource. Therefore, it is fundamental to reevaluate such perception in order to guarantee the accessibility of water not only from a quantity but a quality stand point; the main goal is to safeguard the viability of both humans and ecosystems (Herrero et al., 2009). The annual BWF used by the GPS-CL decreased from 1,930,000 m^3 in 1994 to 830,000 m^3 in 2018, averaging 1,310,000 m^3 per year (Table 2 and Fig. 5). These numbers confirm that the GPS-CL contributed 1,270,000 m^3 y^{-1} to the global freshwater shortage, representing 0.25% of the recharge of the 518.9 million m^3 aquifer in the CL (CONAGUA, 2015). This value represents merely 0.00036% of the contribution to the global water shortage reported for the dairy cattle production system-CL of 3,511,260,000 m^3 y^{-1} during the same period of study (Navarrete-Molina et al., 2019a).

There are few studies concerning goat production's water footprint. Mekonnen and Hoekstra (2010) reported a BWF global average of ***2,667.31*** l kg MMP^{-1}, which includes only non-concentrated, non-sweetened milk, with a fat percentage greater than 1% but inferior to 6%. For Mexico, a BWF of ***4,213.14*** l kg MMP^{-1} has been reported, indicating there are important differences between countries and regions. These values are higher than that observed in our study of 462.99 l kg MMP^{-1}, even much less than the ***3,303.61*** l kg MMP^{-1} for goat milk in Australia (Michael, 2011). The annual average of BWF from the GPS-CL was € 2,480,000 (3,203,986.32 USD), a value significantly lower than the income generated by it. The BWF was 3.40 m^3 $goat^{-1}$ y^{-1}, but once the BWF of forage production was eliminated, this value decreased to 1.89 m^3 $goat^{-1}$ y^{-1}. Moreover, by eliminating the BWF of the other diet components, a scenario observed in at least 90% of the production scheme with daytime grazing-browsing and night confinement, this decrease went down to 1.64 m^3 $goat^{-1}$ y^{-1}. The amount of water required for forage production represented 32.06% of the total water required for goat milk production in the CL. The EV-BWF for EV-GHGE was lower [2.48 vs 3.61 M€ y^{-1} (3.20 vs 3.61 MUSD y^{-1}), respectively], and even more evident when compared with the EV-GPS, because the EV-BWF only represented 13.65% of the EV-GPS-CL. The above is environmentally and economically relevant considering the warm climate, marginal vegetation, and significant water shortage in the CL. Consequently, promoting goat production seems to be a good option, compared to cattle production, if our aim is to reduce environmental impact upon the CL's fragile agro-ecosystem.

By contrasting these results with those obtained by the dairy cattle and the beef cattle fattening production systems (Navarrete-Molina et al., 2019a,b) calculated for the same period and study area by our group, the observed BWF value of ***30.24*** m^3 H_2O kg MMP^{-1} is significantly higher than that obtained from the GPS-CL of 0.46 m^3 H_2O kg MMP^{-1}. This difference evidences the greater efficiency of goats to convert water into protein as compared to cattle, which is particularly important when talking about arid environments like that of the study area. That is, with the water resources needed to produce one kg of bovine MMP in CL, 65.74 kg MMP, of equal or better biological quality, could be produced by goats.

The basis of goat feeding in CL is centered on the green water footprint, since most of the feed requirements are covered by the consumption of natural vegetation available in the rangeland. This is significantly different from dairy cattle, beef cattle, swine and poultry, which base their diet on the blue water footprint. These tendencies place to goats as a species committed with the environment, thoroughly eco-friendly and better adapted to the region's arid and semiarid conditions. The importance of other livestock economic activities is not minimized, but these results suggest that public policies should be aimed at fostering the sustainable use of scarce resources available in CL, especially water. The present study highlights the importance of re-valuing the goat production system as a focal point of agro-livestock development rather than only focusing efforts on supporting bovine (milk and meat), swine and poultry value chains under such marginal and arid schemes.

4.4. What significance does the socio-economic impact of goats embrace?

If we consider human development as the fourth column of sustainability, goat production not only contributes to improving the quality of life of producers from an economic, social and cultural viewpoint (Devendra and Liang, 2012), but also, as shown by the present study, from an environmental perspective. Certainly, goat production in the CL has the potential to generate annual income for almost 4000 families, who are widely distributed in the rural areas. The AMMI correlated in a negative and significant manner with all the economic and efficiency response variables. That is, the AMMI correlates in a low way with the variables milk production (l $head^{-1}$) ($\alpha = 0.04$) and EV-meat ($\alpha = 0.05$), moderately with meat production (kg $head^{-1}$) ($\alpha = 0.001$) and EV-milk ($\alpha = 0.01$) and significantly with the unit price per l of milk ($\alpha = 0.001$) and per kg of meat ($\alpha = 0.001$). These results suggest that the higher the value of any of the calculated response variables, the lower the AMMI and consequently the marginalization degree will tend to achieve lower categories. According to Lopes et al. (2012), productivity per goat is highly correlated with the human development index in Brazil. Elsewhere, in Tanzania, goat milk production was positively related to education level (Chenyambuga et al., 2014), agreeing with the main socio-economic outcomes generated by our AMMI analyses, especially regarding the decreased percentage of people who are up to 15 years old and illiterate, that is, the access to basic education.

Moreover, if we add to this the great ability of goats to produce under extremely marginal environments by transforming food resources that are hardly used by other species into products of high biological value (i.e. milk and meat), the fundamental yet strategic role played by goats in the face of climate change is indisputably clear. Indeed, among the different livestock production systems, goat milk, and meat production is one of the most primordial, least intensive, eco-friendly options, thereby meeting society's demand for clean, green and ethical production systems. The above requires further evaluating the multidimensional nature of goat production sustainability under marginal contexts, where the significant ethological and physiological plasticity of this species undoubtedly arises. Each factor to be explored must have the ability to respond and adapt to change, and goats show a sophisticated adaptive capacity. Consequently, more and more windows of opportunity are opening up, such as those called lifestyle-markets, highlighted by ethical products, fair trade, ecotourism/tourism, organic products, environmental markets and biodiversity, all of which represent a growth opportunity for the goat sector (Peacock and Sherman, 2010).

All these windows of interaction and growth opportunities could be enhanced due to the diverse adaptive characteristics shown by goats to produce and still flourish under challenging conditions: low metabolic heat production, tolerance to water shortage, an anatomical and morphological structure that allows efficient use of low-quality foods, type of skin and hair, sweat glands essential to mitigate heat stress, great reproductive capacity, excellent resistance to disease and parasites, coupled with great productive longevity. All these characteristics, normally present in the genetic material of local animals, show an inordinate physiological plasticity and capacity of adaptation by goats to face the inexorable challenges to come with climate change (Koluman and Silanikove, 2018).

4.5. Goats performed quite well but there will always be room to further reduce the environmental impact

Since our study area is an extremely arid region, with annual precipitation of 225 mm, rational water use must be promoted through regulatory policies and technological improvements. In order to achieve the last, a tangible commitment and involvement of all sectors involved in the GPS, especially the producers, is undeniable. Some policies or improvements may include:

a) protecting and improving the natural vegetation that is part of the goat's diet. The region's rangelands have greatly deteriorated due to overexploitation, originally caused by beef cattle, exacerbated by the producers' incorrect belief that rangelands do not require maintenance care (García-Bonilla et al., 2018),

b) adjusting food and reproductive management considering the seasonal dynamics of the quality and availability of natural vegetation with specific reproductive windows,
c) encouraging the adoption of health management schedules that include the most common and riskiest infectious and parasitic diseases, improving not only animal health but also that of producers and their families, as well as warding off any dangerous type of zoonosis.

These practices would provide real socio-economic benefits for a livestock sector that usually does not receive any kind of technical and social attention. Implementing the most appropriate measures will depend on the objectives set out, which must be carefully planned, considering agricultural, water and social policies for the benefit of the environment, natural resources and goat producers, which should prioritize employment generation, rational resource use and regional economic benefit. Therefore, the information generated in our study suggests a high potential for use by decision-makers whose primary objective should be to maintain the integral sustainability of agro-livestock activity contextualized in the social, economic and environmental benefits of the Comarca Lagunera itself (Navarrete-Molina et al., 2019a,b; Ríos-Flores et al., 2018).

5. Conclusions

This study appears to be the first to clearly demonstrate that the long-term economic benefit of the Comarca Lagunera goat production system is greater than its environmental impact. This system is eco-efficient when comparing its results with those observed at the global level, both for the carbon footprint and for the transformation of blue water into animal protein with an undisputable biological value. Emphasis is placed on the need for measures to improve the availability and quality of products and services for the benefit not only of the goats, but also of the producer and his family. Moreover, promoting the sustainability of goat production will also contribute to improving the socio-economic conditions of the people involved in this livestock activity. In the same vein, our study demonstrates that the greater the economic and productive efficiency of the goat production system, the better the socio-economic conditions of the producer and his family, with a concomitant decrease in both the index and degree of marginalization of families and municipalities where this activity develops. Finally, the implementation of mitigation measures should prioritize rational resource use, employment generation, and regional economic benefits as part of a more efficient and sustainable production process. The multidimensional nature of goat production sustainability under marginal contexts over the evaluated period reveals the refined while sophisticated ethological, adaptive and physiological plasticity of goats; certainly, not all ruminants were created equal.

Submission declaration

This work is original, has not been previously published and is not under consideration for publication elsewhere.

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Ethics statement

Not applicable.

Data repository resources

None of the data were deposited in an official repository, but information can be made available upon request.

Declaration of competing interest

The authors declare that there are no conflicts of interest that could be perceived as prejudicing the impartiality of the research reported herein.

CRediT authorship contribution statement

C. Navarrete-Molina: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing - original draft. **C.A. Meza-Herrera:** Supervision, Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing - original draft. **M.A. Herrera-Machuca:** Resources, Funding acquisition, Writing - review & editing. **U. Macias-Cruz:** Resources, Funding acquisition, Writing - review & editing. **F.G. Veliz-Deras:** Resources, Funding acquisition, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.120237.

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