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UNIDAD REGIONAL UNIVERSITARIA DE ZONAS ÁRIDAS

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INSTITUTO DE ESTUDIOS DE POSGRADO

THE RUMINANT PRODUCTION SYSTEMS IN THE COMARCA LAGUNERA, MEXICO: ENVIRONMENTAL IMPACT, PRODUCTIVE TRENDS, AND MITIGATION STRATEGIES

LOS SISTEMAS DE PRODUCCIÓN DE RUMIANTES EN LA COMARCA LAGUNERA, MÉXICO: IMPACTO AMBIENTAL, TENDENCIAS PRODUCTIVAS Y ESTRATEGIAS DE MITIGACIÓN

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(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

La tesis que presenta el doctorando Cayetano Navarrete Molina, Ingeniero Agrónomo en Sistemas Pecuarios de Zonas Áridas, con Maestría en Cambio Global: Recursos Naturales y Sostenibilidad (UCO, España) y Maestría en Ciencias en Recursos Naturales y Medio Ambiente en Zonas Aridas (URUZA-UACh, México), se ha realizado amparada en el marco del convenio de cotutela entre la Universidad de Córdoba, España y la Universidad Autónoma Chapingo - Unidad Regional Universitaria de Zonas Áridas, México. En dicho convenio se manifiesta la voluntad de instaurar y desarrollar una cooperación científica que favorezca la movilidad de los estudiantes de doctorado, así como la necesidad de desarrollar iniciativas de colaboración en materia de investigación. El objetivo central de la tesis ha sido cuantificar el impacto ambiental y económico de la huella de carbono e hídrica como indicadores de sostenibilidad de los sistemas de producción de rumiantes en la Comarca Lagunera, México. El doctorando desarrolló una investigación sobresaliente, con eficiencia y profesionalidad, completando su formación con cursos de especialización tanto en la Universidad de Cordoba, España y la Universidad Autonoma Chapingo, México.

La presente tesis ha sido realizada bajo nuestra Dirección y destacamos el excelente trabajo de investigación desarrollado por el doctorando, así como las aportaciones y avances que esto supone al conocimiento científico y el estado del arte en el área de impacto ambiental y producción animal. Lo anterior se concretó con base en las conclusiones obtenidas, las cuales encuentran sustento en los resultados de la investigación.

Derivado de la actividad de investigación durante el periodo del desarrollo de la presente tesis, y como indicios principales de calidad de la misma, a continuación se citan las principales publicaciones derivadas de dicha investigación:

1. Navarrete-Molina, C., Meza-Herrera, C. A., Ramirez-Flores, J. J., Herrera-Machuca, M. A., Lopez-Villalobos, N., Lopez-Santiago, M. A., & Veliz-Deras, F. G. (2019). Economic evaluation of the environmental impact of a dairy cattle intensive production cluster under arid lands conditions. *Animal, 13*(10), 2379-2387.

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2. Navarrete-Molina, C., Meza-Herrera, C. A., Herrera-Machuca, M. A., Lopez-Villalobos, N., Lopez-Santos, A., & Veliz-Deras, F. G. (2019). To beef or not to beef: Unveiling the economic environmental impact generated by the intensive beef cattle industry in an arid region. *Journal of Cleaner Production, 231,* 1027-1035. https://doi.org/10.1016/j.jclepro.2019.05.267. Datos para 2018: Factor de impacto JCR: 6.395. Primer cuartil (Q1) en el área temática: Ciencia medioambiental y categoría: Ciencia medioambiental (misceláneo), Factor de impacto del Scimago Ranking Journal: 1.62.

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Tomando en cuenta el desempeño a lo largo de la preparación académica del doctorando, consideramos él ha aplicado todo el rigor científico en la metodología desarrollada. En el mismo sentido, la investigación traza y justifica conclusiones que, sin duda sarán una línea base en esta temática así como para futuras investigaciones tanto en la Universidad de Córdoba, España como en la Universidad Autónoma Chapingo, México.

Finalmente, consideramos que a lo largo de su formación académica, y en especial durante el periodo concreto correspondiente al doctorado, Navarrete-Molina ha obtenido la suficiente madurez científica. Ello le ha permitido obtener resultados en su investigación con una alta calidad científica a nivel internacional. Lo anterior es avalado con los trabajos publicados y/o aceptados en el desarrollo de la presente tesis.

Por todo ello, se autoriza la presentación y la defensa oral de la tesis doctoral.

Córdoba, 18 de Enero de 2020.

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International Mention in the Doctorate Degree

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1. Predoctoral stay in other countries:
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3. The text of the thesis has been made entirely in English.

4. Among the members of the committee is a doctor from a higher education center, in the case of Ph.D. Ricardo Mata-Gonzalez, Professor of Department of Animal & Rangeland Sciences, Oregon State University, Corvallis, Oregon, United States of America.

Cordoba, January 18th, 2019.

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List of abbreviations

€	Euro
°C	Degrees Celsius
B€	Billion of Euros
Banxico	Banco de Mexico – Bank of Mexico
BCFS	Beef Cattle Fattening System
BMXP	Billion of Mexican Pesos
BWF	Blue Water Footprint
CC	Climate Change
CEPAL	Comisión Económica para América Latina y el Caribe - Economic Commission for Latin America and the Caribbean
CF	Carbon Footprint
CH_4	Methane
CL	Comarca Lagunera
CO_2	Carbon Dioxide
$CO_{2\text{-eq}}$	Equivalent units of Carbon Dioxide
CONACYT	Consejo Nacional de Ciencia y Tecnologia - National Council of Science and Technology
CONAGUA	Comisión Nacional del Agua - National Water Comission
DBSI	Department for Business Innovation & Skills
DOF	Diario Oficial de la Federación - Official Journal of the Federation
DRD	District of Rural Development
EC	Economic Cost
ECCF	Economic Cost of the Carbon Footprint
EcF	Economic Footprint
EcI	Economic Impact

ECM	Energy-Corrected Milk
ECWF	Economic Cost of the Water Footprint
EF	Ecological Footprint
EGHG	Emissions of greenhouse gases
EI	Environmental Impact
EV	Economic Value
EVBP	Economic Value of Beef Production
FAO	Food and Agriculture Organization of the United
FCM	Fat Corrected Milk
FPCM	Fat–Protein–Corrected Milk
GCC	Global climate change
GDP	Gross Domestic Product
Gg	Gigagram
GHG	Greenhouse Gases
GPV	Gross Production Value
GRA & SAI	Global Research Alliance on Agricultural Greenhouse Gases & The Sustainable Agriculture Initiative
Gt	Gigaton
GWP	Global Warming Potentials
H_2O	Water
H_2O_{-eq}	Water equivalents
HFC	Hydrofluorocarbons
HSCW	Hot Standard Carcass Weight
INECC	Instituto Nacional de Ecología y Cambio Climático - National Institute of Ecology and Climate Change
INEGI	Instituto Nacional de Estadística, Geografía e Informatica - National Institute of Statistics, Geography and Informatics
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
K	Thousands

K€	Thousands of Euros
kg	Kilogram
Kl	Thousands of liters
KMXP	Thousands of Mexican Pesos
Kt	Thousands of tons
l	Liter
LCA	Life Cycle Assessment
LW	Live Weight
LWP	Livestock Water Productivity
M	Millions
M€	Millions of euros
m^3	Cubic meter
MEA	Millennium Ecosystem Assessment
Ml	Millions of liters
MMm^3	Millions of cubic meters
MMXP	Millions Mexican Pesos
Mt	Millions of tons
MXP	Mexican Pesos
N_2O	Nitrous Oxide
O_3	Ozone
OECD	Organisation for Economic Co-operation and Development
PFC	Perfluorocarbons
PPM	Parts Per Million
SAGARPA	Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación - Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food
SAS	Statistical Analysis System
SCN	United Nations System Standing Committee on Nutrition
SCOPE	Scientific Comittee on Problems of the Environment
SEMARNAT	Secretaría de Medio Ambiente y Recursos Naturales - Ministry of Environment and Natural Resources

SF	Social Footprint
SF_6	Sulfur hexafluoride
SI	Social Impact
SIAP	Servicio de Información Agroalimentaria y Pesquera - Agrifood and Fishery Information System
t	Ton
TMSS	Total Milk Solids in Skim milk
TMSW	Total Milk Solids in Whole milk
UN	United Nations
USD	United States Dollars
WF	Water Footprint
WSI	Water Stress Index
WTA	Water Total Available
WWAP	World Water Assessment Programme

Dedicated to

To God:

For being the founder of my path and directing me on the right pathway.

To my daughters:

For being my strength, support and inspiration for each of the things I do.

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For all her love, affection, patience, support and understanding.

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As a reference and considering the scientific dissemination of the aforementioned research papers, it consolidates an RG score from **11.11 to February 2020,** being this, an indicator of the Social Networking Site of scientific reference or ResearchGate platform.

The ruminant production systems in the Comarca Lagunera, Mexico: Environmental impact, productive trends, and mitigation strategies

Los sistemas de producción de rumiantes en la Comarca Lagunera, México: Impacto ambiental, tendencias productivas y estrategias de mitigación

Navarrete-Molina, Cayetano[1], Meza-Herrera César A.[2], Herrera-Machuca, Miguel A.[2]

RESUMEN

La población mundial se ha incrementado a casi 8,000 millones de personas, lo cual sugiere aumentos en la demanda y consumo de productos de origen animal, provocando una mayor presión en el uso de los recursos hídricos y aumentos en la emisión de gases de efecto invernadero (EGEI). El objetivo de la presente investigación fue cuantificar el impacto ambiental (IA) y económico (IE) de las huellas de carbono (HC) e hídrica (HH) como indicadores de sostenibilidad de los sistemas de producción de rumiantes (SPR), durante el periodo 1994-2018. La investigación se realizó en el norte de México, en la Comarca Lagunera (CL; 102º 22' & 104º 47' LO, 24º 22' & 26º 23' LN), siendo esta una región árida, con promedios anuales de precipitación menores a 240 mm, aunque muy importante en producción ganadera en el país. La cuantificación del IA de la HH consideró sólo el cálculo del uso de agua azul (HHA). La HC consideró la metodología del IPCC para las subcategorías ganadería y agricultura. El cálculo del valor económico (VE) de HHA consideró el precio promedio internacional del agua y para la HC consideró el precio promedio de los bonos de carbono. El valor económico de los SPR (Bovino de leche, Bovino de Carne y Caprinos) se determinó con base su valor bruto de la producción (VBP). En 2018, la CL registró un inventario de rumiantes de 1,163,046, de los cuales 350,280 se encontraban en producción generando 2,503.50 millones de litros de leche, con un sacrificio de 676,769 cabezas, con un rendimiento de 83,716 toneladas de carne. Esta producción de leche y carne representó 99,538 toneladas de proteína. Al contrastar el promedio anual del VBP-SPR de 651.41 M€ (11,754.89 MMXP) respecto al VE-HHA de 11,602.82 M€ (209,377.59 MMXP) sumado al VE-HC de 330.71 M€ (5,967.79 MMXP), se observa un significativo IA e IE de los SPR, en especial los generados por los sistemas bovinos leche y carne, con un impacto negligible del sistema caprino. El VBP-SPR representó el 5.46% del VE de la HH más la HC [11,933.53 M€ (215,345.38 MMXP)]. Por lo anterior, es urgente delinear y adoptar estrategias de mitigación en el manejo de los SPR con respecto al uso del agua y EGEI. Dichas estrategias deben considerar las características de cada especie rumiante y serán fundamentales para lograr la sostenibilidad no sólo de los SPR, sino también la viabilidad ecológica, económica y social de la propia CL.

Palabras clave: gases de efecto invernadero; huella hídrica; impacto ambiental y económico.

ABSTRACT

The world population has increased to almost 8,000 million people, which suggests increases in the demand and consumption of products of animal origin, causing greater pressure on the use of water resources and increases in the emission of greenhouse gases (EGHG). The objective of this research was to quantify the environmental impact (EI) and economic impact (EcI) of the carbon footprint (CP) and water footprint (WP) as indicators of sustainability of ruminant production systems (RPS) during the period 1994-2018. The investigation was carried out in northern Mexico, in the Comarca Lagunera (CL, 102º 22 '& 104º 47' W, 24º 22 '& 26º 23' N), an arid region with annual averages of rainfall less than 240 mm, although it is very important in livestock production in the country. The quantification of the EI in WP only considered the calculation of the use of blue water (BWF). The CP considered the IPCC methodology for the livestock and agriculture subcategories. The calculation of the economic value (EV) of BWF considered the average international water price, while the CP considered an international average price of the carbon credits. The economic value of RPS (Dairy cattle, Beef cattle and Goats) was determined based on its gross production value (GPV). In 2018, the CL recorded a ruminant inventory of 1,163,046 heads, with 350,280 heads in production, generating 2,503.50 million liters of milk with a total of 676,769 slaughtered heads, and a yield of 83,716 tons of meat. This production of milk and meat represented 99,538 tons of protein. When comparing the annual average of the GPV-RPS of 651.41 M€ (11,754.89 MMXP) regarding the EV-BWF of 11,602.82 M€ (209,377.59 MMXP) added to the EV-CF of 330.71 M€(5,967.79 MMXP) a significant EI and EcI is observed from RPS, especially those generated by the dairy and beef cattle systems, with a negligible impact of the goat system. The GPV-RPS represented 5.46% of the EV of the WF plus the CF [11,933.53 M€ (215.345.38 MMXP)]. Therefore, it is fundamental to delineate and adopt mitigation strategies in the management of RPS with respect to water use and EGHG. These strategies must considerer the characteristics of each species of ruminant and they will be essential to achieve the sustainability not only of the RPS, but also the ecological, economic and social viability of the CL itself.

Keywords*:* greenhouse gases; water footprint; environmental and economic impact

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THE RUMINANT PRODUCTION SYSTEMS IN THE COMARCA LAGUNERA, MEXICO: ENVIRONMENTAL IMPACT, PRODUCTIVE TRENDS, AND MITIGATION STRATEGIES

I. INTRODUCTION

Doctorado en ciencias en recursos naturales y medio ambiente en zonas áridas

Doctorado en recursos naturales y gestión sostenible

The increase in living standards has generated a greater demand for food of animal origin, which has led to devoting more and more areas to the production of food, causing a constant change in land use (Cardoso, 2012). These increases are due not only to the improvement in the human quality of life, but also to the significant increase in human population which has quadrupled during the last century up to 7,530 million in 2017, expecting an increase to 9,551 million in 2050. Such scenario will generate an increased intensity use of global resources to a point where land cannot regenerate them (UN, 2014; Wackernagel et al., 2002; World Bank, 2019).

This consumption of natural resources by food production is driven by the strong demand of an emerging global middle class, with richer and more diversified diets. This demand for food, especially those of animal origin, will be significant, since it is estimated that the demand for meat and milk in 2050 will grow 73% and 58%, respectively, with respect to the observed levels in 2010 (FAO, 2011). The above, has caused food production models to be more uncertain, so their analysis should consider trends in demographic dynamics, consumption patterns, the threat of climate change and the irreversible degradation of ecosystem services (Thiaw et al., 2011).

This uncertainty in the models and systems of food production must be analyzed with a comprehensive vision of the environmental impact (EI) that it generates. This analysis must be based on the quantification of the ecological footprint (EF), which must be evaluated considering more than one indicator, considering instead a family of indicators (Ridoutt & Pfister, 2013). The main EF indicators are: carbon footprint (CF), water footprint (WF), economic footprint (EcF) and social footprint (SF).

Of the group of ecological footprints mentioned, the first two (CF and WF), are those that have been most addressed in various scientific investigations. In this context, the CF, could be the most important since 2014 was the warmest year (since 1880) and temperatures are now 0.8 °C higher than pre-industrial levels (Kossoy et al., 2015). Several research groups agree that this fact is related to the increase in atmospheric concentrations of greenhouse gases (GHG), which continue to increase, particularly during the past 250 years, coinciding with the start of the industrial revolution and the increase in the use of fossil fuels (Chukwuocha et al., 2011).

Currently, there are evidence of such increases, which is why it is considered one of the main global problems of our time. These evidences suggest that human or anthropogenic activities have been responsible. Almost all the activities we carry out (transport, food, agricultural activities, etc.) and goods that we own and use (consumer goods, vehicles, appliances, etc.) involve consuming energy, which means contributing to the emissions emanated from the atmosphere (Pingali & McCullough, 2010).

The measurement of these emissions of GHG (EGHG) gives us valuable information about the degree of the CF impact, since it identifies the sources of emissions of a product or activity. This quantification makes possible to define better objectives, more effective emission reduction policies and better targeted cost savings initiatives, which tend to develop a better knowledge of the critical points for the reduction of emissions, which may or may not be the direct responsibility of the activity analyzed (Hermansen & Kristensen, 2011).

There are different methodologies for the calculation of EGHG, yet those proposed by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007), are quite important when calculating the anthropogenic GHG emissions. Using this methodology, the National Institute of Ecology and Climate Change (INECC for abbreviation in spanish), estimated in 2010 that in Mexico, the agriculture sector contributed 12.3% of the total GHG, and the livestock subsector issued 6.07%, equivalent to 50% of the sector; the cattle subsector contributed 91.69% of such emissions (SEMARNAT, 2013).

In this regard, in relation to ruminants, monogastric animals are emitters of GHG of little importance. For pigs, the IPCC (2006) assumes enteric emission factors of CH_4 that correspond to approximately 1.2% and 2.8% of the emission factors of cattle. Recent work has calculated that EGHG from pigs is equivalent to approximately 9.5% of the total emissions produced by livestock (Gerber et al., 2013), while the contribution of poultry generates 9.7%.

Consequently, ruminants and their gaseous emissions, whether direct (through enteric fermentation or manure) or indirect (by activities developed during forage production and the conversion of forests into pastures or croplands), must be a focus of attention in mitigation measures and policies. Steinfeld et al. (2009) have calculated, based on the life cycle analysis (LCA), that the livestock sector emits approximately 7.1 Gt of $CO_{2\text{-eq}}$ yr^{-1}, equivalent to almost 18% of the total the anthropogenic EGHG. These emissions can be calculated by inventory, by head or by unit of product. One of the most recommended is the calculation per unit of product. Figure 1 shows the EGHG of some products of animal origin per unit of product.

Of the groups of ecological footprints mentioned, the second group to be addressed is the WF, because the anticipated increase in the production and consumption of products of animal origin could put more pressure on the freshwater resources of the world. Like CF, the size and characteristics of WF vary according to animal types and production systems (Mekonnen & Hoekstra, 2010) (Figure 2).

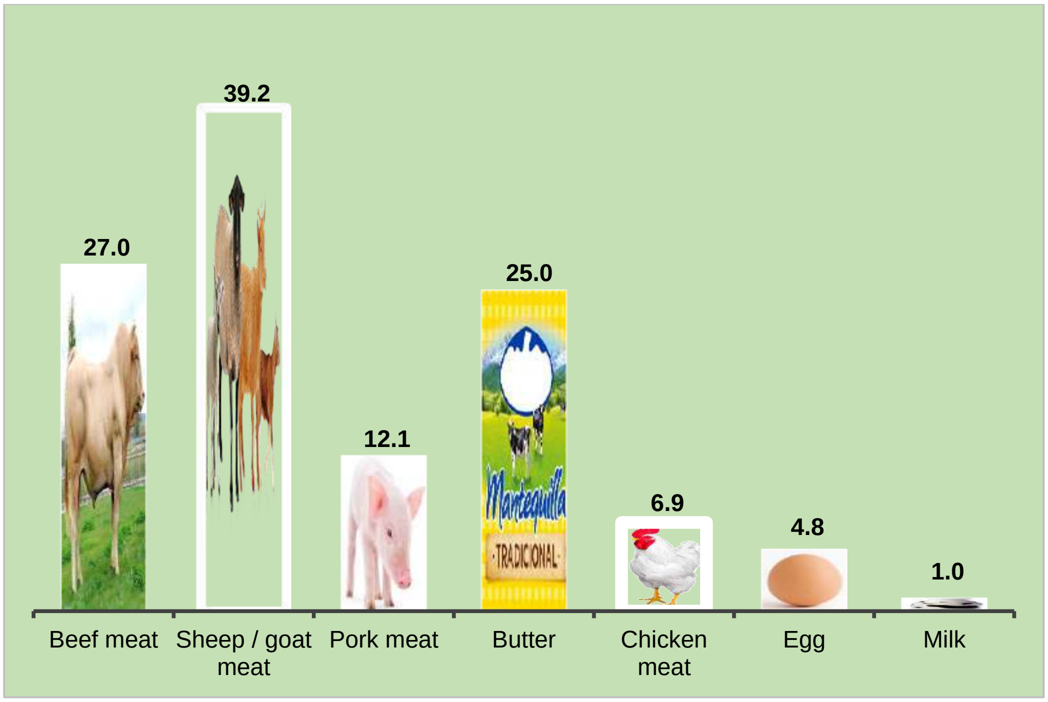

Figure 1. Carbon footprint of some products of animal origin (kg $CO_{2\text{-eq}}$ kg^{-1}) (Source: Hamerschlag & Venkat, 2011)

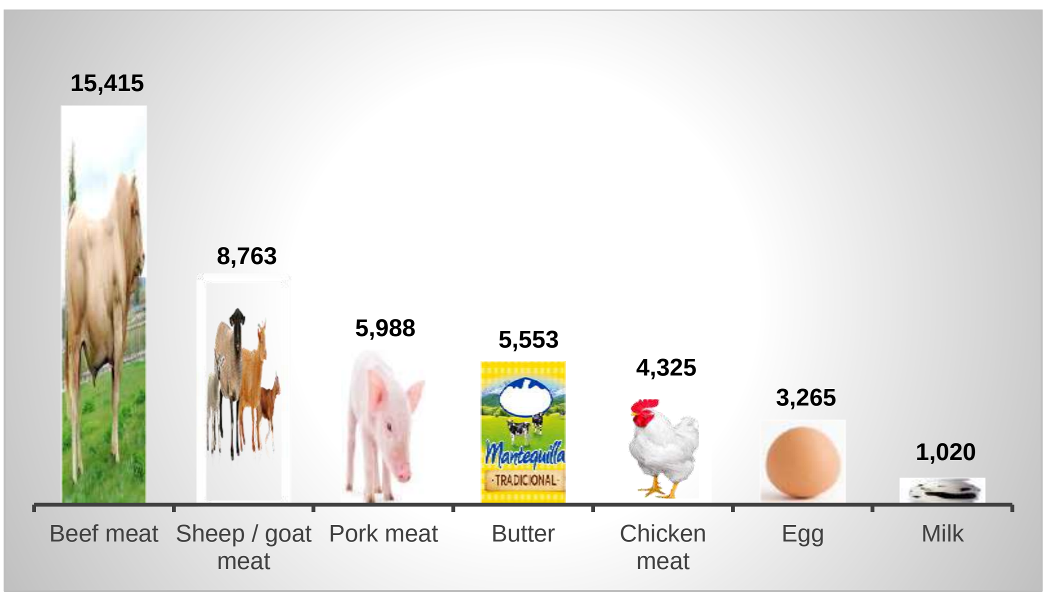

Figure 2. Water footprint of some products of animal origin (l kg^{-1}) (Source: Mekonnen & Hoekstra, 2011)

The WF of a nation, company or product is an empirical indicator of how much water is consumed, when and where, measured over the entire supply chain. It is a multidimensional indicator, showing volumes, but also specifying the type of water used - rainwater, surface water or contaminated water - and the place and time of water use (AgroDer, 2012). The calculation of the WF is especially important in products that have their origin in endorheic basins as the study area considered in this thesis. This area of study, within the national context, is one of the main agricultural basins of Mexico, but it is more important because it is located in an arid zone. This region, the Comarca Lagunera (CL), has a large concentration of farm animals, occupying the first place at the national level in both dairy cattle and poultry.

Therefore, this research is of importance since there is currently no relevant, accurate and long-term information on the potential of EGHG in the region. Likewise, there is no information regarding the potential implementation of strategies to mitigate the production of these gases, which is why this research is fundamental for the adoption of such measures in the region. Moreover, we would like to find the best, the most efficient and the most applicable mitigation strategies according to the potential aptitudes observed in the study area. As previously discussed, ruminants are, within the cattle subsector, those that have the highest CF and WF. In the CL the number of heads of this type of cattle amounted to 1.17 million in 2018, generating a production of 2,503.50 million liters of milk and 1 million tons of meat, with a market value of 20,794 million of Mexican pesos (MMXP), equivalent to 925.65 million euros (M€) per year (SIAP, 2019).

In the CL the dairy cattle and feedlot cattle production systems have infrastructure that is characterized by well-designed management pens in addition to that in this type of mechanized farms the labor used is minimal, acquiring the product a high added value for the level of quality obtained in these processes. In contrast, both small ruminants and beef cattle extensive production systems under range conditions have generally poor facilities.

Considering the above, it is essential to quantify the CF and WF of the ruminant production systems in CL, Mexico. Later, when weighing them for economic value, would be possible to compare such value with respect with the economic value of production generated in the region. The above will allow to quantify the

EI and economic (EcI) of such productive activities. Our hypothesis proposes that the long-term environmental impact of ruminant production systems in the CL is greater than the economic benefit generated by these production systems. This will allow generating information that can assist as a reference to better channel financial resources, take appropriate measures and specific mitigation actions that contribute to focus efforts that ensure the reduction of the ecological footprint of livestock in arid and semi-arid areas. Besides, such analyses would facilitate decision making, in order to contribute to the fulfillment of the goals set forth in the reduction of EGHG and the efficient use of water in Mexico.

II. OBJETIVES

2.1. General objetive

- To quantify the environmental and economic impact of carbon and water footprint as indicators of sustainability of the ruminant production systems in the Comarca Lagunera, Mexico.

2.2. Specific objetives

- To quantify the carbon and water footprint of the ruminant production systems in the Comarca Lagunera, Mexico.

- To determine the environmental impact of the main ruminant production systems in the Comarca Lagunera, Mexico.

- To develop a comparative analysis between the direct economic benefits of the ruminant production systems and the economic costs of the carbon and water footprint of this production in the Comarca Lagunera, Mexico.

- To measure and transform the economic value of the environmental impact, so that, it serves as a basis for the generation of mitigation policies and actions.

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III. HYPOTHESIS

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Ho. The environmental impact, evaluated as the economic cost of the carbon and water footprint, generated by the milk-meat bovine production systems is greater than the economic value, while such environmental insult will be decreased in the milk-meat goat production system when compared with its economic value in the Comarca Lagunera, Mexico.

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IV. THEORETICAL - CONCEPTUAL FRAMEWORK

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4.1. Global climate change (GCC)

While the world population is close to 8 billion, the UN has estimated that by 2050 that figure will increase to 9.6 billion. Parallel to this growth, both income and urbanization will also increase, a situation that will pose unprecedented challenges to agriculture, especially food production. However, the natural resources needed for the production and provision of services are limited and without capacity for expansion or growth (FAO, 2011).

The foregoing has been a matter of great concern and analysis among the scientific community and the consequences of the overexploitation of natural resources have been studied. Therefore, in view of the changes observed in terrestrial dynamics, in 1992, the United Nations Conference on Environment and Development, Rio de Janeiro, was the scenario for the Framework Convention on Climate Change to approve the definition of climate change (CC). On this respect, "Climate change attributed directly or indirectly to human activities that alter the composition of the global atmosphere, and which adds to the natural variability of the climate observed during comparable periods of time". Therefore, the concept of CC is associated with anthropogenic consequences and adds to the natural variability of climate (Del Valle Melendo, 2014).

One of the consequences of CC is global warming, caused by increased concentrations of greenhouse gases (GHG), which have reached levels that had not been present in the earth in at least 800,000 years (Moore, 2017). This has led to an increase in the average temperature of the earth from 0.85 °C (0.65 to 1.06) during the period 1880-2012. For the case of the northern hemisphere, the period between 1983-2012 was probably the hottest of the last 1,400 years (IPCC, 2014a).

This scenario has meant that the number of cold days and nights decreased and the number of warm days and nights increased. In this regard, as of 1950, the number of severe precipitations has increased in more regions than those in which it has decreased (IPCC, 2013). Likewise, Lopez Feldman and Hernández Cortés

(2016), mention that the effects of climate change will be heterogeneous, both between countries and within them and can also be extremely large.

Although the conclusions of the CC studies are clear and the impact increasingly visible, measures to adapt or mitigate are not enough. The Paris climate agreement aims at holding global warming to well below 2 °C and to “pursue efforts” to limit it to 1.5 °C. To accomplish this, countries have submitted Intended Nationally Determined Contributions (INDCs) outlining their post-2020 climate action. However, the INDCs collectively lower emissions of greenhouse gas (EGHG) compared to where current policies stand, but still imply a median warming of 2.6 – 3.1 °C by 2100. More can be achieved, because the agreement stipulates that targets for reducing EGHG are strengthened over time, both in ambition and scope (Rogelj et al., 2016). Adaptation and mitigation measures may include social, cultural, administrative and process changes, behavioral modifications, construction of new infrastructure or use of technologies, structural transformations and modifications of products, inputs or services, public policy transformations for the purpose to cushion or take advantage of new climate conditions (IPCC, 2007, 2014a; OECD, 2012; World Bank, 2010).

Therefore, it is essential to carry out impact studies at the local level, since most of the studies involve national scales, complicating the analysis of local components such as topography, soil cover, intensity of land use, industrialization, population growth and urban development (López Santos et al., 2015). Indeed, the IPCC (2014a) mentioned that the effects of CC will reduce economic growth, complicate efforts to reduce poverty and affect food security. Certainly, the CC has a great diversity of negative consequences on economic activities, the welfare of the population and ecosystems (IPCC, 2013, 2014b). There is important evidence on this impact in agricultural activities, water, biodiversity, sea level rise, forests, tourism, health and cities (IPCC, 2014b; ECLAC, 2014).

This impact on practically all the global activities has promoted to both the scientific community and governments to care about the well-being of future generations, and motivate them to undertake urgent mitigation measures; quantification of the ecological footprint has shown that there is a direct relationship among habits, lifestyles and environmental problems (Madrid de Mejía, 2015).

4.2. Ecological footprint

Ecological footprint (EF) can be defined as the impact exerted by a certain human community - country, region or city - on its environment; the resources and waste generated both are considered for the maintenance of production and consumption model community, which is why this is an environmental indicator of inclusiveness (Rees & Wackernagel, 2000). The EF of a population is the biologically productive area necessary to generate the resources it consumes and absorb the waste it generates (Martínez Castillo, 2007). When considering the analysis of consumption and waste patterns, and expressing them in biologically productive areas, the EF shows the calculation of specific resources and adds the effects due to lack of resources. Therefore, it is a tool that helps analyze the demand of nature by humanity (Wackernagel & Rees, 1999). It is, in the words of Wackernagel, an ecological accounting system (Amen et al., 2011), which shows the consequences of actions and activities on the planet.

It should be noted that the EF does not provide information that could be useful to understand all the dimensions of environmental complexity, such as economic and social. Nor does it provide data on the magnitude of the depredation of natural resources and the environment by privileged economic sectors, whose levels of consumption and generation of waste is extraordinary. This is because the calculation does not consider what they consume and dispose of indirectly through their companies and businesses, or in their countries of origin, much less in the nations where their economic interests are rooted (SEMARNAT, 2012). However, the EF is a starting point to analyze global relations, as well as to reflect on the type of world to inherit from future generations. For this reason, the research processes on EF can be a reference for the scientific community and, in general, the population, to reflect on current lifestyles and the values on which they rest (SEMARNAT, 2012).

Therefore, the analysis of EF should consider all scientific rigor, as the evaluation of a system, and especially agricultural production systems is not simple, often presenting the interrelationships between sources of impact. For example, actions to reduce EGHG could require greater use of water, and interventions to achieve water efficiency and water quality objectives could require greater use of energy and, consequently, increase EGHG (Ridout et al., 2014).

Due to these interrelations, it is necessary to evaluate the environmental impact (EI) using more than one indicator of EF, emerging in recent years several studies that suggest a more comprehensive assessment of the impacts, such as those reported by Bosire et al., 2016; Bragaglio et al., 2018; Cardoso et al., 2016; Gerber et al., 2015; Huerta et al., 2016; Mogensen et al., 2014; Mogensen et al., 2016; Ogino et al., 2016; Ridoutt et al., 2014, among others. With this approach, the concept of a comprehensive family of trace foot´s indicators were coined (Ridoutt & Pfister, 2013). Then, it is essential to quantify the greatest number of environmental indicators, especially those related to the production of food for human consumption. Within these EF indicators, the attention paid during the last few years, the carbon footprint and the water footprint stand out, which, in order to better understand their dimensions, must be complemented with the measurement of the economic footprint (EcF) and the Social footprint (SF). Because CF and WF are widely addressed, the EF and SF are defined below:

Economic footprint: Its refers to EcI of an activity, service or product. For example, in many places tourism is seen as a great engine of the economy since it drives other activities. But often it also generates places of very precarious works, often seasonal, and the benefits are distributed in a very asymmetric way. In this case, although this activity has a high EF, it is necessary to complement it with the calculation of the CF, WF and mainly the SF, in order to be able to more correctly measure the impact of this activity.

Social footprint: The SF quantifies the impact of an activity, service or product in human, labor and social matters. In the determination of the SF, factors such as the jobs created, the distribution of resources, the excesses that may occur in the productive sector are used. For example, some companies, through the decisions that are made, create jobs, can put at risk human rights, fundamental principles and rights at work, can have an impact on culture, etc. Therefore, labor practices may or may not correctly manage working conditions and social protection, may be sensitized to a greater or lesser extent with health and safety in the workplace and may make a clear and convinced commitment to development and training of people. The previous causes a footprint in society and that is precisely what we try to measure with the HS (Ruano, 2016).

4.3. Carbon footprint

The concept of carbon footprint (CF) originated from the definition proposed by Wackernagel and Rees, (1999). The CF refers to the area of land required to assimilate all the CO_2 produced by humanity during its useful life. However, as global warming became important in the global agendas, the global conception of CF became important and became common independently of EcF, however, in a modified form (East, 2008). The term CF has been in use for several decades but is more related as an indicator of the impact of the life cycle expressed in global warming potential (Finkbeiner, 2009). Therefore, in recent years, it is common for the CF concept to be seen as a hybrid, which derives its name from the EcF concepts, and is conceptually an indicator of global warming potential (Pandey et al., 2011). Despite the importance of knowing the capacity of the planet to sustain life, there are few studies that report CF in terms of global hectares (Browne et al., 2009).

Other terms used as synonymous with CF include: carbon incorporated, carbon content, integrated carbon, virtual carbon, GHG footprint and climate footprint (Courchene & Allan, 2008; Edgar & Peters, 2009; Peters, 2010; Wiedmann & Minx, 2007). For Wiedmann and Minx (2007) the CF is the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or that accumulates during the life stages of a product. However, subsequent research and the use of more precise methods for the calculation of CF, suggested including other GHGs, in addition to only CO_2 (Browne et al., 2009; Edgar & Peters, 2009; Eshel & Martin, 2006; Ferris et al., 2007; Garg & Dornfeld, 2008; Good Company, 2008; Johnson, 2008, Mays et al., 2009).

Considering that the CF is associated with money transactions in the form of taxes, carbon credits, or certifications, the precise calculations of the CF are essential to facilitate comparisons. Despite the dissents prevailing in its calculation, the amount of CO_2 equivalents ($CO_{2\text{-eq}}$) based on the global warming potential of 100 years, has been accepted as a reporting unit of the CF (DBSI, 2011). Hammond (2007) mentions that "footprints are spatial indicators". Therefore, the term CF should be called "carbon weight" or "carbon mass" (Jarvis, 2007). But the calculation of the amount of $CO_{2\text{-eq}}$ has been proposed as the unit measure of the CF because its calculation is adequate and widely accepted (Lynas, 2007).

Thus, CF can be defined as "the amount of GHG expressed in terms of $CO_{2\text{-eq}}$, emitted to the atmosphere by an individual, organization, process, product or event within a specified limit". Also, the type of GHG and the limits are defined according to the methodology adopted and the objective of the calculation of the CF (Pandey et al., 2011).

4.3.1. Carbon footprint from the livestock industry

Greenhouse gases (GHG) are the gaseous components of the atmosphere, whether natural or anthropogenic, that absorb and emit radiation at certain wavelengths of the infrared radiation spectrum emitted by the Earth's surface, atmosphere and clouds. The main GHG are water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3); sulfur hexafluoride (SF_6); hydrofluorocarbons (HFC) and perfluorocarbons (PFC) were created entirely by humans (Benavides Ballesteros & León Aristizabal, 2007). The contribution to the greenhouse effect is different and depends on at least three factors:

1) the concentration or abundance, referred to the amount of gas present in the air, generally measured in parts per million (ppm),

2) the permanence or time that said gas persists in the atmosphere for different time scales, there are ranges ranging from tens to hundreds of years, and

3) its warming potential; for each gas a heating potential (GWP) has been calculated to reflect how much energy they absorb; the more they absorb energy, the more efficient they are to make the planet warm (Table 1) (EPA, 2017).

Table 1. Global warming potentials (GWP) (100-year time horizon)

Gas	GWP
Carbon Dioxide (CO_2)	1
Methane (CH_4)[a]	25
Nitrous Oxide (N_2O)	298
Hexafluoropropane-23 (HFC-23)	14,800
Hexafluoropropane-32 (HFC-32)	675
Hexafluoropropane-125 (HFC-125)	3,500
Hexafluoropropane-134a (HFC-134a)	1,430
Hexafluoropropane-143a (HFC-143a)	4,470
Hexafluoropropane-152a (HFC-152a)	124
Hexafluoropropane-227ea (HFC-227ea)	3,220
Hexafluoropropane-236fa (HFC-236fa)	9,810
Hexafluoropropane-431mee (HFC-431mee)	1,640
Tetrafluoromethane (CF_4)	7,390
Hexafluoroethane (C_2F_6)	12,200
Perfluorobutane (C_4F_{10})	8,860
Perfluorohexane or Tetradecafluorohexane (C_6F_{14})	9,300
Sulfur Hexafluoride (SF_6)	22,800
Nitrogen trifluoride (NF_3)	17,200

[a] The CH_4 GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to production of CO_2 is not included. Source: IPCC (2006)

Several investigations have reported that the concentration of GHG in the atmosphere has increased markedly during the last 250 years, since the beginning of the industrial revolution and the increase in the use of fossil fuels (Chukwuocha et al., 2011). Of these gases, methane is the second most abundant gas in the atmosphere after CO_2 and in the last 25 years, its emissions have doubled (Denman et al., 2007; IPCC, 2007). For its part, nitrogen dioxide has a residence time in the atmosphere of 125 years and its emissions have increased by 19% since the industrial revolution (Flückiger et al., 2004), contributing to the imbalance observed in the nitrogen cycle to the great increase in the use of fertilizers in crops (Delgado & Follet, 2010).

If the evident global warming potential of these GHG is considered, small changes in the productive sectors can contribute significantly to mitigate global warming. It is also necessary to consider the environmental costs of productive activities, including agricultural production and especially animal production, which have been subject to extensive analysis and discussion (Meza-Herrera et al., 2015, 2016).

Several studies have been published, with different results on the responsibility of agriculture on the anthropogenic emissions of GHG (Cardoso, 2012). Where we find ranges that range from 30 to 35% of emissions (Foley et al., 2011), 22.5% (Rota & Sidahmed, 2010), and close to 20% (IPCC, 2007). More specifically, it has been reported that agricultural activities emit 25% anthropogony's CO_2 flows, 60% of total CH_4 emissions, and 65-80% of total N_2O flows (Denman et al., 2007; Robertson, 2004). Figure 3 concentrates the main sources and sinks of these EGHG in ecosystem processes including the livestock sector.

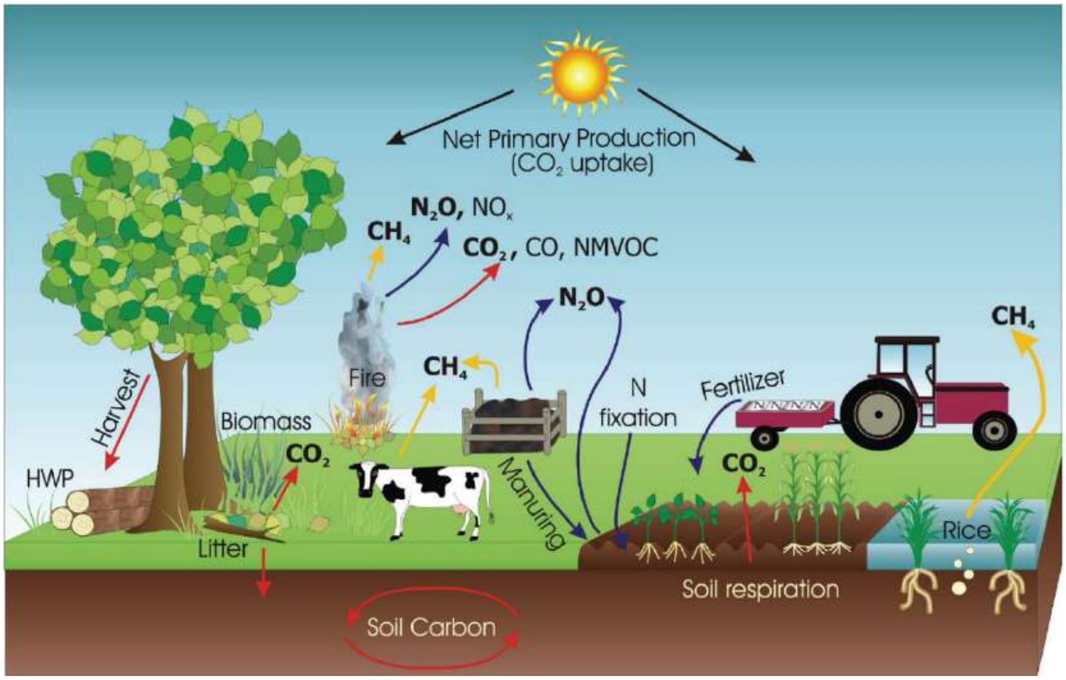


Figure 3. The main greenhouse gas emission sources/removals and processes in managed ecosystems

(Source: IPCC, 2006)

Globally, the livestock sector is responsible for 18% of the total EGHG, mainly due to deforestation to establish grasslands, cultivation of grains for animal feed, fermentation of the rumen and livestock waste (Steinfeld et al., 2006). Considering only the agricultural sector, livestock represents 80% of total emissions (Cardoso, 2012); this sector occupies 30% of the tundra-free land surface (Steinfeld et al., 2006). However, livestock is of central importance since nearly one billion people in poverty depend on livestock for at least part of their survival in the absence of viable economic alternatives, mainly in developing countries (SCOPE, 2010).

Additionally, livestock systems have positive and negative effects on natural resources, public health, social equity and economic growth (World Bank, 2009). Livestock is one of the fastest growing subsectors of agriculture in developing countries (Thornton, 2010). This growth is induced by the situations already mentioned with respect to the growing demand for products of animal origin, and this in turn is induced by the increase in human world population, urbanization and economic growth in developing countries (Delgado, 2005).

Cattle’s EI must be evaluated in terms of direct and indirect GHG emissions. Direct emissions of CH_4 include enteric fermentation and manure excretion, while urine is responsible for N_2O emissions (Jungbluth et al., 2001). Emissions of CO_2 by means of respiration are considered to be the equilibrium of the plant species that integrate atmospheric CO_2 into organic compounds and that are used in animal feed (Steinfeld et al., 2006). Indirect emissions are no directly generated by livestock, but depend on emissions from manure, the cultivation of grains for animal feed and the use of fertilizers, deforestation linked to livestock raising, desertification and transport (Mosier et al., 1998).

Some aspects that determine the emission of CH_4 by livestock are: a) level of food consumption, b) digestibility of the same, c) feeding method, and d) supply of unsaturated fatty acids in the diet (Enishi, 2007). This emission is part of the natural process of digestion and the gas is produced in the livestock rumen due to methanogenesis carried out in the reticulum-rumen and large intestine of cattle (Alemu et al., 2011). Chukwuocha et al., (2011) reported high concentrations of methane gas in livestock farms, compared to dry air at sea level (2.80 ± 0.46 ppm vs. 2.0 ppm, respectively).

For the estimation of the EGHG, this research is related to the factors and emission indices for the IPCC (Hongmin et al., 2006), including the inventory of livestock, the level of production, and the type, consumption and digestibility of the maintenance allowance. The IPCC establishes the conversion rates of these emissions in equivalents of Global Warming Potential of carbon dioxide. These equivalences correspond to: a unit of CH_4 = 25 units of CO_2 and one unit of N_2O = 296 units of CO_2 (IPCC, 2006). Likewise, we have established an international price for carbon emissions, which allows us to calculate the impact of emissions from an economic perspective, the price of 15.75 € t^{-1} of $CO_{2\text{-eq}}$, (309.48 MXP) (Environmental Finance, 2011; Thompson Reuters, 2011).

4.3.2. Carbon footprint of ruminant production

The future of food security and energy supply are of great importance. Livestock, mainly ruminants, occupy 80% of anthropogenic land use (Stehfest, 2009) and consume about 35% of agricultural crops (Foley et al., 2011), so they are in direct competition with production of crops for human consumption, and with alternative land uses with great potential for the production of bioenergetic crops and nature conservation, in addition to being responsible for a significant percentage of the EGHG (Smith et al., 2010).

As of the year 2000, the EGHG directly related to animal production have increased by around 1.1%. Also, since the 1960's the intensity of the EGHG of animal production, that is, the emissions generated on the farm per kilo of meat or per liter of milk produced, has decreased significantly (38% to 76% for different livestock products). However, it is expected that the demand for food of animal origin will continue to increase in the coming decades, requiring a greater reduction in the intensity of expression of these emissions, to reduce the environmental burden generated by products of animal origin and thereby guarantee enough supply of high-quality food. Intensive systems tend to generate higher total GHG emissions, but less intensity when compared to extensive low-performance systems. The gap between producers of high and low emission intensity is indicative of the significant mitigation opportunities that exist (GRA & SAI, 2015).

Of the GHG other than CO_2, methane is the most abundant and has the potential for faster reductions in radioactive forcing, since it has a shorter atmospheric life, approximately 9 years, compared to CO_2. There are several important anthropogenic sources of CH_4 emission: ruminants, fossil fuel industry, landfills, biomass burning and rice production (Figure 4). However, ruminants stand out for four reasons: a) ruminant production is the largest source of anthropogenic emissions of CH_4 and occupies more land area than any other use; b) the relative negligence of this source of GHG suggests that the importance given to it has been underestimated; c) reductions in the number of ruminants and the production of ruminant meat would simultaneously benefit world food security, human health and environmental conservation, and finally d) decreases in ruminant populations throughout the world could be achieved quickly and relatively cheaply throughout the right policies (Ripple et al., 2013).

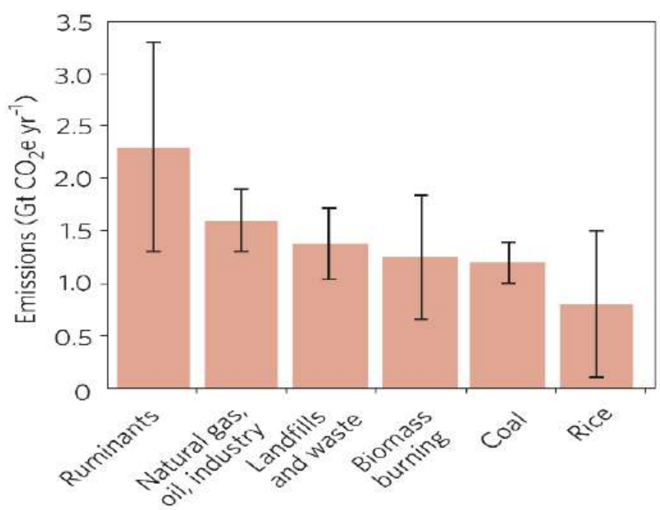


Figure 4. Estimated annual anthropogenic emissions from major sources of methane in recent years. Error bars represent 1 standard deviation.
(Source: Ripple et al., 2013)

Ruminants are herbivores that consume and digest plants through the process of enteric fermentation in a stomach of multiple cameras. In rumen, methane is produced as a byproduct of microbial digestive processes. Monogastric animals, such as pigs and poultry, have a single chamber stomach to digest food, and their methane emissions are negligible compared to ruminants. There are no available estimates of the number of wild ruminants, but it is likely that domestic ruminants greatly exceed the wild population and on average, 25 million domestic ruminants add each year to the planet, with 2 million per month in the last 50 years (Ripple et al., 2013).

4.4. Water footprint (WF)

Water covers approximately three quarters of the earth's surface, however, less than 2.5% is fresh water, accessible to meet human needs (Liu et al., 2015). Both water resources and the range of ecosystem services it provides, promote poverty reduction, stimulate economic growth and enhance environmental protection (WWAP, 2006; Hu et al., 2016). Therefore, water is considered the main axis for sustainable development (Gao et al., 2014; Malghan, 2010).

Although the water flow seems constant, the anthropic intervention has altered its global cycle, mainly modifying its speeds and residence times in the different reservoirs (Haddeland et al., 2014; Hanasaki et al., 2013; Nilsson & Pettersson, 2015). One of the main reasons why water is extracted from reservoirs is food production (Konar et al., 2011). Indeed, agricultural withdrawals represent 70% of total water directly (WWAP, 2006). By 2050, it has been proposed that the demand for water for agriculture be increased by 55%, particularly in developing countries and with emerging economies (Gray & Sadoff, 2007; Wang et al., 2016). In these countries it is a priority to implement a consensual water policy, since the lack of water resource management, the expansion of irrigation agriculture and climate change, have significantly deteriorated this natural resource (Fulton et al., 2014; Hu et al., 2016; Wang et al., 2016). Therefore, it is essential to evaluate the resource through indicators such as the water footprint (De Miguel et al., 2015; Hoekstra et al., 2015; Martínez-Austria, 2013).

The concept of WF was introduced by Hoekstra and Hung in 2002 and represents a useful indicator to estimate the consumption of water invested in the production of goods or associated with the different sectors of economic activity (Hoekstra & Hung, 2005; Allan, 2006). In addition, it has been proposed as a tool that identifies the effects of agricultural production, providing information and possible solutions for decision-making, thus contributing to efficiently manage water resources (Cazcarro et al., 2015; Hoekstra, 2010a, b; Hoekstra, 2013). The WF as an integral indicator of the direct and indirect use of freshwater resources, recognizes the importance of surface and groundwater freshwater, as main components of the environment and society (Chapagain & Orr, 2009; Falkenmark & Rockström, 2004, 2006; Rodríguez-Casado et al., 2009). The WF can be calculated and applied for a process, product, consumer, in a country, basin or geographic area, measured in terms of volume of water used and(or) contaminated (Hoekstra et al., 2016).

Traditionally, WF as an indicator of sustainability, was calculated using the same input values, independent of the extent of the area or its seasonal variability (Hoekstra & Hung, 2005). However, recently, more complexity is included in the models, when estimating the limits on water consumption (Mekonnen et al., 2011; Nana et al., 2014). To calculate the WF values, water balance variables are used in different time resolutions and spatial scales, so they vary in complexity and in the data input (Mekonnen et al., 2015; Liu, 2009; Liu et al., 2012; Siebert & Döll, 2010).

4.4.1. Water footprint from the livestock industry

The livestock sector is attributed a very important part of the WF generated by agriculture, it has been estimated that approximately 30% of the WF of agriculture is directly related to the livestock sector (Mekonnen & Hoekstra, 2012; Schlink et al., 2010). In this way, numerous researchers have reported the volume of water consumed and/or contaminated by various livestock production systems, identifying in all of them that the production of fodder for livestock feed is one of the activities with the greatest impact, highlighting the reports by Chapagain and Hoekstra, 2003; Gerbens-Leenes et al., 2013, 2011; Hoekstra, 2010c; Mekonnen and Hoekstra, 2012; Ridoutt et al., 2012a; Ridoutt et al., 2010; among many others. According to FAO (2019), during 2012, 37% of the cereals produced in the world were destined for livestock feed.

In this sense, the livestock sector is an important user of natural resources such as soil and water, estimating that it uses about 35% of the total farmland and about 20% of the blue water for forage production (Opium et al., 2011). In addition, it has been estimated that this sector uses an equivalent of 11,900 km^3 per year of fresh water, which is approximately 10% of the global annual water flow, estimated at 111,000 km^3 (Deutsch et al., 2010). For the year 2010, the green water allocated for forage production was 2,290 km^3 (Weindl et al., 2017). A comparison between the results of different models confirmed that the use of green water in world crop production is 4 to 5 times higher than the human consumption of blue water. The above demands that of all available options and resources for green-blue water management in food production (Hoff et al., 2010).

Given the demand and competition between users, sectors and uses of available water, it is essential to understand the distribution and demand of fresh water in livestock production (Busscher, 2012; Hoekstra et al., 2012; Ridoutt et al., 2014). The use of water for the livestock sector should be considered as an integral part of the management of agricultural water resources, considering the type of production system (pasture cultivation, mixed crop-livestock systems) and the scale (intensive or extensive), the species and breeds of cattle and the social and cultural aspects of livestock (Schlink et al., 2010). For example, for every liter of milk produced, a cow needs at least three liters of drinking water (Krauß et al., 2016).

For high performance cows, the water requirement corresponds to 150 liters of water per day, and the reduction in the amount of water consumed is directly correlated with a reduction in milk production. Water intake is mainly related to the size of the animal, age, diet (type of food, dry matter content, etc.), activity, productivity and temperature, among other factors. Livestock production is a complex process, characterized by a wide variety of practices and production systems, some of which depend on a wide range of inputs to function (FAO, 2018).

4.4.2. Water footprint from the ruminant production

Globally, ruminants play a crucial role in food production, since they make use of plant resources, such as pastures, from which humans can obtain little nutritional value (Guyader et al., 2016). Besides, the intensive production of ruminants uses water for drinking, growing food or fodder, eliminating waste, cleaning in general (Legesse, et al., 2017). The quantification of the water footprint of anthropogenic activities that involve the production of ruminants is a relatively new research field, in which methodologies are still being developed (Legesse, et al., 2017). Interest in the use of water for the production of food of animal origin has increased in the last two decades, in part, in response to consumer concerns about the environmental impacts of food production (Hoekstra, 2012; Ridoutt et al., 2012a).

The expected increase in demand for livestock products and the increase in the number of animals will put an increased pressure on freshwater resources. In some arid areas where crop production is not viable due to scarcity and unequal distribution of water, grazing cattle, mainly ruminants, may be the only viable means to make use of erratic rain for production of grassland and shrubs that would not otherwise have been used (Cook et al., 2009). Therefore, quantifying the use of water associated with the production of ruminants and their products is crucial to identify strategies for the sustainable use of available water resources and prevent the expansion of desertification (Legesse, et al., 2017).

In tables 2 and 3, the use of water associated with the production of bovine and sheep meat and bovine milk is compared. The variation in water use estimations reflects the differences in the methods, the assumptions assumed, the scale of the analysis, as well as the functional units used. In general, water use estimates from life cycle assessment (LCA) studies are generally lower than those obtained with livestock water productivity (LWP). This could be a consequence of the exclusion of green and gray waters and the exclusion of blue water based on the local water shortage with the LCA approach (Legesse, et al., 2017). There are regional differences in water consumption associated with livestock products, as a result of differences in production systems and their productivity (Mekonnen & Moekstra, 2012; Gerbens-Leenes et al., 2013; Sultana et al., 2015).

Table 2. Some water utilization values associated with the production of beef, milk and sheep meat reported as an assessment of the water footprint

Product	Funcional unit[1]	Region/ country	Estimate Blue	Green	Gray	Total	Source
Milk	l H_2O kg^{-1}	Germany	3.94	-	-	3.94	Drastig et al., 2010.
	l H_2O kg^{-1}	World	-	-	-	990	Hoekstra & Chapagain, 2007.
	l H_2O kg^{-1}	World	86	863	72	1,021	Mekonnen & Hoekstra, 2012.
	l kg $(ECM^2)^{-1}$	World	121	1,466	106	1,693	Sultana et al., 2014.
	l H_2O kg $(FPCM^3)^{-1}$	New Zealand	-	-	-	945 and 1,084	Zonderland-Thomassen & Ledgard, 2012.[4]
Beef	l H_2O kg^{-1}	England	67	14,900	2,690	17,657	EBLEX, 2010.
	l H_2O kg^{-1}	World	-	-	-	15,497	Hoekstra & Chapagain, 2007.
	l H_2O kg^{-1}	World	550	14,414	451	15,415	Mekonnen & Hoekstra, 2012.
Sheep meat	l H_2O kg^{-1}	England	49	55,800	1,910	57,759	EBLEX, 2010.[5]
	l H_2O kg^{-1}	World	-	-	-	6,143	Hoekstra & Chapagain, 2007.
	l H_2O kg^{-1}	World	522	9,813	76	10,412	Mekonnen & Hoekstra, 2012.
	l H_2O kg $(LW^6)^{-1}$	Chile	193	6,034	151	6,378	Toro-Mujica et al., 2016.

[1]Unless specified, the functional unit is a kilogram of the respective product.
[2]ECM = energy-corrected milk.
[3]FPCM = fat–protein–corrected milk.
[4]Investigated dairy operations in 2 contrasting regions.
[6]Green water estimate in this study includes rainfall used to produce all feed crop biomass (including pasture) at the place where it falls.
[6]LW = live weight.

Table 3. A comparison of water use values associated with beef, milk, and sheep meat production from various approach

Product	Funcional unit	Estimate	Region/country	Approach	Source
Milk	l H_2O kg (FPCM[1])$^{-1}$	66	The Netherlands	LCA[2]	De Boer et al., 2013.
	l H_2O kg^{-1}	1,000	Ethiopia	LWP[3]	Gebreselassie et al., 2009.
	l (H_2O-eq[4]) kg FPCM^{-1}	461	California, United States	LCA	Huang et al., 2014.
	l H_2O-eq kg FPCM^{-1}	11	China	LCA	Huang et al., 2014.
	l H_2O-eq kg FPCM^{-1}	0.01	New Zealand	LCA	Huang et al., 2014.
	kg (FCM[5]) m^{-3}	1.0-1.7	Germany	LWP	Krauß et al., 2015.
	l H_2O kg (TMSW[6])$^{-1}$	108.0	Australia	LCA	Ridoutt et al., 2010.
	l H_2O kg (TMSS[7])$^{-1}$	15.8	Australia	LCA	Ridoutt et al., 2010.
	l H_2O-eq kg TMSW^{-1}	14.4	Australia	LCA	Ridoutt et al., 2010.
	l H_2O-eq kg FPCM^{-1}	0.011-11.1	New Zealand	LCA	Zonderland-Thomassen & Ledgard, 2012.
Beef	l H_2O kg boneless beef^{-1}	3,682	United States		Beckett & Oltjen, 1993.
	l H_2O kg beef carcass^{-1}	1,763	United States		Capper, 2011.
	l H_2O kg (LW[8])$^{-1}$	9,818-12,855	Australia	LCA	Eady et al., 2011.
	l H_2O kg meat^{-1}	11,500	Ethiopia	LWP	Gebreselassie et al., 2009.
	l H_2O kg (HSCW[9])$^{-1}$	18-540	Australia	Hybrid LCA	Peters et al., 2010.
	l H_2O kg beef^{-1}	43,000	United States		Pimentel et al., 2004.
	l H_2O kg beef^{-1}	105,400	United States		Pimentel et al., 1997.
	l H_2O-eq kg LW^{-1}	3.3-221	Australia	LCA	Ridoutt et al., 2011.
	l H_2O kg LW^{-1}	24.7-234	Australia	LCA	Ridoutt et al., 2012b.
	l H_2O kg beef^{-1}	200,000	United States		Thomas, 1987.
	l H_2O-eq kg LW^{-1}	0.37	New Zealand	LCA	Zonderland-Thomassen et al., 2014.
	l H_2O-eq kg beef^{-1}	15.1-20.0	United Kingdom	LCA	Zonderland-Thomassen et al., 2014.
Sheep meat	l H_2O kg LW^{-1}	58.1-238.9	Australia	LCA	Wiedemann et al., 2016.
	l H_2O-eq kg meat^{-1}	0.26	New Zealand	LCA	Zonderland-Thomassen et al., 2014.
	l H_2O-eq kg meat^{-1}	8.4-23.1	United Kingdom	LCA	Zonderland-Thomassen et al., 2014.

[1]FPCM = fat–protein–corrected milk.
[2]LCA = life cycle assessment.
[3]LWP = livestock water productivity.
[4]H_2O-eq = water equivalent.
[5]FCM = fat corrected milk.
[6]TMSW = total milk solids in whole milk.
[7]TMSS = total milk solids in skim milk.
[8]LW = live weight.
[9]HSCW = hot standard carcass weight.

Likewise, as with the EGHG, in the present study, an international price of the cubic meter of water has been established, in order to calculate the impact of the estimates made on the use of water, from an economic approach. For this economic quantification of WF, the average price per cubic meter of water was considered in some countries of the European Union (Denmark, Germany, the Netherlands, Belgium and France, among others), as reported by Kjellsson and Liu (2012) of € 3.5 m^{-3} (59.81 MXP).

4.5. Livestock production

4.5.1. Livestock production in the world

Livestock occupies more than 3,900 million hectares that represent about 30% of the land area, of these, 500 million are intensively cultivated, 1,400 million are relatively high-productivity pastures and 2,000 million are extensive-use pastures, with relatively low productivity (Pérez-Espejo, 2008). In Latin America, the expansion of grazing lands is a very important factor for deforestation: 70% of arid and semi-arid grazing lands are degraded, mainly due to intensive grazing, soil compaction and erosion caused by the cattle (FAO, 2006). Another of the most notable effects of grazing is the gradual substitution of native vegetation with monocultures which threatens biodiversity (García & Jurado, 2008). It is estimated that in the last 100 years the extinction of species has increased at rates 1,000 times higher than that recorded in the entire history of mankind; there are well-documented extinctions of birds, mammals and amphibians (MEA, 2005) and at least 15 of 24 ecosystems are in decline (Steinfeld et al., 2009).

However, globally, cattle contribute to the diet of 7,000 million people; this contribution is very complex and multidimensional (Smith et al., 2013). This multidimensionality increases when faced with one of the most pressing challenges, which is to feed the world's poor, due to the growth of the human population and, consequently, to the increasing pressure they exert on natural resources. In this sense, livestock has an important function, since it provides high quality protein to consumers and middle income to producers (FAO, 2011).

In addition, foods of animal origin are preferred by many people in various societies, as they add flavor, texture and variety to the diet. The products of the livestock sector represent about 13% of the energy and 28% of the protein consumed worldwide; in developed countries, this rises to 20% and 48%, respectively (FAO, 2009). Globally, around 17 billion cattle are produced in three types main production systems: a) intensive or confined systems, b) mixed systems crop-livestock, c) extensive grazing (Herrero et al, 2013, 2012).

Despite the above and considering that there is a general agreement on the potential benefits of animal foods, there are no global guidelines that provide an ideal level of consumption of these products for an individual. Excessive or inappropriate consumption of livestock products is risky and harmful to health; a high consumption of red meat can increase the risk of colon cancer, while a high intake of saturated fats and cholesterol from meat, dairy products and eggs can increase the risk of chronic non-infectious diseases such as cardiovascular diseases (SCN, 2005).

However, the consumption of food of animal origin depends not only on availability, but also on the volume of production and the trade balance of exports and imports (FAO, 2011). During the last decades, the production of meat, eggs, milk and honey experienced a constant growth. This growth being significant, especially in the production of poultry meat, which was multiplied by 10.32, that of eggs by 4.62 and that of pork by 3.54 (Table 4). In addition, in the decade between 1995 and 2005, the global growth rate of meat and milk consumption and production presented an average of 3.5% and 4.0%, respectively, representing twice the growth rate of the main staple crops during the same period (FAO, 2012).

Table 4. Changes in global livestock production total and per person 1967 to 2017

Item	Production (Mt)			Production per person (kg)			GPV (B€; BMXP)[1]
	1967	2017	2017/1967	1967	2017	2017/1967	
Pig meat	33.86	119.89	354%	9.73	15.88	163%	0.034; 0.750
Beef meat	35.27	66.25	188%	10.14	8.77	87%	0.255; 5.550
Poultry meat	10.57	109.1	1,032%	3.04	14.44	476%	0.182; 3.966
Sheep and goat meat	6.49	15.35	236%	1.87	2.03	109%	0.073; 1.583
Eggs, primary	17.32	80.09	462%	4.98	10.61	213%	0.089; 1.931
Milk, total	381.80	827.9	217%	109.74	109.65	100%	0.291; 6.336
Natural honey	0.75	1.861	247%	0.22	0.25	114%	0.006; 0.132

[1]GPV (B€; BMXP) = Gross Production Value (current billion of euros; current billion of Mexican pesos) in 2016.

Source: FAO, 2019.

Considering, the availability of economic information, which comes from different sources and in different currencies, table 5, presents the equivalences previously used and in the subsequent of all this thesis.

Table 5. Exchange rates used in the current thesis-dissertation

Year*	Coin		
	Mexican pesos (MXP)	United States dollars (USD)	Euros (€)
2014	17.9182	1.2155	1.00
2015	18.7873	1.0892	1.00
2016	21.7741	1.0560	1.00
2017	23.5729	1.1989	1.00
2018	22.4643	1.1432	1.00

*Value reported on the last eligible day of each year

Source: Banxico, 2019.

From 1970 to 1990, meat consumption in developing countries increased by 70 million tons, representing almost three times the increase observed in developed countries (Delgado et al., 2001). Likewise, by 2020 it is expected that developing countries have a consumption of 107 million tons more than what was consumed at the end of the nineties (Delgado, 2003). This increase in consumption has caused an accelerated livestock growth. Certainly, Latin America has become the largest exporter of beef and poultry in the world, representing about 45% of gross domestic product (GDP) agriculture of the region (FAO, 2017).

These increases in meat production, has also caused a growing concern to achieve sustainable food production, the ideal would be that the contribution of livestock to such sustainability was, at least neutral. The conversion of natural resources into food for human consumption should be as efficiently as possible, the foregoing, having as one of the purposes to ensure that the present and future world population have the possibility of consuming a diversified diet that includes products of animal origin. However, globally, this situation does not arise, suggesting a possible negative trend, considering that an annual consumption of 77 million tons of vegetable proteins is estimated to produce 58 million tons of animal proteins (Steinfeld et al., 2006).

4.5.2. Livestock production in Mexico

In Mexico, for 2017, the GDP of primary activities closed with a growth of 3.4%, highlighting agriculture with 3.9%; in the first quarter of 2018 the GDP of primary activities grew to 5.2%. The balance of the food trade balance in 2017 recorded a surplus of 4,394.21 M€ (103,584.16 MMXP), representing an increase of 65.9% over 2016 and the highest since 1993. This trend continued in the first quarter of 2018, where the surplus balance was 3,672.68 M€ (86,575.75 MMXP), 14% higher than the surplus recorded in 2017 in the same period (SAGARPA, 2018). In 2012, primary activities had a 3.4% participation in total GDP, where agriculture stood out with 66%, followed by livestock with almost 30% participation (Table 6). Undoubtedly, these activities are of great relevance for Mexico, since they produce the basic foods that Mexicans consume and in rural areas they inhabit about a quarter of the country's total population (DOF, 2013).

Table 6. Participation of primary activities in Mexico

Activity	Participation in GDP in 2012 (%)
Agriculture	65.9%
Livestock	28.8%
Forestry	2.6%
Fishing, hunting and capture	1.5%
Services related to agricultural and forestry activities	1.2%

Source: DOF, 2013.

In 2017, Mexico ranked 11th place as a world producer of food, agricultural crops and livestock primary; in the case of fisheries and aquaculture, Mexico occupied the 17th place. Livestock in Mexico plays a key economic role; livestock production (meat, milk, egg, honey, fish), contributes 7.4% (21 million tons) of food production, but such production contributes 41.6% to the income of the agri-food sector. In the same way, livestock activities generated labor activities for 776,722 people, which represented 11% of primary sector workers, below agricultural activities (6,006,521 people, 85%), and above fishing activities (171,829 people, 2%) and some other unspecified primary activities (101,672 people, 1%) (SIAP, 2018).

In Mexico, for 2017, 21.6 million hectares were cultivated, in contrast to the 109.8 million hectares dedicated to livestock. The total number of people who raised and/or fed the cattle herd, shown in table 7, amounted to 786,000 (SIAP, 2018).

Table 7. Composition of the cattle herd in Mexico (2017)

Item	Quantity (millions of heads)
Poultry	560.00
Bovine	34.30
Pig	17.20
Sheep	8.90
Goat	8.70
Hives*	1.90

*Millions of hives

Source: SIAP, 2018.

According to INEGI (2016), in its results of the update of the agricultural census framework, there are around 9.3 million rural lands that represent around 97% of the territory of the country and occupy an area of 190.3 million hectares (76.3% social property and 20.9% private property). Large producers have an average of 94 hectares, while medium and small producers have an average of 13 hectares. Of these, 1 million 66 thousand rural lands, report having to livestock as main activity, representing cattle 77.9%, 7.1% poultry, pigs, sheep, goats and hives, and the remaining 15% reported other species. Four entities have a rural area of more than 10 million hectares: Chihuahua 24.3 million, Sonora 17.8 million, Coahuila 14.7 million and Durango 12.1 million hectares (INEGI, 2016).

The livestock areas of Mexico are divided mainly by the climatic characteristics and the ecology of the places, since it has a great diversity of soils, topographies, vegetation and climates. Due to the different climatic characteristics and the soil-plant-animal relationship, the Mexican geography has been divided into five large regions, which were described by Jaramillo-Villalobos (1994), the main characteristics being the following:

1.- Arid. It circumscribes 28% of the national surface with an area of 55.7 million hectares. It is located in the states of: Baja California, Baja California Sur, Sonora, Chihuahua, Coahuila, Nuevo León, Sinaloa, Durango, Zacatecas and San Luis Potosi. General characteristics: It has at least 7 dry months per year, rainfall less than 350 mm per year, average annual temperature between 15°C and 25°C.

With a vegetation cover less than 70% and is dominated mainly by xerophytic species. The study area is located within this region.

2.- Semi-arid. It contains 20% of the national surface with an area of 39.2 million hectares. It is located in the states of: Sonora, Durango, Coahuila, Nuevo Leon, Zacatecas, San Luis Potosi, Tamaulipas, Sinaloa, Guanajuato, Jalisco, Hidalgo, Puebla, Queretaro, Mexico, Oaxaca, Aguascalientes, Michoacan, Tlaxcala and Veracruz. General characteristics: They have 6 to 8 dry months per year, rainfall between 350 mm and 600 mm per year, average annual temperature between 18°C and 25°C. With a vegetation cover greater than 70% and is mainly dominated by thickets and grasslands.

3.- Tempered. It represents 24% of the national surface with an area of 46 million hectares. It is located in the states of: Baja California, Chihuahua, Durango, Jalisco, Puebla, Chiapas, Oaxaca, Michoacan, Guerrero and Mexico. General characteristics: In this region there is a diversity of climates with rainfall ranging from 500 to 2,500 mm, for dry climates it can descend to 200 mm and for hot climates it can increase to 4,000 mm. The average temperature can vary between 12°C and 22°C, being able to descend to 6°C in temperate climates and reach 24°C in dry ones. The vegetation that predominates in this region are the oak forests.

4.- Dry Tropic. It constitutes 16% of the national surface with an area of 31.7 million hectares. It is located in the states of: Sinaloa, Jalisco, Nayarit, Sonora, Tamaulipas, Veracruz, Michoacan, Guerrero, Oaxaca, Chiapas, Yucatan and Campeche. General characteristics: In this region there are rainfalls ranging from 600 mm to 1,300 mm per year, with an average annual temperature of around 18°C. The vegetation that predominates in this region is the deciduous forest and subcaducifolia.

5.- Humid tropics. It makes up 12.2% of the national surface with an area of 24 million hectares. It is located in the states of: Veracruz, Puebla, San Luis Potosi, Nayarit, Oaxaca, Chiapas, Tabasco, Campeche, Quintana Roo, Yucatan and

Michoacán. General characteristics: In this region there is an annual rainfall of more than 1,300 mm, and an average annual temperature of 20°C. The vegetation that predominates are evergreen and sub-evergreen jungles.

In each region different production systems are carried out, with different use of technologies and different production market or purpose according to ecological conditions, which has contributed to the growth in production in Mexico in recent years (Table 8).

Table 8. National summary of livestock production in Mexico, over the years (2014-2018)

Item/Year	2014	2015	2016	2017	2018
Milk*	**11,285.44**	**11,553.55**	**11,767.73**	**11,969.88**	**12,171.89**
Bovine	11,129.92	11,394.66	11,607.49	11,807.56	12,008.24
Caprine	155.52	158.89	160.24	162.32	163.65
Meat**	**6,114.63**	**6,263.32**	**6,449.95**	**6,690.89**	**6,910.64**
Bovine	1,827.32	1,850.13	1,879.32	1,925.36	1,980.21
Porcine	1,290.48	1,322.51	1,376.10	1,439.93	1,501.22
Caprine	58.29	59.40	60.36	61.60	62.94
Ovine	39.75	39.36	39.53	39.66	39.85
Chicken***	2,879.56	2,972.96	3,077.87	3,207.35	3,309.34
Guajolote	19.24	18.97	16.76	16.99	17.08
Other products**	**2,626.88**	**2,714.17**	**2,775.83**	**2,876.05**	**2,993.91**
Egg	2,567.18	2,652.29	2,720.74	2,825.06	2,931.59
Honey	59.69	61.88	55.08	51.00	62.32

* In millions of liters
** In thousands of tons
*** Refers to chicken, light and heavy hen that has finished its productive cycle.
Source: SIAP, 2019.

4.5.3. Livestock production in the Comarca Lagunera

The CL is located in the central part of northern United Mexican States, between the meridians 102° 22' and 104° 47' west longitude, and the parallel 24° 22' and

26° 23' north latitude. The average altitude above sea level is 1,139 meters. It has a mountainous extension and a flat surface where agricultural areas are located, as well as urban areas (SAGARPA, 2014). According to the Köppen climate classification modified by García (1973), the climate of the CL is of the desert type with low atmospheric humidity and average annual rainfall of 240 mm; the rain period lasts from May to September, concentrating 70% of the precipitation. Most of the region shows an annual evaporation of 2.600 mm and an average temperature of 20°C (De la Cruz et al., 2003).

The region has a total area of 4.79 million hectares, which include mountain, agricultural and livestock areas, as well as urban areas. The agricultural area under the irrigation modality represents 3.62% of the total extension, while the surface under the temporary modality only reaches 1.10% of said extension. It should be noted that the irrigation mode includes both pumping and gravity irrigation. Surface´s sown, the ejido sector accounted for 57% and industry small property remaining 43%, however, most of the ejido sector´s production is leased by the private sector, specialty for the production of fodder. The area sown by pumping is mostly concentrated by the private sector (64%); 91.70% of the territory of the CL (4.39 million hectares), presents livestock-forestry aptitude (SAGARPA, 2014).

The Comarca Lagunera is made up of 10 municipalities in the state of Durango and 5 in the state of Coahuila (Figure 5).

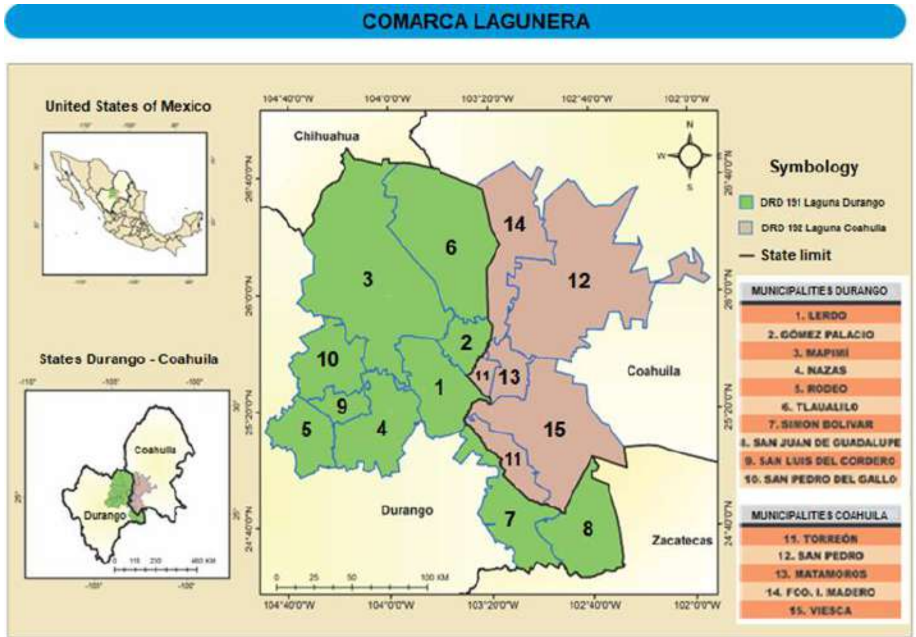


Figure 5. Location of the Comarca Lagunera
(Source: Prepared with information from the SAGARPA, 2014).

In relation to the total livestock activity of the CL, in 2018 it is observed a growth rate below the average national growth but exceeding the growth of the agricultural sector of the region, and even of the region itself. In an historical analysis considering five years (2014-2018), while the country showed an increase of 6.55%, the CL decreased 2.65%; the agricultural sector of the CL had a 7.72% increase and the livestock subsector decreased by 11.49%. Please note that such decreasing trend was observed when converting Mexican pesos to euros, as shown in Table 9 (INEGI, 2019; SIAP, 2019).

Table 9. Evolution of regional growth (millions of current euros), over the years (2014-2018)

GDP*	2018**	2017**	2016**	2015**	2014**	% var. 18/17
National	1,090,351.41	970,355.53	981,089.40	1,027,935.22	1,020,440.01	12.37%
	(24,493,981.10)	(22,874,093.90)	(21,362,338.80)	(19,312,127.30)	(18,284,448.20)	(7.08%)
Comarca Lagunera (CL)	9,889.66	8,979.83	9,102.74	10,199.31	10,158.88	10.13%
	(222,164.35)	(211,680.55)	(198,204.05)	(191,617.55)	(182,028.80)	(4.95%)
CL Agro-livestock sector	1,902.42	1,732.84	1,897.47	2,044.07	2,061.52	9.79%
	(42,736.61)	(40,848.16)	(41,315.71)	(38,402.52)	(36,938.71)	(4.62%)
CL Livestock subsector	1,515.47	1,369.54	1,504.15	1,707.51	1,712.16	10.66%
	(34,044.08)	(32,283.96)	(32,751.49)	(32,079.59)	(30,678.91)	(5.45%)

*GDP : Gross Domestic Product

**GDP in millions of current euros (millions of Mexican pesos)

Source: Prepared with information from the INEGI, 2019; SIAP, 2019.

The livestock sector of the CL-Durango, in 2018 contributed 60.3% of the income generated by the sector, and despite the fact that the different production systems that compose it, had a mixed performance; while some systems increased, others decreased, yet, the general balance in the CL reported a growth rate of 10.66%, compared to 2017. However, it is worth mentioning the goat production system, which presented a negative behavior for meat production (-17.95%), but positive for the case of milk (11.48%) (Table 10) (SIAP, 2019).

In 2018, the meat-milk cattle production system in the CL contributed 59.81% to the income generated by livestock, and although the number of animals slaughtered and therefore the meat production decreased, the value of the milk-meat bovine production increased 13.19 % over the previous year, reflecting the improvement in market conditions and prices. Regarding bovine milk production, despite its major contribution to the agricultural GDP of the CL (37.52%) it only grew by 11.83 %, a lower value presented by the production of beef and pork from 18.52% and 25.60%, respectively (Table 10) (SIAP, 2019).

An analysis of the period (2014-2018) shown in Table 10, reveals that the only branches that showed economic growth during this period were: bovine meat (83.86%), sheep meat (8.18%) and goat meat (12.65%). Meanwhile, the three branches livestock which recorded the highest decrement were: Beeswax (-63.75%), honey bee (-43.16%) and egg production (-42.82%). The economic importance of ruminants in the CL, is clearly evidenced because it is a family of domestic livestock, which in 2018, it represented a 61.08% of the income of the livestock sector, 48.66% of the income of the agricultural sector and 9.36% of total income in the CL (Tables 9 and 10).

Table 10. Livestock production in the Comarca Lagunera, over the years (2014-2018)

Item	Coah. Lag. 2018	Dgo. Lag. 2018	Comarca Lagunera total 2018	2017	2016	2015	2014	% var. 18/17	% RTEV**
			Milk/Bovine						
Inventory (K)	242.30	248.58	490.88	468.00	493.14	490.09	443.53	4.89%	
Exploded heads (K)	126.82	108.59	235.41	230.80	227.14	225.22	242.33	2.00%	
Production (Ml)	1,321.85	1,126.31	2,448.16	2,371.92	2,386.96	2,412.33	2,260.12	3.21%	47.10%
Value (M€; (MMXP))*	385.70	328.069	713.78	638.25	707.68	834.78	814.60	11.83%	
	(8,664.46)	(7,370.21)	(16,034.67)	(15,045.41)	(15,409.09)	(15,683.33)	(14,596.21)	(6.58%)	
			Milk/Goat						
Inventory (K)	158.70	81.77	240.46	239.00	224.37	234.24	280.18	0.61%	
Exploded heads (K)	70.94	43.93	114.87	126.30	151.38	156.73	154.27	-9.04%	
Production (Ml)	32.89	22.45	55.34	55.90	56.39	58.51	61.68	-1.01%	0.86%
Value (M€; (MMXP))*	7.69	5.33	13.01	11.67	11.60	13.29	15.38	11.48%	
	(172.65)	(119.66)	(292.31)	(275.14)	(252.58)	(249.61)	(275.53)	(6.24%)	
			Meat/Bovine						
Inventory (K)	80.61	351.10	431.71	310.41	287.69	285.49	154.67	39.08%	
Slaughtered heads (K)	85.97	461.74	547.71	761.94	748.06	344.07)	377.05	-28.12%	
Production (Kt)	15.51	65.75	81.26	89.81	89.04	66.60)	61.72	-9.53%	12.71%
Value (M€; (MMXP))*	31.37	161.29	192.66	162.55	166.98	132.08	104.79	18.52%	
	(704.73)	(3,623.18)	(4,327.91)	(3,831.75)	(3,635.93)	(2,481.37)	(1,877.58)	(12.95%)	
			Meat/Goat						
Slaughtered heads (K)	95.40	33.65	129.06	166.60	184.07	195.47	164.96	-22.54%	
Production (Kt)	1.81	0.65	2.46	2.69	2.68	2.72	3.11	-8.65%	0.39%
Value (M€; (MMXP))*	4.25	1.64	5.89	7.18	6.49	7.88	6.56	-17.95%	
	(95.42)	(36.93)	(132.35)	(169.26)	(141.37)	(148.04)	(117.48)	(-21.81%)	
			Meat/Pig						
Inventory (K)	27.85	5.71	33.56	46.25	42.11	43.30	56.03	-27.43%	
Slaughtered heads (K)	47.92	7.42	55.35	65.99	100.81	103.35	112.97	-16.13%	
Production (Kt)	3.82	0.77	4.59	4.55	7.31	7.51	7.94	0.72%	0.62%
Value (M€; (MMXP))*	7.81	1.52	9.33	7.43	12.92	15.70	15.45	25.60%	
	(175.50)	(34.03)	(209.53)	(175.06)	(281.38)	(295.01)	(276.83)	(19.69%)	

Table 10 continued

Item	Coah. Lag. 2018	Dgo. Lag. 2018	Comarca Lagunera total 2018	2017	2016	2015	2014	% var. 18/17	% RTEV**
			Meat/Sheep						
Inventory (K)	3.41	5.77	9.18	15.85	16.14	15.14	14.92	-42.09%	
Slaughtered heads (K)	1.69	4.23	5.92	7.80	7.95	7.43	7.10	-24.10%	
Production (t)	37	89	126	158	161	151	154	-20.25%	0.02%
Value (M€; (MMXP))*	0.11	0.26	0.36	0.33	0.35	0.38	0.34	11.17%	
	(2.38)	(5.78)	(8.15)	(7.70)	(7.64)	(7.22)	(6.01)	(5.94%)	
			Meat/Chicken						
Inventory (M of heads)	10.47	25.10	35.56	32.19	38.87	39.11	38.58	10.47%	
Slaughtered heads (M)	53.33	138.05	191.38	185.86	199.19	199.23	208.37	2.97%	
Production (Kt)	103.99	265.06	369.04	365.28	389.95	392.21	392.57	1.03%	33.37%
Value (M€; (MMXP))*	141.18	364.59	505.77	470.23	495.98	579.24	624.44	7.56%	
	(3,171.58)	(8,190.24)	(11,361.82)	(11,084.67)	(10,799.55)	(10,882.38)	(11,188.76)	(2.50%)	
			Egg/Hen						
Inventory (M of heads)	1.96	3.38	5.34	5.71	6.95	6.00	5.50	-6.58%	
Exploded hens (M)	1.78	3.37	5.15	5.34	6.95	7.35	7.26	-3.49%	
Production (Kt)	30.75	60.22	90.97	91.09	119.46	125.50	124.47	-0.13%	4.90%
Value (M€; (MMXP))*	23.27	50.94	74.20	71.38	101.55	123.38	1229.77	3.96%	
	(522.70)	(1,144.24)	(1,666.94)	(1,682.52)	(2,211.22)	(2,317.92)	(2,325.25)	(-0.93%)	
			Honey/Bees						
Inventory (K)	4.21	2.01	6.23	6.06	7.33	7.68	8.46	2.77%	
Exploded beehives (K)	4.21	2.01	6.23	5.97	6.07	7.68	6.82	4.32%	
Production (t)	141	55	196	192	202	292	260	2.08%	0.03%
Value (M€; (MMXP))*	0.31	0.12	0.43	0.49	0.54	0.71	0.75	-12.79%	
	(6.93)	(2.65)	(9.58)	(11.52)	(11.82)	(13.37)	(13.44)	(-16.90%)	
			Wax/Bees						
Production (t)	8	3	11	12	12	18	26	-8.33%	
Value (M€; (MMXP))*	0.03	0.01	0.04	0.04	0.04	0.07	0.10	-6.72%	0.00%
	(0.59)	(0.23)	(0.82)	(0.93)	(0.92)	(1.35)	(1.81)	(-11.11%)	

Table 10 continued

Item	Coah. Lag. 2018	Dgo. Lag. 2018	Comarca Lagunera total 2018	2017	2016	2015	2014	% var. 18/17	% RTEV**
			Total value of livestock production						
Value (M€; (MMXP))*	**601.71 (13,516.9)**	**913.77 (20,527.1)**	**1,515.47 (34,044.1)**	**1,369.54 (32,284.0)**	**1,504.15 (32,751.5)**	**1,707.51 (32,079.6)**	**1,712.16 (30,678.9)**	**10.66% (5.45%)**	**100.00%**

*Value (M€; (MMXP)) = Value of production in millions of current euros (millions of current mexican pesos)
**% RTEV Respect to the Total Economic Value of the livestock sector in 2018
Source: Prepared with information from the SIAP, 2019.

As mentioned in our study, the CL has its foundations in ruminant livestock. From the ruminant production systems reported for the study area, the milk-meat production system stands out for its importance, both for cattle and goats and the meat production system, and to a much lesser extent the meat production sheep. Indeed, due to its economic and social importance, as well as the size of the herd, during 2018 highlighted its economic importance the dairy cattle production system with a share of 47.10% of the livestock GDP, the 77.11% of the ruminant GDP and 41.88% of the ruminant inventory. Another important system is the beef cattle fattening production system which represented 12.71% of livestock GDP, 20.81% of the ruminant GDP and 20.51% of ruminant inventory. In third place is the goat meat-milk production system, on which reported a stake of 1.25% of the livestock in the CL, 2.04% of ruminant GDP and 36.83% of the ruminant inventory. Finally, inside ruminant system, the sheep meat production system represented a stake of 0.02% of the livestock GDP, 0.04% of ruminant GDP and 0.78% of the ruminant inventory.

For these reasons, the present study focuses its analyses on the first three production systems observed in the CL; bovine milk production, bovine meat production and milk-meat goat production, which all together represent 99.96% of ruminant livestock GDP and 99.22% of ruminant inventory. The sheep meat production system will not be considered for its limited participation from an inventory, production and economic value stand point throughout the years.

The first study of this dissertation corresponds to the bovine milk production system, which aims to make a comparative analysis between the direct economic benefits of bovine milk production and the economic costs of GHG emissions and the WF of this activity in the CL. In order to measure and transform the environmental impact to economic value, so that in turn, it may serve as a basis for the generation of mitigation policies and actions. The working hypothesis that was raised n this first study is that the EI and EcI of the WF and the CF, generated by the production of bovine milk in the CL is greater than the EV that this activity generates in the region.

The second study analyzes the beef-fattening production system, which has a similar objective to the previous one, by measuring and transforming the EGHG and the WF generated by this activity into economic value, and comparing it with its economic benefits, to contribute to the generation and adoption of mitigation measures both regarding the CF, as well as the WF. The working hypothesis of this second study is that the EI and EcI of the WF and CF, generated by the production of meat bovine CL is greater than the economic spill that this activity generates in the region.

Finally, the third study corresponds to the analyses of the goat meat-milk production system, with the same bases as the previous ones, but in this case highlighting the social importance of this system, since the previous two are mostly private farms and the case of the goats are based in the families of the social sector. Therefore, the aim is to measure the EI, EcI and SI of the meat-milk goat production system in the CL; our working hypothesis proposes that the EI, evaluated as the EV of CF and WF generated by the goat production system is less than the EV that this activity generates in the region and that its SI is preponderant in the development of human well-being in rural communities.

UNIVERSIDAD AUTÓNOMA CHAPINGO
UNIDAD REGIONAL UNIVERSITARIA DE ZONAS ÁRIDAS

UNIVERSIDAD DE CÓRDOBA
INSTITUTO DE ESTUDIOS DE POSGRADO

THESIS IN JOINT SUPERVISION
WITH INTERNATIONAL MENTION

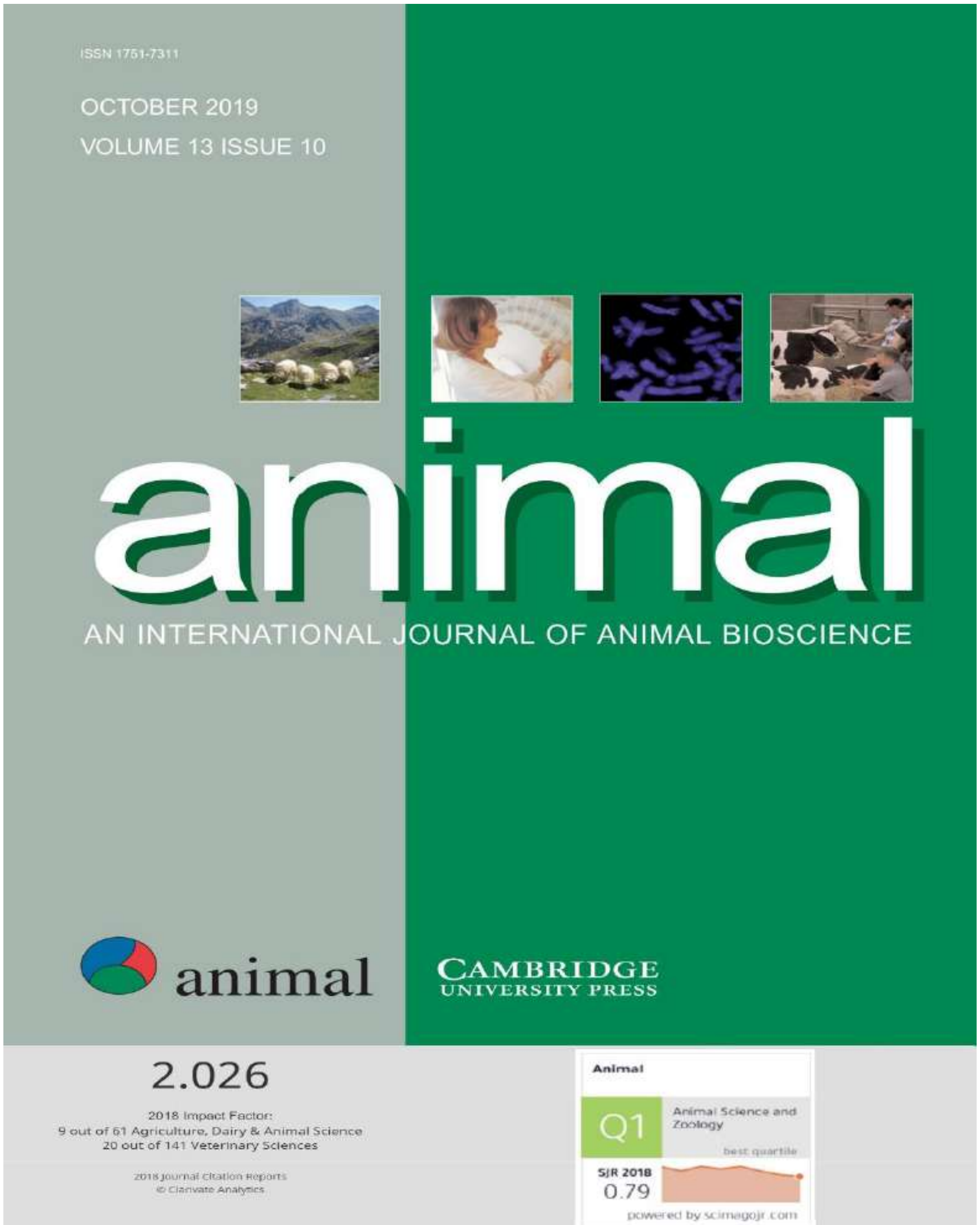
THE RUMINANT PRODUCTION SYSTEMS IN THE COMARCA LAGUNERA, MEXICO: ENVIRONMENTAL IMPACT, PRODUCTIVE TRENDS, AND MITIGATION STRATEGIES

V. ARTICLES

Doctorado en ciencias en recursos naturales y medio ambiente en zonas áridas

Doctorado en recursos naturales y gestión sostenible

5.1. Economic evaluation of the environmental impact of a dairy cattle intensive production cluster under arid lands conditions



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Economic evaluation of the environmental impact of a dairy cattle intensive production cluster under arid lands conditions

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At a global level, dairy cow production systems (DCPS) are important sources of nourishment and profits, but they generate environmental impacts such as overexploitation of different resources including water, lands and fossil energy. Quantification of water and carbon footprint to define mitigation strategies and a more rational use of natural resources, is a reiterated claim. The aim of this study was to perform an economic evaluation of the environmental impact of the DCPS from the Comarca Lagunera, Mexico (24°N, 102°W, 220 mm, hot-semiarid climate) We contrasted the economic value (EV) generated by the DCPS with respect to the economic costs (EC) due to the greenhouse gas emissions (GHGE) and the water footprint (WFP) of this DCPS. While quantifications of GHGE considered those proposed by the Intergovernmental Panel on Climate Change, the WFP involved the use of blue, gray and green water by the DCPS and related activities. Quantification of the EC of WFP considered an international average price of water. In the year 2017, the Comarca Lagunera registered a dairy cow inventory of 493 144 heads, with 227 142 lactating cows, which produced 2386 million liters of milk per year with an annual average EV of €525.3 million. The EC (€, millions) generated by the GHGE and WFP were €311.8 and €11 980.7, respectively, with a total EC of € 12 292.5 million. When the EV of milk production and the total environmental EC are compared, the contrast demonstrates not only the noteworthy environmental impact but also the significant and senseless biological and EC. In addition, having a large dairy cow concentration creates pollution concerns and the DCPS transfers both nutrients and water resources from an ecologically vulnerable arid region. Therefore, some mitigation strategies such as, better cow genotype, feed and manure management combined with the production of forages and grains in a different geographical region are suggested to promote an optimum use of water in order to uphold the social, economic and biologic sustainability of the Comarca Lagunera, Mexico.

Keywords: Holstein, intensive systems, arid lands, water footprint, sustainability

Implications

Dairy cow production systems (DCPS) generate food for the human population and are significant contributors of the global economy, but they generate environmental impacts such as overexploitation of different resources including water, lands and fossil energy. Therefore, mitigation policies and strategies to reduce their ecological footprint are required. We quantified the carbon and water footprint (WFP) and compared these to the milk production economic value (EV) generated by an intensive DCPS under arid conditions. Our study demonstrates that the economic cost (EC) of the environmental impact is significantly higher than the EV generated by dairy production in the Comarca Lagunera, Mexico.

Introduction

Livestock production systems occupy 45% of the global surface area with an estimated EV of € 1.2 trillion being a significant source of livelihoods; more than 1300 million people economically depend on the animal production industry (Herrero *et al.*, 2009; Scientific Committee on Problems of the Environment, 2010; Thornton, 2010). Although the economic and social importance of animal production

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has been extensively documented (Capper *et al.*, 2009; Herrero *et al.*, 2009; Thornton, 2010), there are significant environmental concerns about livestock production, especially when considering both direct and indirect greenhouse gas emissions (GHGE) (Gill *et al.*, 2010; Thornton, 2010; Meza-Herrera *et al.*, 2015 and 2016). While the direct GHGE considers both methane (CH_4) and nitrous oxide (N_2O) (Jungbluth *et al.*, 2001), the indirect GHGE include those emissions generated by animal manure, production of grains and forages for animal consumption, use of fertilizers, deforestation and desertification linked to animal production as well as transport of different inputs and outputs (Mosier *et al.*, 1998). At a global level, the livestock sector generates 18% of the total GHGE (Steinfeld *et al.*, 2006); when considering only the agro-livestock sector, the single livestock subsector comprises 80% of the total GHGE (Herrero *et al.*, 2009; Cardoso, 2012). In addition, dairy cattle is one of the main GHGE producer, only exceeded by those generated by the beef cattle industry (Gerber *et al.*, 2013). Cattle are the main contributors to global manure production (69%), while swine and poultry production account for 9% and 10%, respectively (Herrero *et al.*, 2009).

In the Americas, one of the main bovine milk producing clusters is located in Mexico, specifically in the Comarca Lagunera. The Servicio de Información Agroalimentaria y Pesquera – Agrifood and Fishery Information System (SIAP, 2017) reported a daily milk production of 6.53 million of liters from 227 142 milking cows in this arid-northern region of Mexico. The DCPS in the Comarca Lagunera is characterized by a highly technified, modern and intensive production scheme perfectly linked to a milk-industrialization structure, with national and international branching. This DCPS is based on an extremely intensive groundwater extraction pattern. This has been done so that the main groundwater reserve in the Comarca Lagunera faces a highly significant annual deficit close to 125 million m^3 (Montemayor-Trejo *et al.*, 2012). High environmental temperatures (>40°C in summer) and low annual rainfall (<300 mm) characteristic to this region have promoted this asymmetrical groundwater extraction, generating an environmental risk that may potentially affect not only the DCPS itself but also the societal, biological and economic sustainability of the Comarca Lagunera (Meza-Herrera *et al.*, 2015; Acevedo-Peralta *et al.*, 2017).

In order to propose potential mitigation strategies against the risks associated with DCPS, it is essential to attain environmental indicators such as the level of both the GHGE and the WFP generated by the DCPS (Chapagain and Hoekstra, 2004; Herva *et al.*, 2011). The GHGE are usually quantified as amount of CO_2-equivalent ($CO_{2\text{-eq}}$) associated with the production, processing and sale of food. The WFP is quantified based on consumptive use of rainwater (green WFP) and ground and surface water (blue water footprint (BWF)) and volumes of water polluted (gray WFP) (Hoekstra and Mekonnen, 2012). A global assessment of the WFP of farm animal products stated that from the WFP generated by the agricultural and livestock sector, the beef cattle category has the highest impact (33%), followed by dairy cattle (19%), swine (19%) and poultry (11%) industries (Mekonnen and Hoekstra, 2012).

The objective of this study was to compare the direct economic benefit from the sale of milk with the economic environmental costs generated by the DCPS, regarding both GHGE and WFP, in the Comarca Lagunera, Mexico.

Material and methods

Location of the study area and databases

The Comarca Lagunera in located in northern Mexico at 102° 22′ and 104°47′ West longitude and 24° 22′ and 26° 23′ North latitude, 1139 m altitude. It has an average temperature of 22°C with temperatures ranging lows of 0°C (winter) and highs of 40°C (summer), with an average rainfall of 300 mm (historical range from 88 mm in 1998 to 406 mm in 1997). The region includes 10 municipalities of the State of Durango and five from the State of Coahuila. In order to develop this study, the information published in the Statistical Yearbooks for Agricultural Production by the Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA), were considered. Alongside this, the estimated use of commercial fertilizers for forage production was generated according the procedures outlined by Figueroa-Viramontes *et al.* (2011). In order to conduct these studies, both existing and generated databases were used, therefore, no Animal Care and Use Committee approval was required.

Methods to estimate the economic value of milk production

The annual EV of the DCPS from the Comarca Lagunera was calculated as the total volume of milk produced per year multiplied by the average payment per liter of milk received by the producers. The milk payment was €0.13 in 1997 and increased to €0.29 in 2016.

Methods to estimate the greenhouse gas emissions

To estimate the GHGE, the factors and indexes proposed by the Intergovernmental Panel on Climate Change (IPCC, 2007) were utilized. Livestock inventory, production level, type of diets, consumption and digestibility, were also included. The IPCC conversion rates of such emissions to global potential warming $CO_{2\text{-eq}}$ were also incorporated. These equivalences correspond to: 1 $CH_4 = 25$ CO_2 units and 1 $N_2O = 296$ CO_2 units. The EC of the GHGE considered an international price of carbon emissions of 15.75€/t of $CO_{2\text{-eq}}$ (Environmental Finance, 2011; Thompson Reuters, 2011).

According to the IPCC (2007), the GHGE (CH_4 and N_2O) in the agricultural sector, three subcategories should be considered: livestock, savannas and agriculture. In our particular case, to perform such quantifications, we only included the livestock and agriculture categorizations since the bovine milk production in the Comarca Lagunera is based on an intensive production system.

Livestock subcategory. In order to quantify the CH_4 emissions due to enteric fermentation, to manure production as well as N_2O emissions due to manure management, we used the equations proposed by Hongmin *et al.* (2006).

CH_4 emissions due to enteric fermentation. The volume of CH_4 emissions due to enteric fermentation depends on the physiological stage, weight and age of animals. As previously mentioned, we only considered the dairy cattle inventory to characterize the bovine population:

$$Em_{EFECH4} = \frac{LPOP \times EF}{10^6 kg / Gg}$$

where Em_{EFECH4} is the methane emissions from enteric fermentation, Gg CH_4/year; LPOP the number of animals or heads; EF the emission factor for the specific population, kg/head per year.

In this estimation, the considered emission factor was 118 kg head/year, corresponding to the highly productive dairy cow sector in the North American region.

CH_4 emissions due to manure production. From the two levels for the estimation of CH_4 emissions referred to manure livestock emissions provided by the IPCC guidelines, the Tier 1 methodology was applied:

$$CH_4Em_{mm} = \frac{EF \times LPOP}{10^6 kg / Gg}$$

where CH_4Em_{mm} is the CH_4 emissions from manure management, for a defined population Gg/year. While the other components of the equation have been previously described, the emission factor (EF) used was 76 kg/head per year. This EF corresponds to the hot climates in the North America region with temperature averages greater than 25° C (IPCC, 2007).

N_2O emissions due to manure management. The production of N_2O generated during the manure storage, treatment and management, was also estimated. These emissions include both feces and urine produced by bovines under intensive conditions.

$$(N_2O-N)_{(mm)} = \sum_{(s)} \left\{ \left[\sum_N \times Nex \times MS_{(S)} \right] \times EF_{3(s)} \right\}$$

where $(N_2O\text{-}N)_{(mm)}$ is the N_2O-N emissions from manure management (kg N_2O-N/year); *N* the number of heads of livestock; Nex the annual average N excretion per head of livestock (kg N/animal per year); $MS_{(S)}$ the fraction of total annual excretion per animal managed in manure management system S; $EF_{3(S)}$ the N_2O emission factor for manure management system S (kg N_2O-N/kg N in manure management system S); S the manure management system.

The conversion of $(N_2O\text{-}N)_{(mm)}$ emissions to $N_2O_{(mm)}$ emissions was performed considering the equation proposed by Hongmin *et al.* (2006):

$$N_2O_{(mm)} = (N_2O-N)_{(mm)} \times 44/28$$

Agriculture subcategory. In this subcategory, the direct N_2O emissions from agricultural areas used for the production of forages, were estimated. It considers the nitrogen inputs such as synthetic and organic fertilizers on animal manure; the inputs from N-fixing varieties (F_{BN}) as well as the incorporation of crop residues into soils (Fc_R), were also considered. The equation proposed by Hongmin *et al.* (2006) was used for the estimation of nitrous oxide emissions from manure management:

$$N_2O_{Direct}-N = [(F_{SN} + F_{AM} + F_{CR}) \times EF]$$

where N_2O_{Direct}-N is the emission of N_2O in units of nitrogen; F_{SN} the annual amount of synthetic fertilizer nitrogen applied to soils adjusted to account for the amount that volatilizes as NH_3 and NO_x; F_{AM} the annual amount of animal manure nitrogen intentionally applied to soils adjusted to account for the amount that volatilizes as NH_3 and NO_x; F_{CR} the amount of nitrogen in crop residues returned to soils annually; EF_1 the emission factor for emissions from N inputs (kg N_2O-N/kg N input).

The conversion of $(N_2O\text{-}N)_{(mm)}$ emissions to $N_2O_{(mm)}$ emissions was performed considering the equation proposed by Hongmin *et al.* (2006) as given above.

To estimate the quantity of nitrogenous fertilizer used in the Comarca Lagunera, the level of the extracted nitrogen from soils by different forage crops (i.e. corn, sorghum, rye grass, wheat and triticale) was considered, as suggested by Figueroa-Viramontes *et al.* (2011).

Methods to estimate the blue water footprint

First, the WFP per liter of milk was calculated based on the mathematical methodology proposed by Mekonnen and Hoekstra (2010):

$$WF[a,c,s] = WF_{feed}[a,c,s] + WF_{drink}[a,c,s] + WF_{serv}[a,c,s]$$

where $WF_{feed}[a,c,s]$, $WF_{drink}[a,c,s]$ and $WF_{serv}[a,c,s]$ represent to the WFP of an animal in a c-category, in c-country, in an s-production system, and are related to feed, drinking water and service consumption, respectively. This quantification is related to an a-feed consumed, plus the c-water consumed plus the s-water related to services (Mekonnen and Hoekstra, 2010).

$$WF_{feed}[a,c,s] = \frac{\sum_{p=1}^{n} (Feed[a,c,s,p] X WF^{*}_{prod}[p]) + WF_{mixing}[a,c,s]}{Pop^{*}[a,c,s]}$$

Feed[a,c,s,p] represents the annual amount of the p-feed ingredient consumed by an animal in an a-category, in a c-country, in an s-production system (t/year), $WF^{*}_{prod}[p]$ the WFP of the p-feed ingredient (m^3/t), $WF_{mixing}[a,c,s]$ the volume of water consumed for mixing the feed for an a-animal category, in a c-country, in an s-production system (m^3/year per animal) and Pop*[a,c,s] the number of slaughtered animals per year or the number of milk producing animals in a year for an a-animal category, in a c-country, in an s-production system.

Thereafter, the BWF was calculated considering the stress impact which results from the multiplication of the BWF value by a water stress index (WSI) as suggested by Ridoutt and Pfister (2010). The main concern related to the water consumption in the agro-livestock production sector is the possibility to promote a water shortage and to limit the availability of fresh water for human consumption as well as for the environment. For this reason, the direct consumption of blue water is crucial (Ridoutt and Pfister, 2010). The WSI is used to evaluate the impact related to the fresh water consumption and is considered an indicator which evaluates water deprivation applied to the blue water (Pfister *et al.*, 2009). The WSI considers the water use–availability relationship (WTA). The WTA index is based on withdrawal-to-availability ratio; it has been developed to measure the relationship between water use and freshwater availability (Averyt *et al.*, 2013). The WSI values range from 0.01 to 1, and derivate from the following expression:

$$\mathrm{WSI} = \frac{1}{1 + e^{-6.4 \times \mathrm{WTA}^* \left(\frac{1}{0.1} - 1\right)}}$$

where WTA* is a modified WTA, which considers the total quantity of water extracted for human usage, including both the agro-livestock and industrial usage, as well as the total annual water recharge in a specific region. As mentioned, the WSI value only applies for the BWF, using the methodology proposed by Ríos-Flores *et al.* (2015), which considers the physical WFP of an agricultural crop (Y1, expressed in m^3 of water used in the production of 1 kg of agricultural product), quantified as follows:

$$Y_i = \frac{\sum_{i=1}^{n} Vi}{\sum_{i=1}^{n} Pi} = \frac{10.000 \sum_{i=1}^{n} Si\left(\frac{LRi}{ECi}\right)}{\sum_{i=1}^{n} Pi}$$

where in Y1, 'Vi' is the volume of water expressed in m^3, used to produce a defined quantity of a 'Pi' product expressed in kg. To calculate the physical WFP to produce a liter of milk, 'Si' considers the harvested area (ha), LR is the required water (m), EC the water conduction efficiency, which should be greater than 0 and less than 1.

In this study, we decided to adopt a conservative approach since we did not include the additional hydric resources derived from the agricultural use of the land; the green WFP. Ridoutt and Pfister (2010) proposed that the green water consumption *per se* does not contribute to a water shortage until it is converted to blue water. The green water does not contribute to the environmental water flows which are required for the health of the freshwater ecosystems while it is not accessible for other human uses. In fact, the green water is only one of many other resources acquired throughout the land occupation; the solar radiation, the wind and the soil are some of the other acquired resources. It must be stated that we did not pretend to minimize the importance of the green water as a vital natural resource.

An international average price per m^3 of water in some countries from the European Union (i.e. Dinamarca, Germany, Holland, Belgium and France among others) reported by Kjellsson and Liu (2012), was considered to quantify the EC of the BWF; the EC fluctuated between 0.83 and 5.63 €/m^3.

Data and statistical analyses

Linear trends across the time of CH_4 emissions, the EC of emissions and the EV of milk production were estimated as the linear regressions of these traits on year, fixing the year 1995 as the intercept, using the REG procedure of SAS software (version 9.4.; SAS Institute Inc., Cary, NC, USA). Minitab (Minitab Inc., State College, PA, USA) and Mathworks Inc. (Natick, MA, USA) programs were used for editing, data management and calculations.

Results

Dairy cow population and milk production

Cow inventory and total milk production is shown in Table 1. While the number of dairy cows producing milk increased by 54%, the total milk produced augmented by 87%, generating a cow productivity increase by 21%.

Greenhouse gas emission quantification

The analysis of methane emissions during the period considered in this study showed a growing trend with a total

Table 1 *Milk production, methane (CH4) and nitrous oxide (N_2O) emissions, and blue water footprint (BWFP; million m^3) generated by the dairy cattle intensive production system in the Comarca Lagunera, Mexico, across years (1995–2016)*

			CH_4 emissions (Gg)			N_2O emissions (Gg)			
Year	Inventory (heads)	Milk produced (million liters)	Enteric fermentation	Manure	Total emission	N_2O-N	N_2O	Equivalence of CO_2	BWFP (million m^3)
1995	319 305	1056	37.68	24.27	61.95	8.27	13.00	3846.73	1613
2000	415 556	1628	49.04	31.58	80.62	10.76	16.91	5006.29	2486
2005	438 476	1995	51.74	33.32	85.06	11.36	17.85	5282.41	3047
2010	420 846	2092	49.66	31.98	81.64	10.90	17.13	5070.02	3196
2015	490 086	2412	57.83	37.25	95.08	12.69	19.95	5904.16	3569
2016	493 144	2386	58.19	37.48	95.67	12.77	20.07	5941.00	3640

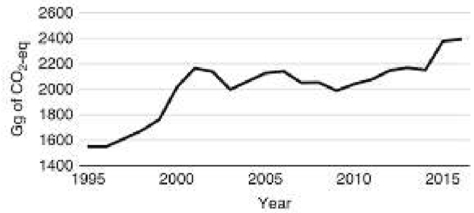

Figure 1 Evolution of the total methane (CH4) emissions (Gg of $CO_{2\text{-eq}}$) generated by the dairy cattle intensive production system in the Comarca Lagunera, Mexico, across years (1995–2016).

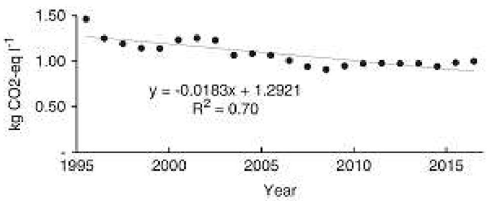

Figure 2 Total methane (CH4) emissions ($CO_{2\text{-eq}}$ per liter of milk) generated by the dairy cattle intensive production system in the Comarca Lagunera, Mexico, across years (1995–2015).

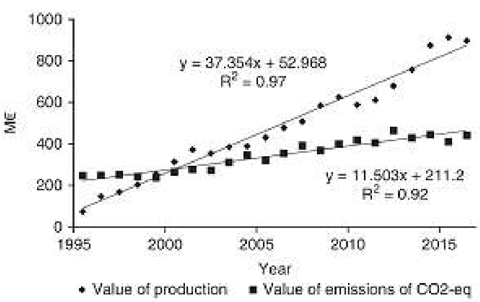

Figure 3 Comparative analysis between the economic value of milk production and the economic cost of the $CO_{2\text{-eq}}$ emissions generated by the dairy cattle intensive production system in the Comarca Lagunera, Mexico, across years (1995–2016).

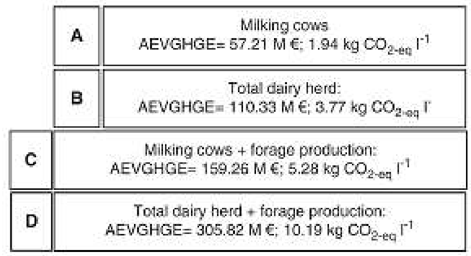

Figure 4 Average economic value of the greenhouse gas emissions (AEVGHE) and greenhouse gas emissions (kg $CO_{2\text{-eq}}$) per liter of milk generated by A: milking cows, B: total dairy herd, C: milking cows + forage production and D: total dairy herd + forage production by the dairy cattle intensive production system in the Comarca Lagunera, Mexico (1995–2016). Annual average value of the dairy cow production = 525.37 million of euros. AEVGHE is the economic value of the greenhouse gas emissions considering an estimated price of 15.75 euros per Ton $CO_{2\text{-eq}}$, as proposed by Environmental Finance (2011) and Thompson Reuters (2011).

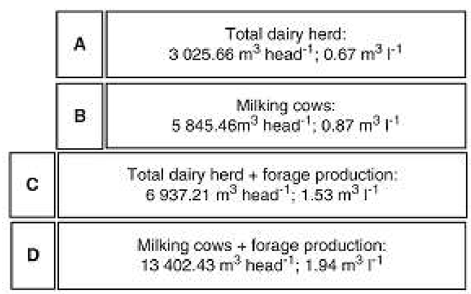

Figure 5 Annual average water use (m^3/head and m^3/l of milk) generated by A: total dairy herd, B: milked cows, C: total dairy herd + forage production and D: milked cows + forage production by the dairy cattle intensive production system in the Comarca Lagunera, Mexico (1995–2016).

increase of 54% from 1995 to 2006 (Table 1). A very rapid rise occurred from 1995 to 2000, then a small decline in 2002, with no significant changes up to 2010, and then another increase (Figure 1).

During the analyzed period, the amount of $CO_{2\text{-eq}}$ emissions generated by the production of forage increased from 8.18 tons of $CO_{2\text{-eq}}$ in 1995 to 17.29 tons of $CO_{2\text{-eq}}$ in 2016, due mainly to an increased use of nitrogenous fertilizers. The main forages produced were corn (51%), sorghum (30%) and oats (15%).

The CH_4 emissions reported as $CO_{2\text{-eq}}$ per liter of milk showed a negative trend from 1995 to 2016 with small up and downs during intermediate years (Figure 2). The total decrease from 1995 to 2016 was 46% with an annual decrease of 0.0183 kg of $CO_{2\text{-eq}}$ per liter of milk ($R^2 = 0.70$).

The N_2O emissions are presented in gigagrams of $CO_{2\text{-eq}}$, and are directly proportional to the CH_4 emissions, and followed the same trend across time; the largest N_2O increase (14%) was observed in 1999–2000 (Table 1).

The trend of both the EV of milk produced as well as the environmental cost of these emissions are presented in Figure 3. From 1995 to 2016 the EV of milk produced increased by €37 354 million per year, whereas the environmental cost of $CO_{2\text{-eq}}$ emissions increased by €11 503 million per year.

Figure 4 shows the total environmental cost of GHGE and the GHGE per liter of milk considering only milking cows or the total dairy herd and accounting for forage production. The total environmental cost of GHGE by the milking cows was €57.21 million with 1.94 kg of $CO^2_{\text{-eq}}$ per liter of milk. These numbers increased to €305.82 million and 10.19 kg of $CO^2_{\text{-eq}}$ per liter of milk, respectively, when the total herd is considered and forage production is accounted for in the calculations.

Blue water footprint quantification

Growth in both the dairy cattle inventory and the BWF in the Comarca Lagunera (1995–2016) is shown in Table 1. The volumetric BWF of the DCPS in the Comarca Lagunera was estimated to be 1613 million m^3 in the year 1995 with an

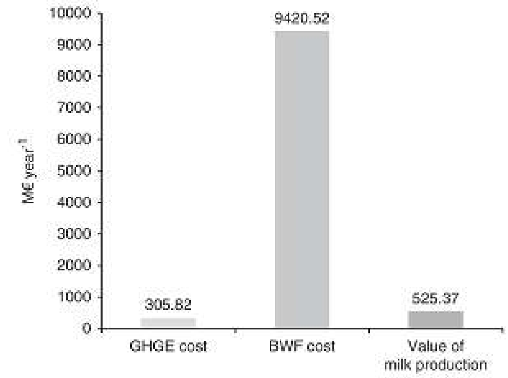

Figure 6 Annual economic cost of greenhouse gas emissions (GHGE) and Blue Water Footprint (BWF) and the value of milk production (M€ year^{-1}) by the dairy cattle intensive production system in the Comarca Lagunera, Mexico (1995 – 2016).

increase of 125% in 2016, whereas the cow inventory increased by 54%.

Figure 5 shows the annual BWF used per cow and per liter of milk under four situations. A: total dairy herd, B: milking cows alone, C: total dairy herd + forage production and D: milking cows + forage production, during the period considered in this study (1995–2016). A total of 3025 m^3 of water per year was required per milking cow with a water use of 0.67 m^3/l of milk. When water is accounted for the production of forages and calculations were performed for the total dairy herd, the amount of annual water use was estimated at 6 937 m^3/head and 1.53 m^3/l of milk.

Figure 6 shows the comparison between the average annual environmental costs of the GHGE and BWF compared with the annual average value of milk production. The EV of milk production represented only 5.6% of the environmental cost of BWF and only 4.4% of total environmental costs. The environmental cost of GHGE represent 58.2% of the EV of milk production.

Discussion

The main objective of this study was to contrast the EV of milk production against the EC of the GHGE and WFP related to the DCPS in the Comarca Lagunera, Mexico. Our results demonstrate that the EV of milk production from the DCPS increased to a higher rate than the EC of GHGE (Figure 3). The main factor explaining the differential rates is an increase in the productivity of milk per cow, which is reflected in a negative trend in methane emissions per liter of milk (Figure 2). Our results also demonstrate that the EV of milk production only represents 5.6% of the EC of BWF (Figure 6). All together, these main results highlight the substantial environmental costs of the DCPS, especially in an agro-ecological dryland context, as in the Comarca Lagunera.

From these results, it is evident the enormous challenges that the dairy cattle sector of the Comarca Lagunera faces to produce milk under a more sustainable way considering the high cost of GHGE and BWF. Mexico, as a country, does not produce enough milk to match the milk's demand and more than 30% of the total milk consumed was imported (SIAP, 2017). This deficit could increase in the coming years as the human population is also growing (Gerber *et al.*, 2013). New policies to increase milk production have to be carefully planned to mitigate the high BWF and GHGE, with concomitant increases not only in feed conversion efficiency but also cow's productivity. These proposed policies need also to consider the changes in the population's consume pattern and the climate changes linked to a dramatic and intense degradation of the ecosystems, which compromise the existence of a DCPS in an agro-ecological region of Mexico where water will have a priority use for human needs (Kumar *et al.*, 2011; Meza-Herrera *et al.*, 2015 and 2016).

Greenhouse gas emissions

The estimated methane production from the enteric fermentation and manure production and management was 532 g/cow per day, which is greater than the range from 282 to 321 g/cow per day in Swedish Holsteins reported by Patel *et al.* (2011). Such difference may arise because of dissimilarities from the production systems, suggesting a more intensified system in Sweden when considering milk production per cow per year; 5795 l in the Comarca Lagunera *v.* 10 494 l in Sweden.

The CH_4 emissions per liter of milk decreased from 1.47 kg $CO_{2\text{-eq}}$ in 1995 to 0.91 kg $CO_{2\text{-eq}}$ in 2016, showing that dairy cattle from the Comarca Lagunera have been efficient in transforming feed into milk with less loss of energy as methane. The average value during the period considered in this study was 1.10 kg $CO_{2\text{-eq}}$ per liter of milk, which is similar to the value reported for North America dairy cattle (1.05 kg $CO_{2\text{-eq}}$ per liter of milk), less than that reported for Latin America and the Caribbean (2.10 kg $CO_{2\text{-eq}}$ per liter of milk) and at the world level (1.49 $CO_{2\text{-eq}}$ per liter of milk), although greater than that reported for European dairy cattle (0.72 kg $CO_{2\text{-eq}}$ per liter of milk) (Gerber *et al.*, 2013). Annual fluctuations in the GHGE (Figure 1) and BWF (Table 1) are related to changes in the dairy herd inventory and feed inputs such as grains, forages and concentrates used in these calculations.

The water footprint

The relationship between livestock production and water consumption has not received much attention as other issues associated to the relationship between livestock and environment (Herrero *et al.*, 2009). Unfortunately, in most parts of the world, water is considered a free or low-cost resource, a situation that needs to be reassessed in order to protect this crucial ecosystem service (Herrero *et al.*, 2009). At the world level, freshwater resources are quite limited, representing only 2.5% of all water resources (Tiu and Cruz, 2017). Besides, and as previously shown, groundwater is of paramount importance for almost 3 billion people which depend on this resource for drinking, with an increasing number of regions depicting a continuous groundwater deficit (Thornton, 2010). Certainly, while at the beginning of this century 38% of the world population lived in water-stressed basins, it is projected that by 2025 such proportion will rise up to 64% (Rosegrant *et al.*, 2009). Moreover, according to de Fraiture *et al.* (2007) the water use for livestock is around 2180 km^3/year. Unquestionably, this is a sensitive and quite significant issue, particularly when considering a DCPS located in an arid region as that observed in the Comarca Lagunera. The annual BWF generated by the DCPS in the Comarca Lagunera increased from 1613 million m^3 in 1995 to 3640 million m^3 in 2016. This significant increase is directly related to the overexploitation of the groundwater used for forage production. In fact, according to our projections, the DCPS in the Comarca Lagunera contributed to the shortage of fresh water of 2811.66 million m^3 across the analyzed period.

The BWF in the Comarca Lagunera incurred in an annual average EC of €9420.52 million, which was significantly greater than the annual EV of milk production generated by the DCPS. This very high environmental cost of BWF was comprised of €1715.06 million (18%) originated from the milking cows, and €7705.46 million (82%) originated from forage production. Quantification of BWF per milking cow considered 5845 m^3/year, but, once the BWF used for forage production was added, this figure increased up to 13 402 m^3/year. The amount of water required for forage production is more than 100% of the water required by the cows.

When quantifying both the GHGE and the BWF it is evident that the highest environmental impact of the DCPS arises from the BWF, which surpasses in a highly substantial fashion to the EV of the milk produced by the DCPS. These results are economically and environmentally relevant if we consider that the DCPS is located within an arid land and hot climate agro-ecosystem, where water availability is quite limited. It is of high importance the search for mitigation strategies in order to reduce the environmental impacts generated by the dairy industry in the Comarca Lagunera. A viable, long-term option could be the reconversion to other environmentally friendly economic activities, such as goat, sheep, pig or poultry production or vegetable production (tomato, asparagus, lettuce, etc.) using hydroponic and high technology in indoor vertical farms (Daniels, 2018).

A medium-term option is to promote the stratification of the DCPS moving the more water-demanding animal stratum of the DCPS to better suited agro-ecological regions from a water availability stand point. Nowadays, some amounts of maize silage and alfalfa hay are produced in other regions of Mexico, where water is less limited, and then transported to the Comarca Lagunera's DCSP. Another example is the raising of replacement animals in other regions of the Mexico where these animals can be developed under grazing conditions. Nonetheless, the carbon footprint generated by transportation of either forage or animals, must be seriously evaluated.

Some potential strategies to mitigate the carbon footprint of the dairy cow production system

The proposed interventions to reduce the environmental impact of livestock production must be based on technologies and practices which would help to improve the efficiency at the herd level. There is a growing claim to produce more livestock commodities per unit of methane as well as per liter of water. This option includes the use of better quality foods balanced in such a way that help to reduce the GHGE at both enteric level and at manure management level (Herrero *et al.*, 2009; Gerber *et al.*, 2013; Moate *et al.*, 2016). Manure management practices must assure both recuperation and recycling of nutrients and energy, coupled to improvements in the energy use efficiency along the supplement chain in order to better contribute to the mitigation efforts (Gerber *et al.*, 2013).

Some promising technologies to improve forages and food additives include bioactive compounds, fat, ionophores/antibiotics, propionate boosters, arqueobacteria inhibitors, nitrates and sulfate supplements along with the development of vaccines and genetic selection methods. All of these have a great potential to reduce GHGE and must therefore be developed as viable options as short-term mitigation strategies (Herrero *et al.*, 2009; Smith *et al.*, 2014; Gerber *et al.*, 2013; Moate *et al.*, 2016).

Improved animal genotypes with increased productive efficiency generating low GHGE per unit of product, or those with a better potential to decrease enteric fermentation emissions must also be evaluated. Microbial technologies to develop arqueas vaccines, methanotrophic microorganisms, rumen defaunation, bacteriophages and the use of probiotics to improve reproductive efficiency are all middle-term options to scale-up mitigation schemes (Smith *et al.*, 2014). Genomic selection aligned to direct measurements of methane emissions as well as food conversion efficiency would promote reductions regarding the intensity of methane emissions (Herrero *et al.*, 2009; Moate *et al.*, 2016). In addition, in order to reduce the N_2O emissions, Smith *et al.* (2014) proposed diet manipulation to decrease fecal N, diet nitrification inhibitors, urease inhibitors, best selection of fertilizers as well as to use better practices when managing the manure incorporated into soils. Up to 30% reductions from manure emissions can be achieved throughout existing manure management technologies generated in Europe (Oenema *et al.*, 2007). In addition, policy makers and professionals involved in the agro-livestock management sector must be able to implement different strategies to mitigate the impact upon the ecosystemic services (De Groot *et al.*, 2002). When considering strategies to mitigate the GHGE, bioenergy could be an interesting alternative, however, it is important to consider different issues such as the implementation of practices to enhance sustainability as well as the efficiency of the bioenergy systems (Smith *et al.*, 2014).

Some potential strategies to mitigate the water footprint of the dairy cow production system

We need to accentuate that in the Comarca Lagunera, several parties from both the rural and urban sectors economically depend, either directly or indirectly, from the DCPS. Rather than propose radical actions to reduce or even eliminate this economically important dairy industry, smart alternatives to reduce the environmental impact of this activity must be proposed.

Since the DCPS in the Comarca Lagunera is performed under extremely arid conditions, with an annual rainfall <300 mm, the search of technological protocols and regulatory policies to promote a rational use of water must be considered. As the greatest impact of the DCPS arises from the animal food production and management, it seems plausible, as a short-term strategy, to stimulate the stratification of the DCPS. As previously mentioned, this could be done by promoting the production of forages and grains in a different geographical region better suited to sustain such production without compromise the hydrological balance of a defined region. In addition, it is of particular importance to promote the use of more technified and efficient irrigation systems in the agricultural area of the Comarca Lagunera. Besides, the stratification scheme of animal production must be considered to be implemented in the animal management of the DCPS, so that those non-productive animals could be raised in a different geographical region and could promote their growth and development under a less vulnerable production system. Of paramount importance will be curbing the environmental deterioration of the Sierra of Durango by proposing a healthy, efficient and sensible management of the upper basin of the Nazas River, which aside to the groundwater as well as the blue water, are the main hydrological sources for the agricultural activities in the Comarca Lagunera. Such strategy should privilege management practices to promote the arrival of an increased volume of water to the lower river basin located in the Comarca Lagunera. In line with this idea, the promotion of payments for environmental services to the settlers of the higher basin not only to stop forest deterioration but also to support its conservation and enhance water recollection and carbon capture, must be seriously considered.

Unquestionably, such potential mitigation schemes would be only viable with the involvement and commitment of the different entities implied in this complex production system, especially the dairy farmers themselves. Certainly, both methodologies and logistics must be planned carefully in order to achieve these goals to mitigate the impacts of the animal industry on both the environment and natural resources. Alternatively, the use of other dairy genotypes or crosses such as Jersey or Brown Swiss, because their reduced body size, are quite efficient regarding both energy and water utilization with reasonably favorable results for the dairy industry, could be also considered. Despite a potential reduction in the milk produced volume, the use of these genotypes can compensate for any losses using this strategy because of the increased total solid milk content, especially fat and protein content.

To conclude, the environmental impact of the DCPS of the Comarca Lagunera was economically quantified during the period from 1995 to 2016. When compared with the EV of milk production, it can be observed a null profitability since the EV of milk production represented only 4.4% of environmental costs. Certainly, the dairy cattle industry is responsible of this significant anthropogenic environmental impact in the Comarca Lagunera. The greatest environmental and EC is generated because of the WFP of the DCPS, and water is an extremely limited and scarce natural resource in this hot-arid region with an awfully water-stressed basin. A very strict policy to mitigate this impact could be the establishment of a differential payment or taxation scheme. This could be done by considering both the amount of water used as well as the quantity of GHGE, based on international prices. The last is not proposed as a monetary-collecting strategy but to promote a more efficient and rational production process while a reduction of the anthropogenic environmental impact. Future studies are required to quantify the societal and economic benefit of the dairy cattle industry in the Comarca Lagunera while testing different mitigation strategies.

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Declaration of interests

None.

Ethics statement

In order to conduct this study, both existing and generated databases were used, therefore, no Animal Care and Use Committee approval was required.

Software and data repository resources

None of the data or models were deposited in an official repository.

References

Acevedo-Peralta AI, Leos-Rodríguez JA, Figueroa-Viramontes U and Romo-Lozano JL 2017. Environmental policy: use and manure management in Comarca Lagunera. Acta Universitaria 27, 3–12.

Averyt K, Meldrum J, Caldwell P, Sun G, McNulty S, Huber-Lee A and Madden N 2013. Sectoral contributions to surface water stress in the coterminous United States. Environmental Research Letters 8, 035046, 9pp.

Capper JL, Cady RA and Bauman DE 2009. The environmental impact of dairy production: 1944 compared with 2007. Journal of Animal Science 87, 2160–2167.

Cardoso LA 2012. Environmental and economic impacts of livestock productivity increase in sub-Saharan Africa. Tropical Animal Health and Production 44, 1879–1884.

Chapagain AK and Hoekstra AY 2004. Water footprints of nations. Value of Water Research Report Series No. 16. UNESCO-IHE, Delft, The Netherlands. Retrieved on 15 August 2017, from http://www.waterfootprint.org/Reports/Report16Vol1.pdf.

Daniels J 2018. Giant indoor vertical farm backed by Chinese firm launching just east of Las Vegas Strip, CNBC. Retrieved on 18 July 2018 from https://www.cnbc.com/2018/07/17/las-vegas-indoor-vertical-farm-set-to-launch-deliveries-next-week.html.

De Fraiture C, Wichelns D, Rockstrom J and Kemp-Benedict E 2007. Looking ahead to 2050: scenarios of alternative investment approaches. In Water for food, water for life: a comprehensive assessment of water management in agriculture (ed. D Molden), pp. 91–145. International Water Management Institute, London, UK and Sterling, VA, USA.

De Groot RS, Wilson MA and Boumans RMJ 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics 41, 393–408.

Environmental Finance 2011. Carbon price. Retrieved on 10 November 2012 from http://www.environmental-finance.com/news/view/1970.

Figueroa-Viramontes U, Delgado JA, Cueto-Wong JA, Núñez-Hernández G, Reta-Sánchez DG and Barbarick KA 2011. A new Nitrogen Index to evaluate nitrogen losses in intensive forage systems in Mexico. Agriculture, Ecosystems & Environment 142, 352–364.

Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A and Tempio G 2013. Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Gill M, Smith P and Wilkinson JM 2010. Mitigating climate change: the role of domestic livestock. Animal 4, 323–333.

Herva M, Franco A, Carrasco EF and Roca E 2011. Review of corporate environmental indicators. Journal of Cleaner Production 19, 1687–1699.

Herrero M, Thornton PK, Gerber O and Reid RS 2009. Livestock, livelihoods and the environment: understanding the trade-offs. Current Opinion in Environmental Sustainability 1, 111–120.

Hoekstra AY and Mekonnen MM 2012. The water footprint of humanity. Proceedings of the National Academy of Sciences 109, 3232–3237.

Hongmin D, Mangino J, Mcallister TA, Hatfield JL, Johnson DE, Lassey KR, Aparecida de Lima M and Romanosvskaya A 2006. Emissions from livestock and manure management. In 2006-IPCC guidelines for national greenhouse gas inventories (Volume 4 (ed. HS Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe), pp. 10.1–10.87. Institute for Global Environmental Strategies (IGES), Hayama, Japan.

Intergovernmental Panel on Climate Change (IPCC) 2007. Agriculture. In: Climate change 2007: contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change (ed. B Metz, OR Davidson, PR Bosch, R Dave and LA Meyer), pp. 497-540. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Jungbluth T, Hartung E and Brose G 2001. Greenhouse gas emissions from animal houses and manure stores. Nutrient Cycling in Agroecosystems 60, 133–145.

Kjellsson J and Liu S 2012. Transboundary waters. Retrieved on 27 March 2012 from http://docplayer.net/32447281-International-water-pricing.html.

Kumar P, Thiaw I, Yashiro M and Molinero C 2011. Food and ecological security: identifying synergy and trade-offs. UNEP Policy Series: Ecosystem Management 4, 1–12.

Mekonnen MM and Hoekstra AY 2010. The green, blue and grey water footprint of farm animals and animal products volume 1: Main Report. Appendices. Value of Water. Research Report Series No. 48. Retrieved on 15 May 2018 from http://doc.utwente.nl/76912/2/Report-48-WaterFootprint-AnimalProducts-Vol2.pdf.

Mekonnen MM and Hoekstra AY 2012. A global assessment of the water footprint of farm animal products. Ecosystems 15, 401–415.

Meza-Herrera CA, Ramirez-Flores JJ, Lopez-Villalobos N, Garcia-Martinez A, Veliz FG and Lopez-Santiago MA 2015. Unveiling the economic costs of the environmental impact and the water footprint of the Holstein intensive production system in the arid lands of northern Mexico. In CoBo-Congress-Controversies & Consensus in Bovine Health, Industry & Economics, 27–30 August 2015, Berlin, Germany, PL01, p. 68.

Meza-Herrera CA, Ramirez-Flores JJ, Lopez-Villalobos N, Silanikove N, Garcia-Martinez A and Veliz FG 2016. Economic costs of greenhouse gas emissions and water footprint of the intensive milk production system in the arid lands of northern Mexico. In Steps to Sustainable Livestock – International Conference. CABOT Institute, University of Bristol, 12–15 January 2016, Bristol, UK, p. 109.

Moate PJ, Deighton MH, Williams SRO, Pryce JE, Hayes BJ, Jacobs JL, Eckard RJ, Hannah MC and Wales WJ 2016. Reducing the carbon footprint of Australian milk production by mitigation of enteric methane emissions. Animal Production Science 56, 1017–1034.

Montemayor-Trejo JA, Lara-Mireles JL, Woo-Reza JL, Munguía-López J, Rivera-González M and Trucios-Caciano R 2012. Producción de maíz forrajero (Zea mays L.) en tres sistemas de irrigación en la Comarca Lagunera de Coahuila y Durango, México. Agrociencia 46, 267–278.

Mosier A, Kroeze C, Nevison C, Oenema O, Seitzinger S and Van Cleemput O 1998. Closing the global N2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutrient Cycling in Agroecosystems 52, 225–248.

Oenema O, Oudendag D and Velthof GL 2007. Nutrient losses from manure management in the European Union. Livestock Science 112, 261–272.

Patel M, Wredle E, Börjesson G, Danielsson R, Iwaasa AD, Spörndly E and Bertilsson J 2011. Enteric methane emissions from dairy cows fed different proportions of highly digestible grass silage. Acta Agriculturae Scandinavica, Section A-Animal Science 61, 128–136.

Pfister S, Koehler A and Hellweg S 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environmental Science & Technology 43, 4098–4104.

Ridoutt BG and Pfister S 2010. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Global Environmental Change 20, 113–120.

Rios-Flores JL, Torres-Moreno M, Castro-Franco R, Torres-Moreno MA and Ruiz-Torres J 2015. Determinación de la huella hídrica azul en los cultivos forrajeros del DR-017, Comarca Lagunera. México. Revista de la Facultad de Ciencias Agrarias. Universidad Nacional de Cuyo 47, 93–107.

Rosegrant MW, Fernandez M, Sinha A, Alder J, Ahammad H, de Fraiture C, Eickhour B, Fonseca J, Huang J, Koyama O, Omezzine AM, Pingali P, Ramirez R, Ringler C, Robinson S, Thornton P, van Vuuren D and Yana-Shapiro H 2009. Looking into the future for agriculture and AKST. In International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD): agriculture at a crossroads, global report (ed. BD McIntyre, HR Herren, J Wakhungu and RT Watson), pp. 307–376. Island Press, Washington, DC, USA.

Scientific Committee on Problems of the Environment 686 (SCOPE) 2010. Livestock and the Global Carbon Cycle. In: Livestock in a changing landscape: drivers, consequences, and responses, volume 1 (ed. H Steinfeld, HA Mooney, F Schneider and LE Neville) pp. 69-82. Island Press, Washington, DC, USA.

Servicio de Información Agroalimentaria y Pesquera – Agrifood and Fishery Information System (SIAP) 2017. Livestock yearling production book. Retrieved on 15 October 2017 from http://infosiap.siap.gob.mx/repoAvance_siap_gb/pecAvanceEdo.jsp.

Smith P, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, Haberl H, Harper R, House J, Jafari M, Masera O, Mbow C, Ravindranath NH, Rice CW, Robledo-Abad C, Romanovskaya A, Sperling F and Tubiello F 2014. Agriculture, forestry and other land use (AFOLU). In Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (ed. O Edenhofer, R Pichs-Madruga, Y Sokona, E Farahani, S Kadner, K Seyboth, A Adler, I Baum, S Brunner, P Eickemeier, B Kriemann, J Savolainen, S Schlömer, C von Stechow, T Zwickel and JC Minx), pp. 811–922. Cambridge University Press, Cambridge, UK and New York, NY, USA.

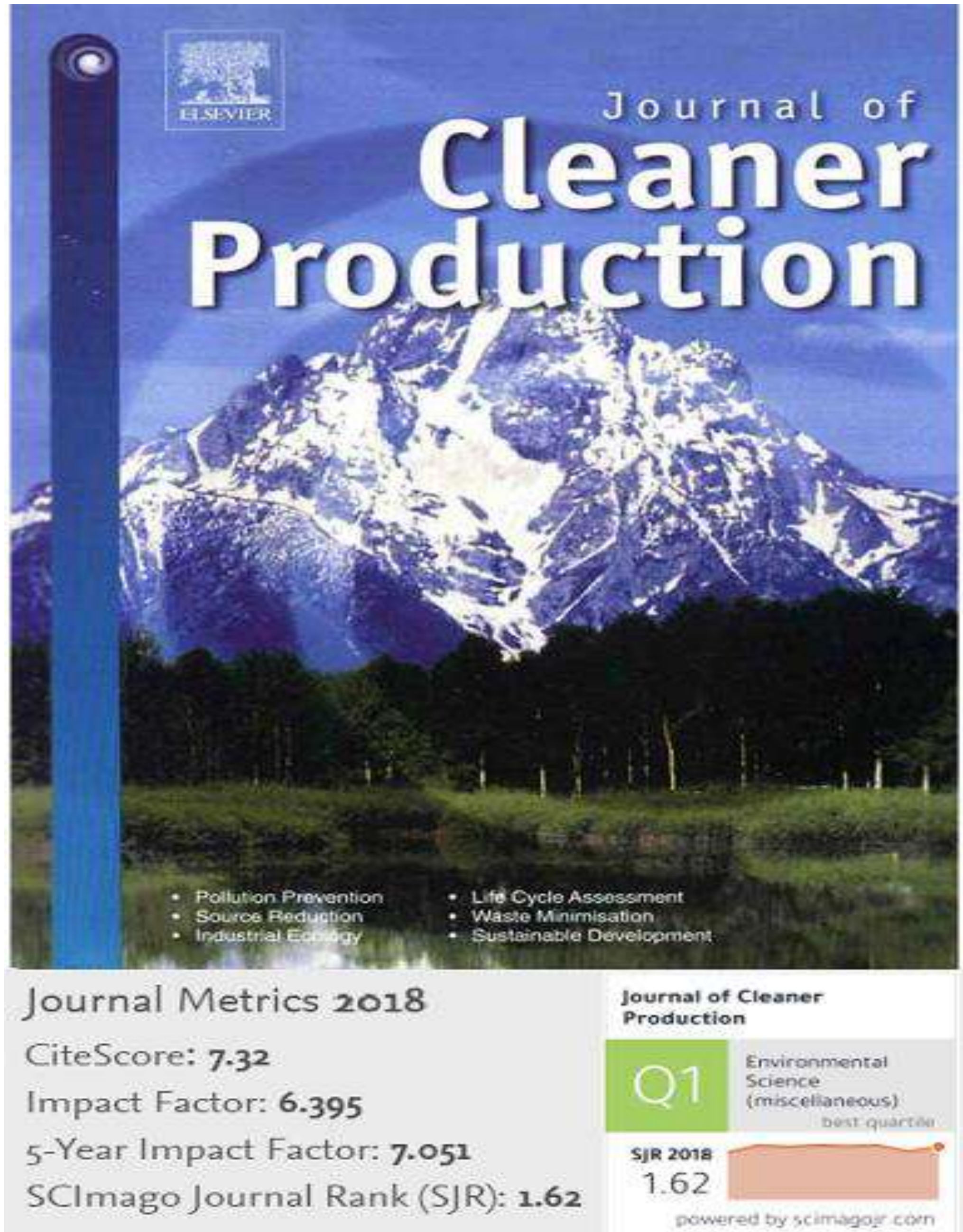
Steinfeld H, Gerber P, Wassenar T, Castel V, Rosales M and De Haan C 2006. Livestock's long shadow environmental issues and options. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Thompson Reuters 2011. Point carbon. Retrieved on 10 November 2011 from http://pointcarbon.com/aboutus/pressroom.

Thornton PK 2010. Livestock production: recent trends, future prospects. Philosophical Transactions of the Royal Society of London B: Biological Sciences 365, 2853–2867.

Tiu BTC and Cruz DE 2017. An MILP model for optimizing water exchanges in eco-industrial parks considering water quality. Resources, Conservation and Recycling 119, 89–96.

5.2. To beef or not to beef: Unveiling the economic environmental impact generated by the intensive beef cattle industry in an arid region



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To beef or not to beef: Unveiling the economic environmental impact generated by the intensive beef cattle industry in an arid region

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A B S T R A C T

The world population is close to 8 billion, which generates not only an increase in the demand and consumption of products of animal origin, but also greater pressure on the use of water resources while an increase in the greenhouse gases emission (GHGE). Therefore, a comprehensive assessment of environmental impacts is required. The aim of this study was to quantify the economic impact of the Water Stress Index (WSI), water footprint (WF) and carbon footprint (CF) during the period 1994–2018, as indicators of the sustainability of the beef cattle fattening industry (BCFS) and compare them with the economic value (EV) generated by that system. The study was conducted in the Comarca Lagunera (CL) located in the arid north of Mexico (24° 22′ and 26° 23′ N, 102° 22′ and 104° 47′ W; 240 mm), which has an important beef industry. The value of each of the variables (WF, CF and EV) was adjusted to 2011 euros, indicating the value in United States Dollars (USD) between parentheses. During the period analyzed, the CL recorded an annual average of 381,319 slaughtered animals, with a production of 53,705 tons of meat. When comparing the average annual EV of the production of M€ 89.52 (MUSD 112.07), with the economic cost (EC) of the WF (ECWF) of € 2344.01 million added to the ECCF of M€ 20.29 (MUSD 25.40), a significant environmental and economic impact of the BCFS is unveiled. In fact, the BCFS' EV represents only 3.79% of the ECWF and ECCF. Regarding the WSI, the CL's BCFS potentially contributed to the world's freshwater scarcity by 699.60 MMm^3 per year (13.16 m^3 of H_2O_{-eq} kg of meat^{-1}). Different mitigation strategies are proposed to be managed by the BCFS with respect to water use and the GHGE. Adoption of such strategies will be essential to achieve not only the sustainability of the BCFS, but also the ecological, economic and social viability of the CL itself.

1. Introduction

The increase in the world population has led to an over-exploitation of global resources, with a positive correlation between the standard of living with respect to the demand for and production of food of animal origin (Cardoso, 2012). Food production requires a comprehensive assessment of environmental impacts. However, the evaluation of agri-food production systems is not simple, as they present interrelationships among the various sources of impact. For example, actions to reduce greenhouse gas emissions (GHGE) may require greater water use, and interventions to achieve water efficiency and water quality objectives may also require greater energy use and, consequently, increase GHGE (Ridoutt et al., 2014).

Because of these complex interrelationships, it is necessary to assess environmental impact using more than one ecological footprint (EF) indicator, and in recent years a number of studies have emerged that suggest a more integral assessment (Bosire et al., 2016; Bragaglio et al., 2018; Cardoso et al., 2016; Gerber et al., 2015; Huerta et al., 2016; Mogensen et al., 2014, 2016;

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Navarrete-Molina et al., 2019; Ogino et al., 2016; Ridoutt et al., 2014). With this approach, the concept of an integral family of footprint indicators was developed (Ridoutt and Pfister, 2013). Therefore, it is critical to quantify the largest number of environmental indicators, especially those related to the production of food for human consumption. Of the foods of animal origin, beef is not only identified as a food product of high nutritional value, but also generates a high environmental impact compared to other products, such as pork and chicken (Weber and Matthews, 2008).

In Latin America and the Caribbean, beef production totaling 1,927 thousand tons was reported in 2017; Mexico ranked third in beef production, below Brazil and Argentina (FAO, 2019). In Mexico, the Comarca Lagunera (CL, literally "region of lagoons") agroecological region located in the semi-arid north ranked tenth in beef production, covering an area of 43,912.96 km^2 with potential for livestock use (rangelands and forests), with beef production being the main livestock activity that is carried out under extensive schemes; the cattle inventory for meat production in rangeland recorded 431,708 head in 2018. The complement of this industry is beef cattle fattening in an intensive scheme (feedlot), highly intensified and of an industrial character. In 2017, the number of beef cattle head slaughtered in the CL amounted to 761,939, representing an increase of 121% over 2015, with production totaling 89,813 tons of meat with a market value of M€ 162.55 (MUSD 203.50) (SIAP, 2019).

In the CL, the intensive beef cattle fattening industry is based on an extremely intense groundwater extraction pattern, generating a deficit in the main aquifer of close to 125 MMm^3 per year (Montemayor-Trejo et al., 2012). High environmental temperatures (>40 °C in summer) and low annual rainfall (240 mm), characteristic of this region, have generated an asymmetric extraction of groundwater, creating an environmental risk that may affect not only the beef cattle fattening industry (BCFS), but also conspires against the ecological, economic and social sustainability of the CL (Acevedo-Peralta et al., 2017; Navarrete-Molina et al., 2019). Based on the above information, it was hypothesized that the environmental and economic impact of the water footprint (WF) and carbon footprint (CF) generated by beef production in the CL is greater than the economic value (EV) that this activity generates in the region. Based on this working hypothesis, it is in our interest to propose measures to mitigate the environmental impact that could be generated by the intensive BCFS in the CL.

2. Materials and methods

2.1. Location, environmental information of the study area, and databases

The CL is located between 102° 22′ and 104° 47 ′ W and 24° 22′and 26° 23′ N, at an elevation of 1,139 m. The development of this study considered the information published in the Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food's Statistical Agricultural Production Yearbooks (SIAP, 2019). According to Hristov et al. (2013), ruminants in extensive schemes are minor emitters of GHGs, presenting a similar trend regarding the consumption of blue water; therefore, in the present study the cattle inventory under extensive schemes was not considered. Additionally, the use of commercial fertilizers for forage production was estimated using the methodology described by Figueroa-Viramontes et al. (2011). To carry out this study, both existing and generated databases were used; consequently, the approval of the Committee for the Care and Use of Experimental Animals was not required. The value of each of the variables (WF, CF and EV) was considered in 2011 euros, indicating the value in United States Dollars (USD) between parentheses.

2.2. Methods for estimating the economic value of beef production (EVBP) and greenhouse gas emissions (GHGE)

The annual EVBP of the CL's BCFS was calculated as the total volume of meat produced per year multiplied by the average payment per kilogram of meat received by the producers. The EV of a kilogram of meat was € 0.46 (USD 0.58) in 1994 and increased to € 3.04 (USD 3.81) in 2018. Besides, factors and indices proposed by the Intergovernmental Panel on Climate Change (IPCC) in 2016 (Hongmin et al., 2006) were used to estimate GHGE. The length of time for fattening in a feedstock, the number of animals slaughtered, the level of production, as well as the type, consumption and digestibility of the diet were considered. The global warming potential values proposed by the IPCC were used. These equivalences correspond to: 1 unit of methane (CH_4) = 25 equivalent units of CO_2 ($CO_{2\text{-eq}}$) and 1 unit of nitrous oxide (N_2O) = 296 of $CO_{2\text{-eq}}$. The economic cost of GHGs considered an international carbon emission price of 15.75 € t^{-1} of $CO_{2\text{-eq}}$ (USD 19.72) (Environmental Finance, 2011; Thompson Reuters, 2011). According to the IPCC in 2016 (Hongmin et al., 2006), the quantification of GHGs (CH_4 and N_2O) in the agricultural sector includes the categories of livestock and agriculture since beef production in CL is based on an intensive feedlot production system.

2.2.1. Beef cattle subcategory

CH_4 emissions from enteric fermentation. The volume of these emissions depends on the physiological stage, weight and age of the animals. As mentioned above, only the days of the feedlot fattening period and the number of animals slaughtered were considered. According to the equation proposed by Hongmin et al. (2006), these emissions are calculated annually, so it was multiplied by the fraction (0.34) that represents the days in fattening expressed in years:

$$Em_{EFECH4} = \frac{LPOP \times EF}{10^6\ kg \cdot Gg^{-1}} \text{ X } 0.34$$

where:

Em_{EFECH4} = Methane emissions by enteric fermentation, Gg CH_4 $year^{-1}$.
LPOP = Number of head of cattle slaughtered.
EF = Emission factor for the defined livestock population, kg CH_4 $head^{-1}$ $year^{-1}$.

In this estimate, the emission factor (EF) considered was 53 kg CH_4 $head^{-1}$ $year^{-1}$, corresponding to the category of other highly productive cattle in the North American region, which includes steers for fast-growing meat, finished in the feedlot and fed a grain-based diet (Hongmin et al., 2006).

CH_4 emissions from manure management. The Tier 1 methodology proposed by Hongmin et al. (2006) was applied:

$$CH_4Em_{mm} = \frac{EF * LPOP}{10^6\ kg \cdot Gg^{-1}} \text{ X } 0.34$$

where:

CH_4Em_{mm} = CH_4 emissions from manure management, Gg CH_4 $year^{-1}$.

The other components of the equation were previously described. The EF used was 2 kg $head^{-1}$ $year^{-1}$, which corresponds to warm climates in the North American region with temperature averages above 25 °C. Under this production scheme, cattle manure is managed as solids and deposited on agricultural lands.

N_2O emissions from manure management. The production of N_2O

generated during manure storage, treatment and handling was estimated. These emissions include both feces and urine produced by cattle under intensive conditions, and were calculated according to the following equation proposed by Hongmin et al. (2006):

$$(N_2O - N)_{(mm)} = \sum_{(s)} \left\{ \left[\sum N * Nex * MS_{(S)} \right] * EF_{3(S)} \right\}$$

where:

$(N_2O{-}N)_{(mm)} = N_2O$ emissions from manure management, kg N_2O - N $year^{-1}$.
N = Number of head of slaughtered cattle.
Nex = Annual average N excretion per head of cattle, kg N $animal^{-1}$ $year^{-1}$.
$MS_{(S)}$ = Fraction of total annual nitrogen excretion for beef cattle managed in the manure management system S.
$EF_{3(S)}$ = Emission factor for N_2O from manure management system S, kg $N_2O - N$ kg N^{-1} in manure management system S.
S = Manure management system.

The conversion of $(N_2O$ - $N)_{(mm)}$ emissions to $N_2O_{(mm)}$ emissions was done considering the equation proposed by Hongmin et al. (2006):

$$N_2O_{(mm)} = (N_2O - N)_{(mm)} \text{ X } \frac{44}{28} \text{ X } 0.34$$

2.2.2. Agriculture subcategory

In this subcategory, direct N_2O emissions from agricultural areas used for forage production were estimated. Nitrogen inputs such as synthetic and organic fertilizers in animal manure were considered, as well as the incorporation of crop residues in soils (F_{CR}). The equation proposed by Hongmin et al. (2006) to estimate N_2O emissions from manure management was used:

$$N_2O_{Direct} - N = [(F_{SN} + F_{AM} + F_{CR}) \times EF]$$

where:

N_2O_{Direct} - N = N_2O emission in nitrogen units.
F_{SN} = Annual amount of nitrogen in synthetic fertilizers applied to soils, adjusted to account for the volume volatilized as NH_3 and NO_x.
F_{AM} = Annual amount of nitrogen in animal manure intentionally applied to soils, adjusted to account for volume volatilized as NH_3 and NO_x.
F_{CR} = Amount of nitrogen in crop residues that are reintegrated annually into soils.
EF = Emission factor for N inputs, kg N_2O - N kg input N^{-1}.

The conversion of $(N_2O$ - $N)_{Direct}$ emissions to N_2O $_{Direct}$ emissions was done considering the equation proposed by Hongmin et al. (2006) previously indicated. In order to estimate the amount of nitrogen fertilizer used in the production of forage for feeding beef cattle in the CL, the level of nitrogen extracted from soils by different forage crops (corn and oats) was considered, as suggested by Figueroa-Viramontes et al. (2011).

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

The basis for calculating the BWF per kilogram of meat was the mathematical methodology proposed by Mekonnen and Hoekstra (2010):

$$WF[a,c,s] = WF_{feed}[a,c,s] + WF_{drink}[a,c,s] + WF_{serv}[a,c,s]$$

Where $WF_{feed}[a,c,s]$, $WF_{drink}[a,c,s]$ and $WF_{serv}[a,c,s]$ represent the WF of an animal for animal category "a" in country "c" in production system "s" related to feed, drinking water and service water consumption, respectively. That is, this quantification is related to the water contained in feed "a" consumed, plus the drinking water "c" consumed, plus the water "s" related to the services (Mekonnen and Hoekstra, 2010).

$$WF_{feed}[a,c,s] = \frac{\sum_{p=1}^{n} \left(Feed[a,c,s,p] \text{ X } WF^*_{prod}[p] \right) + WF_{mixing}[a,c,s]}{Pop^*[a,c,s]}$$

Feed[a,c,s,p] represents the annual amount of feed ingredient "p" consumed by an animal, by animal category "a" in country "c" and production system "s" (t $year^{-1}$), $WF^*_{prod}[p]$ represents the WF of feed ingredient "p" consumed (m^3 t^{-1}), $WF_{mixing}[a,c,s]$ is the volume of water consumed for mixing the feed consumed for animal category "a" in country "c" in production system "s" (m^3 $year^{-1}$ $animal^{-1}$) and Pop*[a,c,s] is the number of slaughtered animals per year for animal category "a" in country "c" and production system "s".

Thereafter, it was then calculated as a stress-weighted BWF value, which results from multiplying the BWF value by a water stress index (WSI) as suggested by Ridoutt and Pfister (2010). These authors emphasize that the main concern related to water consumption in agricultural production is the possibility of contributing to water scarcity and limiting the availability of freshwater for human use and the environment. The WSI is used to assess the impact related to freshwater consumption and is considered a midpoint indicator that assesses water deprivation and applies only to blue water (Pfister et al., 2009). This index is derived from the WTA ratio, defined as the ratio between total annual freshwater withdrawals for human uses in a specific region and the renewable water supply available annually in that region (Frischknecht et al., 2006). WSI values range from 0.01 to 1 and are derived using the following exponential function:

$$WSI = \frac{1}{1 + e^{-6.4 \text{ X } WTA^*} \left(\frac{1}{0.1} - 1 \right)}$$

Where WTA* is a modified WTA resulting from the division of the total amount of water withdrawn for human uses, including agriculture and industrial use, and the total annual recharge of the region. As mentioned, for the calculation, the WSI value applies only to the BWF, so for this purpose we used the methodology of Ríos-Flores et al. (2015), who state that the blue physical water footprint in an aggregate of agricultural crops (Y_1, expressed in m^3 of water used in production per kg of agricultural product) is obtained through the equation:

$$Y_i = \frac{\sum_{i=1}^{n} Vi}{\sum_{i=1}^{n} Pi} = \frac{10,000 \sum_{i=1}^{n} Si \left(\frac{IDi}{HCi} \right)}{\sum_{i=1}^{n} Pi}$$

where:

Y_1, "*Vi*" is the volume of water in m^3 used to produce quantity "*Pi*" of product in kg, "*Si*" is the harvested area in ha, ID is the irrigation depth in m, HC is the hydraulic conduction efficiency, which is greater than zero and less than unity.

In this study, a conservative approach has been adopted and additional water resources derived from agricultural land use (green water footprint) have not been included. This is because Ridoutt and Pfister (2010) have proposed that green water consumption *per se* does not contribute to water scarcity, until it

Table 1
Slaughtered animals, meat production, methane (CH_4) and nitrous oxide (N_2O) emissions, and blue water footprint (BWF; MMm^3) generated by the cattle fattening production system in the Comarca Lagunera, Mexico, over the years (1994–2018).

Year	Slaughtered animals (head)	Meat production (t)	CH_4 emissions (Gg)			N_2O emissions (Gg)			BWF (MMm^3)
			E. F	M. M.	Total emission in $CO_{2\text{-eq}}$	N_2O–N	N_2O	Total emission in $CO_{2\text{-eq}}$	
1994	313,206	33,571	5.6	0.2	146.42	1.32	2.08	614.21	592.40
1998	200,283	40,552	3.6	0.1	93.63	0.84	1.33	392.76	378.82
2002	399,019	49,489	7.2	0.3	186.54	1.68	2.64	782.49	754.71
2006	394,983	53,459	7.1	0.3	184.66	1.67	2.62	774.58	747.08
2010	328,729	55,498	5.9	0.2	153.68	1.39	2.18	644.65	621.76
2014	377,052	61,724	6.8	0.3	176.27	1.59	2.50	739.42	713.16
2018	547,712	81,256	9.9	0.4	256.01	2.31	3.63	1,074.09	1,035.95

E.F. = Enteric Fermentation & M.M. = Manure Management.

becomes blue water, as green water does not contribute to the environmental flows that are necessary for the health of freshwater ecosystems, nor is it accessible for other human uses. Green water can only be accessed through access to and occupation of land. In fact, green water is only one of many resources acquired through land occupation; access to solar radiation, wind and soil are other acquired resources. This is not to minimize the importance of green water as a vital natural resource. For quantifying the economic costs of the BWF, the international average price per m^3 of water in some European Union countries (Denmark, Germany, the Netherlands, Belgium, and France, among others) reported by Kjellsson and Liu (2012), of 3.5 € m^{-3} (USD 4.38), was considered.

2.4. Statistical analyses

During the period analyzed, linear regressions were estimated for CH_4 emissions, the economic cost of the emissions and the EVBP, setting 1994 as the intercept, using the REG procedure of SAS version 9.4 (SAS Inst., Inc., Cary, North Carolina). The Minitab (Minitab Inc., State College, Pensilvania) and Mathworks Inc. (Natick, Massachusetts) programs were used for data management and calculations.

3. Results

3.1. Slaughtered animals and meat production

The cattle inventory in the CL showed an annual growth trend of 7,381 head during the period analyzed, with the inventory increasing from 121,337 in 1994 to 431,708 in 2018, equivalent to 256%. The number of slaughtered cattle and total beef production are shown in Table 1. The number of animals slaughtered increased by 75% and total meat production rose by 142%. When comparing 2017 vs. 2015, these increases amounted to 121% and 35%, respectively.

3.2. Quantification of the greenhouse gas emissions (GHGs)

Regarding the calculation of methane emissions during the period under consideration, a growing trend was observed with a total increase of 75% from 1994 to 2018 (Table 1). There were fluctuations from 1994 to 2015, with a significant increase from 2015 to 2016 of 117%, mainly due to the increase in the number of head of cattle (Fig. 1). During the period analyzed, the amount of $CO_{2\text{-eq}}$ emissions generated by forage production increased from 297.41 Gg of $CO_{2\text{-eq}}$ in 1994 to 520.09 Gg of $CO_{2\text{-eq}}$ in 2018, mainly due to a greater use of nitrogen fertilizers for the production of forage required to feed the region's meat inventory. The two forage crops produced for bovine fattening were: corn (80%) and oats (20%).

CH_4 emissions reported as $CO_{2\text{-eq}}$ per kilogram of meat showed a negative trend from 1994 to 2018, exhibiting a significant decrease at the beginning of the period, but a significant increase at the end of the period analyzed (2016) (Fig. 2). The total decrease from 1994 to 2018 was 28% with an annual reduction of 0.0372 kg of $CO_{2\text{-eq}}$ per kilogram of meat.

N_2O emissions, in gigagrams of $CO_{2\text{-eq}}$, are directly proportional to CH_4 emissions; the largest increase in N_2O (117%) was observed in 2015–2016 (Table 1). Fig. 3 shows the EVBP and GHG trends. From 1994 to 2018, the EV of meat increased by M€ 7.05 (MUSD 8.83) per year, while the environmental cost of GHGE in terms of $CO_{2\text{-eq}}$ rose by M€ 0.57 (MUSD 0.71) per year. Table 2 shows the environmental cost of the GHGE in M€ and the value of these emissions per head and per kilogram of meat. When considering the production of forage for cattle feed, these variables increase by 28%.

3.3. Quantification of the blue water footprint

The volume of water used for meat production by the BCFS in the CL was 721.23 MMm^3 per year, equivalent to 1,891.42 m^3 per

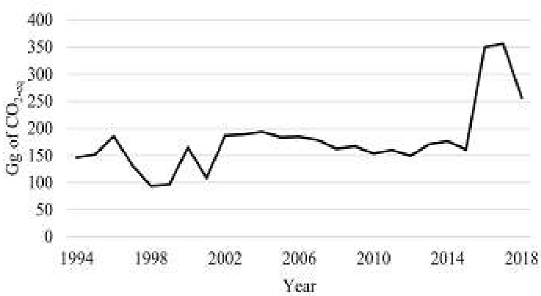

Fig. 1. Evolution of total methane (CH_4) emissions (Gg of $CO_{2\text{-eq}}$) generated by the cattle fattening production system in the Comarca Lagunera, Mexico (1994–2018).

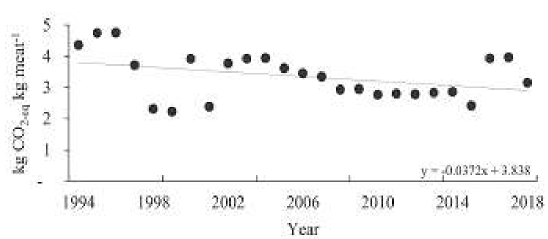

Fig. 2. Total methane (CH_4) emissions (kg $CO_{2\text{-eq}}$ per kilogram of meat) generated by the cattle fattening production system in the Comarca Lagunera, Mexico (1994–2018).

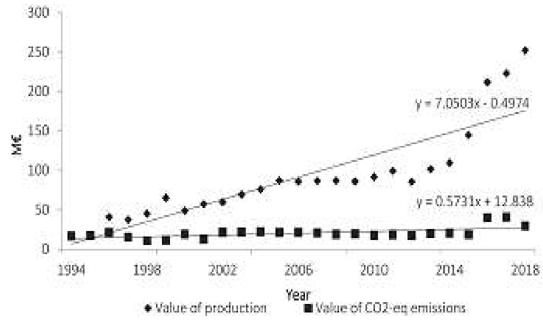

Fig. 3. Comparative analysis between the value of production and the economic cost of GHGs in $CO_{2\text{-eq}}$, generated by the cattle fattening production system in the Comarca Lagunera, Mexico (1994–2018).

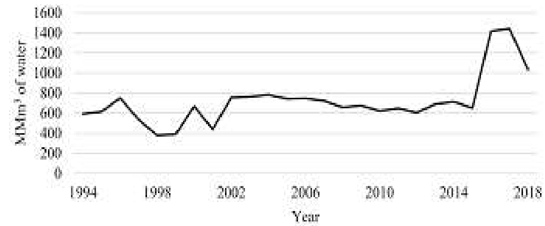

Fig. 4. Evolution of the blue water footprint (MMm^3) generated by the cattle fattening production system in the Comarca Lagunera, Mexico (1994–2018).

head and to 13.57 m^3 per kilogram of meat produced. The evolution of both slaughtered animals and the BWF in the CL (1994–2018) is shown in Table 1. While the number of slaughtered animals increased by 75% during this period, the BWF per kilogram of meat produced decreased by 28% over the years (Fig. 4).

Table 3 shows the BWF per slaughtered bovine with and without forage production, as well as the economic value of this footprint, during the period 1994–2018. When considering the production of forage for cattle feed, these variables increase 51%, that is, the production of forage for cattle fattening in the CL represents little more than half of the water used for meat production in that system. The WSI reported for the CL was 0.97 and falls into the "extreme" category according to the following classification: WSI <0.1 low; 0.1 ≤ WSI <0.5 moderate; 0.5 ≤ WSI <0.9 severe and WSI >0.9 extreme (Pfister et al., 2009; CONAGUA, 2015), generating an average stress-weighted water footprint of 699.60 MMm^3 per year of H_2O-equivalents ($H_2O_{\text{-eq}}$), corresponding to 1,834.67 m^3 of $H_2O_{\text{-eq}}$ per head and finally to 13.16 m^3 of $H_2O_{\text{-eq}}$ per kilogram of meat produced. According to this methodology, the weighted impact of the production of 1 kg of meat by the CL's BCFS potentially contributes to freshwater scarcity equivalent to the consumption of 13,163 L of drinking water by an average global citizen. This impact is mainly due to the irrigation of forage crops. Fig. 5 shows the comparison between the average environmental costs per year of the GHGE and BWF and their comparison with the EVBP. The EV of meat production represented only 3.79% of the total environmental cost. The environmental cost of GHGs represents 22.66% of the EV of meat production in the period analyzed.

4. Discussion

Based on the working hypothesis set out, the main question to be answered in this study was: Was the economic cost of the GHGE and BWF produced by the BCFS in the CL for the study period greater than the economic income generated by this activity? The results show that the BCFS' EVBP increased at a higher rate than the economic cost of the GHGE (Fig. 3). The main factor explaining the discrepancy between these differential rates is an increase in productivity in kilograms of meat per animal, observing a negative trend in emissions of CH_4 kg^{-1} of meat produced (Fig. 2). It was also shown that the EVBP represented only 3.82% of the BWF's economic cost (Fig. 5). These results show a significant impact on the environmental costs of the BCFS, especially in an agro-ecological context of arid lands, such as the CL. Certainly, the quantification of the BCFS's environmental impact is crucial since it directly competes with the human population regarding the use of natural resources while it is contextualized in an arid region with limited vegetation and water resources. Moreover, the rangeland in the CL is mainly composed by bushes which have a limited ability for CO_2 sequestration while the restricted blue water supply is mainly supported by endorheic hydrological basin which, with its actual use, is not able to support the water needs in the region.

The results obtained demonstrate the great challenge faced by the livestock sector in the CL to produce beef in a more sustainable manner in light of the high cost of the GHGE and BWF. Therefore, new policies to increase meat production based on mitigating the high cost of the BWF and GHGE must be carefully planned. They must also consider changes in the population's consumption patterns and climate changes linked to a strong and intense degradation of ecosystems, which compromise the existence of the BCFS in regions of Mexico, where the use of water to cover human needs will be a priority (Kumar et al., 2011; Navarrete-Molina et al., 2019).

4.1. Greenhouse gas emissions

The estimated production of GHGE per kilogram of meat in this

Table 3
Average annual blue water footprint per head (m^3 $head^{-1}$) and per kilogram (m^3 kg $meat^{-1}$) and its economic value (Million € & Million USD) generated by the cattle fattening production system in the Comarca Lagunera, Mexico, over the years (1994–2018).

Forage	Blue water footprint (annual average)		
	m^3 $head^{-1}$	m^3 kg $meat^{-1}$	Economic value (M €) & (MUSD)
With	1,891.42	13.57	2,344.01 & 2,934.48
Without	933.84	6.70	1,157.29 & 1,448.82

Note: An estimated price of 3.5 € m^{-3} (USD 4.38) was considered (Kjellsson and Liu, 2012).

Table 2
Average annual GHGs per head (t $CO_{2\text{-eq}}$ $head^{-1}$) and per kilogram (kg $CO_{2\text{-eq}}$ kg $meat^{-1}$) and its economic cost (Million € & Million USD), generated by the cattle fattening production system in the Comarca Lagunera, Mexico, over the years (1994–2018).

Forage	Greenhouse gas emissions (annual average)		
	t $CO_{2\text{-eq}}$ $head^{-1}$	kg $CO_{2\text{-eq}}$ kg $head^{-1}$	Economic cost (M€) & (MUSD)
With	3.38	23.98	20.29 & 25.40
Without	2.43	17.42	14.59 & 18.27

Note: An estimated price of 15.75 euros per ton $CO_{2\text{-eq}}$ was considered, as proposed by Environmental Finances (2011); Thompson Reuters (2011).

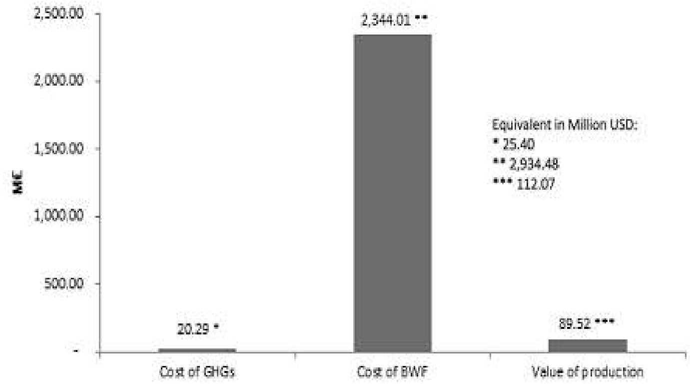

Fig. 5. Average annual economic cost of greenhouse gas (GHG) emissions, the blue water footprint (BWF) and the value of meat production (M€ year^{-1}) generated by the cattle fattening production system in the Comarca Lagunera, Mexico (1994–2018).

study is similar to other results found in various countries and regions of the world (Table 4). These differences may find their origin in different production systems, and suggest that a more intensified system produces a smaller carbon footprint than a more extensive one, as it is generally complemented by breeding and better diets and management practices, which together foster the sustainability of the production process (Buratti et al., 2017). In the same sense, the BCFS's lower GHG values in other regions of the world are indicative of the low efficiency in beef production in the CL, demonstrating the need to implement measures that significantly reduce this ecological footprint.

The CH_4 emissions per kilogram of meat decreased from 4.36 kg $CO_{2\text{-eq}}$ to 3.15 kg $CO_{2\text{-eq}}$ from 1994 to 2018, demonstrating that CL cattle fattening would be more efficient in transforming feed into meat with less energy loss from methane production. The average value of GHGE in the CL during 1994–2018 was 24.24 kg of $CO_{2\text{-eq}}$ kg meat^{-1}, this value being lower than that reported for Asia (27.17 kg of $CO_{2\text{-eq}}$ kg meat^{-1}), Latin America and the Caribbean (28.68 kg of $CO_{2\text{-eq}}$ kg meat^{-1}), Oceania (25.61 kg of $CO_{2\text{-eq}}$ kg meat^{-1}), Africa (32.04 kg of $CO_{2\text{-eq}}$ kg meat^{-1}) and even lower than the one reported for Mexico (25.56 kg of $CO_{2\text{-eq}}$ kg meat^{-1}). However, this value is higher than the reported value for meat production worldwide (19.24 kg of $CO_{2\text{-eq}}$ kg meat^{-1}), in North America (15.57 kg of $CO_{2\text{-eq}}$ kg meat^{-1}) and Europe (14.47 kg of $CO_{2\text{-eq}}$ kg meat^{-1}) (FAO, 2017). The annual fluctuations in the GHGE (Fig. 1) and BWF (Table 1 and Fig. 4) are related to changes in the number of cattle slaughtered and the integration of feed (i.e. grains, forage and concentrates) used in the calculations. Nowadays, there are different methodologies to calculate the use of energy for diverse productive activities such as the Life Cycle Assessment (LCA) and the Data Envelopment Analysis (DEA); under an agricultural context, an excessive energy consumption has a negative and significant impact in the environment. Therefore, both optimization and a sustainable use of energy help to reduce the environmental impact associated to the agriculture subsector (Kouchaki-Penchah et al., 2017). Other studies have also used such LCA and DEA methodologies with quite interesting outcomes (Kaab et al. (2019); Kouchaki-Penchah et al. (2016); Nabavi-Pelesaraei et al. (2014); Qasemi-Kordkheili and Nabavi-Pelesaraei (2014); Sabzevari et al. (2015); among others.

4.2. *The water footprint*

Erroneously, in most parts of the world, water is generally not given a value because it is considered a low-cost resource and, in most cases, a free resource; this vision must be re-analyzed to ensure the availability of water in quantity and quality to warrant the health of the human population and ecosystems (Gerber et al., 2013). Globally, freshwater availability is very limited, accounting for only 2.5% of all water resources on the planet (Tiu and Cruz, 2017). In the same way, groundwater is vital for almost 40% of the world's population, which depends on this resource for drinking, and a significant increase has been observed in the number of regions with a deficit between groundwater withdrawal and recharge (Thornton, 2010). Moreover, groundwater has a key role in water supply, since around 2 to 3 billion people depend on such resource for drinking while in several regions the hydrological balance is diminishing incessantly (Rodell et al., 2009). Certainly, it has been projected that in 2025, 65% of the world's population will live in water-stressed basins (Rosegrant et al., 2002).

According to Mekonnen and Hoekstra (2010), globally, beef cattle make the largest contribution (33%) to the water footprint of farm animals, followed by dairy cattle (19%), pigs (19%) and broilers (11%). Beef cattle requires on average 22 m^3 kg^{-1}, with differences

Table 4
Comparison of the average greenhouse gas (GHG) emissions (kg of $CO_{2\text{-eq}}$ kg meat^{-1}) generated by the cattle fattening production system in the Comarca Lagunera, Mexico, over the years (1994–2018) and other studies.

Source	GHG (kg of $CO_{2\text{-eq}}$ kg meat^{-1})	Country and comment
This study	24.24	Comarca Lagunera, Mexico (includes only the feedlot fattening period)
Weber and Matthews (2008).	22.10	USA (conventional feedlot production)
Nguyen et al. (2010).	16.00–27.30	USA (includes different production systems)
Weiss and Leip (2012).	24.40	Average of 27 European Union countries
Ruviaro et al. (2015).	29.82	Brazil (fattening on native pastures)
Buratti et al. (2017).	15.26	Italy (organic system)
	11.29	Italy (conventional system)
Vitali et al. (2018).	24.46	Italy (organic meat)

between countries and categories depending on the type of cut. Pork uses 3.5 $m^3 kg^{-1}$, chicken 2.3 $m^3 kg^{-1}$, goat 6 $m^3 kg^{-1}$, horse 8 $m^3 kg^{-1}$ and sheep 9 $m^3 kg^{-1}$ (Chapagain and Hoekstra, 2003). This contrasts with Mekonnen and Hoekstra (2010), who indicate requirements for beef cattle of 15,415 l kg^{-1} (as a global average), significantly greater than the water footprint for sheep meat (10,400 l kg^{-1}), pork (6,000 l kg^{-1}), goat meat (5,500 l kg^{-1}) or chicken (4,300 l kg^{-1}). The estimated BWF per kilogram of meat in this study was 1,570 l kg^{-1}, similar to that reported worldwide by Mekonnen and Hoekstra (2010) of 15,415 L kg^{-1} and of 14,219 L kg^{-1} for Mexico. The average annual BWF used by the BCFS in the CL increased from 592.4 MMm^3 to 1,035.9 MMm^3 between 1994 and 2018. This significant increase is directly related to the overexploitation of groundwater used for forage production. In fact, the CL's BCFS contributed to the worldwide scarcity of freshwater during the evaluated period with 699.6 MMm^3 per year, higher than the aquifer recharge of 518.9 MMm^3 (CONAGUA, 2015). The BCFS's BWF in the CL incurred an average annual economic cost of M€ 2,344.01 (MUSD 2934.48), significantly higher than the EVBP average. This high environmental cost of the BWF considered M€ 1,148.56 (MUSD 1,437.89) (49%) caused by the animals and non-forage ingredients of the diet, and M€ 1,195.44 (MUSD 1,496.58) (51%) resulting from forage production. The quantification of the BWF per animal in production was 933.8 m^3 $head^{-1}$, but once the BWF was added for forage production, this figure increased to 1,891.4 m^3 $head^{-1}$. The amount of water required for forage production is equivalent to slightly more than 100% of the water required for the animal component.

When quantifying the EC of both the GHGE and the BWF, it is clear that the BCFS' greatest environmental impact comes from the BWF, substantially exceeding the economic value of meat production. These results are economically and environmentally significant when considering that this livestock activity is carried out in an arid agro-ecosystem, with limited water availability. Considering the increasing trend in the BCFS' environmental impact in the CL, the importance of the search for comprehensive mitigation strategies to reduce the significant environmental damage generated by the BCFS in the CL is evident. A viable long-term option could be to convert to more environmentally friendly economic activities or at least promote stratification in the cattle fattening stages, shifting forage production to more suitable agro-ecological regions in terms of water availability, which would contribute to decreasing the observed trend. If adequate measures are not taken, this unfavorable trend could significantly increase in the CL. In fact, starting in 2016, a private initiative project has been underway that includes the installation of single beef cattle feedlot enterprise with an initial capacity of 300,000 head. This excessive figure would make the CL one of the regions with the highest concentration of cattle in the world, with all meat production destined to a single processing plant with the capacity to process 240,000 tons of meat annually, obtained from the slaughter of 800,000 head of cattle. Unfortunately, this is not an encouraging scenario in a region with a significant water deficit.

4.3. Some potential strategies for mitigating the carbon footprint

Globally, there is increasing pressure to produce more product of animal origin per unit of $CO_{2\text{-eq}}$, as well as per liter of $H_2O_{\text{-eq}}$. These may include the use of better-quality balanced feeds in the diet and reduction of GHGs, both at enteric and manure management levels (Gerber et al., 2013; Moate et al., 2016; Smith et al., 2014). Manure management practices that improve nutrient and energy recovery and recycling, linked to improvements in energy use efficiency along the supplement chain, may contribute to strengthening mitigation efforts (Gerber et al., 2013). In this regard, some promising technologies to improve the digestibility of the feed (forages and concentrates) include: bioactive compounds, fats, ionophores/antibiotics, propionate boosters, inhibitors of archaebacteria, methanotrophs, acetogens, rumen defaunation, bacteriophages and probiotics. Other technologies to consider include improvements in fertility; handling and storage of manure bedding; use of anaerobic digesters and biofilters; nitrate and sulfate supplements, along with the development of vaccines and genetic selection methods, among others. These technologies have great potential to reduce GHGs and should therefore be considered as viable options in mitigation strategies ((Gerber et al., 2013; Moate et al., 2016; Smith et al., 2014). When considering strategies to mitigate GHGE, bioenergy could be an interesting alternative; however, it is important to consider it from different points of view, such as the implementation of practices to improve sustainability, as well as the efficiency of bioenergy systems (Smith et al., 2014). Moreover, an integral technology can be the use of bio-digesters in the BCFS, in that it contributes to decrease the GHG emissions, produces bioenergy and organic fertilizers while it helps to clean the gray water. Nonetheless, special attention should be paid to the biological treatment provided to the microbial population and consequently the C/N ratio, which will help to improve the treatment of residual waters, mitigate wear and enhance the operation of the biodigestor membrane, as demonstrated by Sepehri and Sarrafzadeh (2018).

4.4. Some potential strategies for mitigating the water footprint

We must be aware that beef cattle farming in the CL is the only source of income for many families, either directly or indirectly; this is especially true in rural areas. Therefore, proposals or actions must be measured and intelligent, rather than radical in nature, in order to maintain this important activity. Given that cattle fattening in the CL is carried out in extremely arid conditions (<240 mm per year), policies and technological improvements that promote rational water use must be pursued. In fact, little more than 50% of the impact of the BCFS' WF comes from the production and handling of animal feed, hence the importance of the stratification of the BCFS, as a short-term strategy. This could be done by promoting the production of forages and grains in a different and more suitable geographical region to sustain this production without compromising its hydrological balance. The definition and implementation of appropriate measures and strategies will ultimately depend on agro-ecological, water and social policies that provide a real benefit to the community. These mitigation strategies should prioritize the generation of employment, the rational use of resources and the economic and social benefit of the region. For this reason, the information generated in this study should be useful for decision-making bodies, whose primary objective should be to maintain the overall sustainability of the agro-livestock activity in harmonious balance with other productive, economic, biological and social sectors in the CL (Navarrete-Molina et al., 2019; Ríos-Flores et al., 2018).

5. Conclusions

This is the first study that clearly and forcefully demonstrates with a long-term information base that the environmental and economic impact of the blue water footprint and the emission of greenhouse gases generated by the intensive beef cattle fattening system in the CL is significantly greater than the economic value that this activity generates in the region. Indeed, when contrasting the environmental impact with the economic value of the intensive beef production, the result is zero profitability, since the economic value of beef production only represented 3.79% of the environmental costs; the main environmental and economic cost was the one associated with the water footprint. In this semi-arid region, water is an extremely scarce and limited natural resource, especially when there is an endorheic basin significantly deficient in water, at least under the current water resource use scheme. Undoubtedly, the trends observed in the last 25 years demand an immediate application of measures and policies aimed at mitigating the ecological footprint of this production system. It is therefore fundamental and essential to promote actions that foster an intensive beef cattle fattening system based on a responsibility not only environmental but also social, in order to form a more efficient, rational, and sustainable production process, which at the same time reduces the anthropogenic impact. Ignoring this complex situation jeopardizes the viability and sustainability not only of the beef cattle feedlot system, but also of the CL itself as a productive, economic, biological and social entity.

Declaration of interest

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

Ethics statement

This study did not include the use or management of animals; neither specific international or national guidelines regarding the use and care of animals nor institutional approval from the Internal committee for the use of animal in experimentation and research, were required to develop the study.

Data repository resources

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

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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.2019.05.267.

References

Acevedo-Peralta, A.I., Leos-Rodríguez, J.A., Figueroa-Viramontes, U., Romo-Lozano, J.L., 2017. Environmental policy: use and manure management in Comarca Lagunera. Acta Univ. 27 (4), 3–12 (in Spanish). https://doi.org/10.15174/au.2017.1270.

Bosire, C.K., Krol, M.S., Mekonnen, M.M., Ogutu, J.O., de Leeuw, J., Lannerstad, M., Hoekstra, A.Y., 2016. Meat and milk production scenarios and the associated land footprint in Kenya. Agric. Syst. 145, 64–75. https://doi.org/10.1016/j.agsy.2016.03.003.

Bragaglio, A., Napolitano, F., Pacelli, C., Pirlo, G., Sabia, E., Serrapica, F., Serrapica, M., Braghieri, A., 2018. Environmental impacts of Italian beef production: a comparison between different systems. J. Clean. Prod. 172 (20), 4033–4043. https://doi.org/10.1016/j.jclepro.2017.03.078.

Buratti, C., Fantozzi, F., Barbanera, M., Lascaro, E., Chiorri, M., Cecchini, L., 2017. Carbon footprint of conventional and organic beef production systems: an Italian case study. Sci. Total Environ. 576 (15), 129–137. https://doi.org/10.1016/j.scitotenv.2016.10.075.

Cardoso, A.S., Berndt, A., Leytem, A., Alves, B.J., de Carvalho, I.D.N., de Barros Soares, L.H., Urquiaga, S., Boddey, R.M., 2016. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. Agric. Syst. 143, 86–96. https://doi.org/10.1016/j.agsy.2015.12.007.

Cardoso, L.A., 2012. Environmental and economic impacts of livestock productivity increase in sub-Saharan Africa. Trop. Anim. Health Prod. 44 (8), 1879–1884. https://doi.org/10.1007/s11250-012-0151-z.

Chapagain, A.K., Hoekstra, A.Y., 2003. Virtual Water Flows between Nations in Relation to Trade in Livestock and Livestock Products. Value of Water. Research Report Series No. 48. UNESCO-IHE, Delft, The Netherlands. Available: https://www.researchgate.net/profile/Ashok_Chapagain/publication/228777116_Virtual_Water_Flows_Between_Nations_in_Relation_to_Trade_in_Livestock_and_Livestock_Products/links/542bdf9a 0cf29bbc126ab921.pdf.

Comisión Nacional del Agua - National Water Comission (CONAGUA), 2015. Actualización de la disponibilidad media anual de agua en el acuífero principal – región Lagunera. Published in Diario Oficial de la Federación on April 20, 2015. México, 28 pp. Available: https://www.gob.mx/cms/uploads/attachment/file/102876/DR_0523.pdf. (Accessed 4 February 2018) (in Spanish).

Environmental Finance, 2011. Carbon price. Available: http://www.environmental-finance.com/news/view/1970.

Food and Agriculture Organization of the United (FAO), 2017. Global Livestock Environmental Assessment Model (GLEAM). Rome. Available: http://www.fao.org/gleam/en/.

Food and Agriculture Organization of the United Nations (FAO), 2019. FAOSTAT Statistics Database. Rome. Available: http://www.fao.org/faostat/en/#data/QL.

Figueroa-Viramontes, U., Delgado, J.A., Cueto-Wong, J.A., Núñez-Hernández, G., Reta-Sánchez, D.G., Barbarick, K.A., 2011. A new Nitrogen Index to evaluate nitrogen losses in intensive forage systems in Mexico. Agric. Ecosyst. Environ. 142 (3–4), 352–364. https://doi.org/10.1016/j.agee.2011.06.004.

Frischknecht, R., Steiner, R., Braunschweig, A., Egli, N., Hildesheimer, G., 2006. Swiss Ecological Scarcity Method: the New Version 2006. Berne, Switzerland. Available: https://www.researchgate.net/profile/Braunschweig_Arthur/publication/237790160_Swiss_Ecological_Scarcity_Method_The_New_Version_2006/links/00b7d52778ba65e30f000000.pdf.

Gerber, P.J., Mottet, A., Opio, C.I., Falcucci, A., Teillard, F., 2015. Environmental impacts of beef production: review of challenges and perspectives for durability. Meat Sci. 109, 2–12. https://doi.org/10.1016/j.meatsci.2015.05.013.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO) 1–115. Rome, Italy 978-92-5-107921-8.

Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Del, l C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J., Oosting, S., 2013. Mitigation of greenhouse gas emissions in livestock production – a review of technical options for non-CO2 emissions. In: Gerber, P.J., Henderson, B., Makkar, H.P.S. (Eds.), FAO Animal Production and Health Paper No. 177. FAO, Rome, Italy. Available: http://www.fao.org/3/i3288e/i3288e.pdf.

Hongmin, D., Mangino, J., Mcallister, T.A., Hatfield, J.L., Johnson, D.E., Lassey, K.R., Aparecida de Lima, M., Romanosvskaya, A., 2006. Chapter 10: emissions from livestock and manure management. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), 2006-IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use, pp. 10.1–10.87. Published by the Institute for Global Environmental Strategies (IGES), Hayama, Japan. Available: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf.

Huerta, A.R., Güereca, L.P., Lozano, M.D.L.S.R., 2016. Environmental impact of beef production in Mexico through life cycle assessment. Resour. Conserv. Recycl. 109, 44–53. https://doi.org/10.1016/j.resconrec.2016.01.020.

Kaab, A., Sharifi, M., Mobli, H., Nabavi-Pelesaraei, A., Chau, K.W., 2019. Combined life cycle assessment and artificial intelligence for prediction of output energy and environmental impacts of sugarcane production. Sci. Total Environ. 664, 1005–1019. https://doi.org/10.1016/j.scitotenv.2019.02.004.

Kjellsson, J., Liu, S., 2012. Transboundary waters. Available: http://docplayer.net/32447281-International-water-pricing.html.

Kouchaki-Penchah, H., Sharifi, M., Mousazadeh, H., Zarea-Hosseinabadi, H., Nabavi-Pelesaraei, A., 2016. Gate to gate life cycle assessment of flat pressed particleboard production in Islamic Republic of Iran. J. Clear. Prod. 112, 343–350. https://doi.org/10.1016/j.jclepro.2015.07.056.

Kouchaki-Penchah, H., Nabavi-Pelesaraei, A., O'Dwyer, J., Sharifi, M., 2017. Environmental management of tea production using joint of life cycle assessment and data envelopment analysis approaches. Environ. Prog. Sustain. 36 (4), 1116–1122. https://doi.org/10.1002/ep.12550.

Kumar, P., Thiaw, I., Yashiro, M., Molinero, C., 2011. Food and ecological security: identifying synergy and trade-offs. UNEP Policy Series: Ecosystem Management

4, 1–12.

Mekonnen, M.M., Hoekstra, A.Y., 2010. The green, blue and grey water footprint of farm animals and animal products. Main Report. Value of Water. Research Report Series No. 48. Delft, The Netherlands. Available: https://ris.utwente.nl/ws/portalfiles/portal/5146067/Report-48-WaterFootprint-AnimalProducts-Vol1.pdf. I.

Moate, P.J., Deighton, M.H., Williams, S.R.O., Pryce, J.E., Hayes, B.J., Jacobs, J.L., Eckard, R.J., Hannah, M.C., Wales, W.J., 2016. Reducing the carbon footprint of Australian milk production by mitigation of enteric methane emissions. Anim. Prod. Sci. 56 (7), 1017–1034. https://doi.org/10.1071/AN15222.

Mogensen, L., Kristensen, T., Nguyen, T.L.T., Knudsen, M.T., Hermansen, J.E., 2014. Method for calculating carbon footprint of cattle feeds–including contribution from soil carbon changes and use of cattle manure. J. Clean. Prod. 73 (15), 40–51. https://doi.org/10.1016/j.jclepro.2014.02.023.

Mogensen, L., Nguyen, T.L.T., Madsen, N.T., Pontoppidan, O., Preda, T., Hermansen, J.E., 2016. Environmental impact of beef sourced from different production systems-focus on the slaughtering stage: input and output. J. Clean. Prod. 133 (1), 284–293. https://doi.org/10.1016/j.jclepro.2016.05.105.

Montemayor-Trejo, J.A., Lara-Mireles, J.L., Woo-Reza, J.L., Munguía-López, J., Rivera-González, M., Trucios-Caciano, R., 2012. Corn forrage (Zea mays L.) production in three irrigation systems in the Comarca Lagunera of Coahuila and Durango, Mexico. Agrociencia 46 (3), 267–278 (in Spanish).

Nabavi-Pelesaraei, A., Kouchaki-Penchah, H., Amid, S., 2014. Modeling and optimization of CO2 emissions for tangerine production using artificial neural networks and data envelopment analysis. Int. J. Biosci. 4 (7), 148–158. https://doi.org/10.12692/ijb/4.7.148-158.

Navarrete-Molina, C., Meza-Herrera, C.A., Ramirez-Flores, J.J., Herrera-Machuca, M.A., López-Villalobos, N., López-Santiago, M.A., Veliz-Deras, F.G., 2019. Economic evaluation of the environmental impact of a dairy cattle intensive production cluster under arid lands conditions. Animal 1–9 (on line). https://doi.org/10.1017/S175173111900048X.

Nguyen, T.L.T., Hermansen, J.E., Mogensen, L., 2010. Environmental consequences of different beef production systems in the EU. J. Clean. Prod. 18 (8), 756–766. https://doi.org/10.1016/j.jclepro.2009.12.023.

Ogino, A., Sommart, K., Subepang, S., Mitsumori, M., Hayashi, K., Yamashita, T., Tanaka, Y., 2016. Environmental impacts of extensive and intensive beef production systems in Thailand evaluated by life cycle assessment. J. Clean. Prod. 112 (1), 22–31. https://doi.org/10.1016/j.jclepro.2015.08.110.

Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43 (11), 4098–4104. https://doi.org/10.1021/es802423e.

Qasemi-Kordkheili, P., Nabavi-Pelesaraei, A., 2014. Optimization of energy required and potential of greenhouse gas emissions reductions for nectarine production using data envelopment analysis approach. Int. J. Energy Environ. 5 (2), 207–219.

Ridoutt, B.G., Pfister, S., 2013. Towards an integrated family of footprint indicators. J. Ind. Ecol. 17 (3), 337–339. https://doi.org/10.1111/jiec.12026.

Ridoutt, B.G., Pfister, S., 2010. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Glob. Environ. Chang. 20 (1), 113–120. https://doi.org/10.1016/j.gloenvcha.2009.08.003.

Ridoutt, B.G., Page, G., Opie, K., Huang, J., Bellotti, W., 2014. Carbon, water and land use footprints of beef cattle production systems in southern Australia. J. Clean. Prod. 73 (15), 24–30. https://doi.org/10.1016/j.jclepro.2013.08.012.

Rios-Flores, J.L., Rios-Arredondo, B.E., Cantú-Brito, J.E., Rios-Arredondo, H.E., Armendáriz-Erives, S., Chávez-Rivero, J.A., Navarrete-Molina, C., Castro-Franco, R., 2018. Análisis de la eficiencia física, económica y social del agua en espárrago (Asparagus officinalis L.) y uva (Vitis vinifera) de mesa del DR-037 Altar-Pitiquito-Caborca, Sonora, México 2014. Rev. Fac. Cienc. Agrar. 50 (1), 101–122 (in Spanish).

Rios-Flores, J.L., Torres-Moreno, M., Castro-Franco, R., Torres-Moreno, M.A., Ruiz-Torres, J., 2015. Determinación de la huella hídrica azul en los cultivos forrajeros del DR-017, Comarca Lagunera, México. Rev. Fac. Cienc. Agrar. 47 (1), 93–107 (in Spanish).

Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite based estimates of groundwater depletion in India. Nature 460, 999–1002. https://doi.org/10.1038/nature08238.

Rosegrant, M.W., Cai, X., Cline, S.A., 2002. Global Water Outlook to 2025, Averting an Impending Crisis. A 2020 Vision for Food, Agriculture, and the Environment Initiative. IFPRI and IWMI, Washington, DC.

Ruviaro, C.F., de Léis, C.M., Lampert, V.D.N., Barcellos, J.O.J., Dewes, H., 2015. Carbon footprint in different beef production systems on a southern Brazilian farm: a case study. J. Clean. Prod. 96 (1), 435–443. https://doi.org/10.1016/j.jclepro.2014.01.037.

Sabzevari, A., Kouchaki-Penchah, H., Nabavi-Pelesaraei, A., 2015. Investigation of life cycle assessment of hazelnut production in Guilan province of IR Iran based on orchards size levels. Biological Forum 7 (1), 807–813.

Servicio de Información Agroalimentaria y Pesquera - Agrifood and Fishery Information System (SIAP), 2019. Livestock yearling production book. Available: http://infosiap.siap.gob.mx/repoAvance_siap_gb/pecCompaEdo.jsp.

Sepehri, A., Sarrafzadeh, M.H., 2018. Effect of nitrifiers community on fouling mitigation and nitrification efficiency in a membrane bioreactor. Chem. Eng. Process 128, 10–18. https://doi.org/10.1016/j.cep.2018.04.006.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo-Abad, C., Romanovskaya, A., Sperling, F., Tubiello, F.N., 2014. Agriculture, forestry and other land use (AFOLU). In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 811–922. Available: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf.

Thompson Reuters, 2011. Point carbon. Available: http://pointcarbon.com/aboutus/pressroom.

Thornton, P.K., 2010. Livestock production: recent trends, future prospects. Phil. Trans. Biol. Sci. 365 (1554), 2853–2867. http://doi.org/10.1098/rstb.2010.0134.

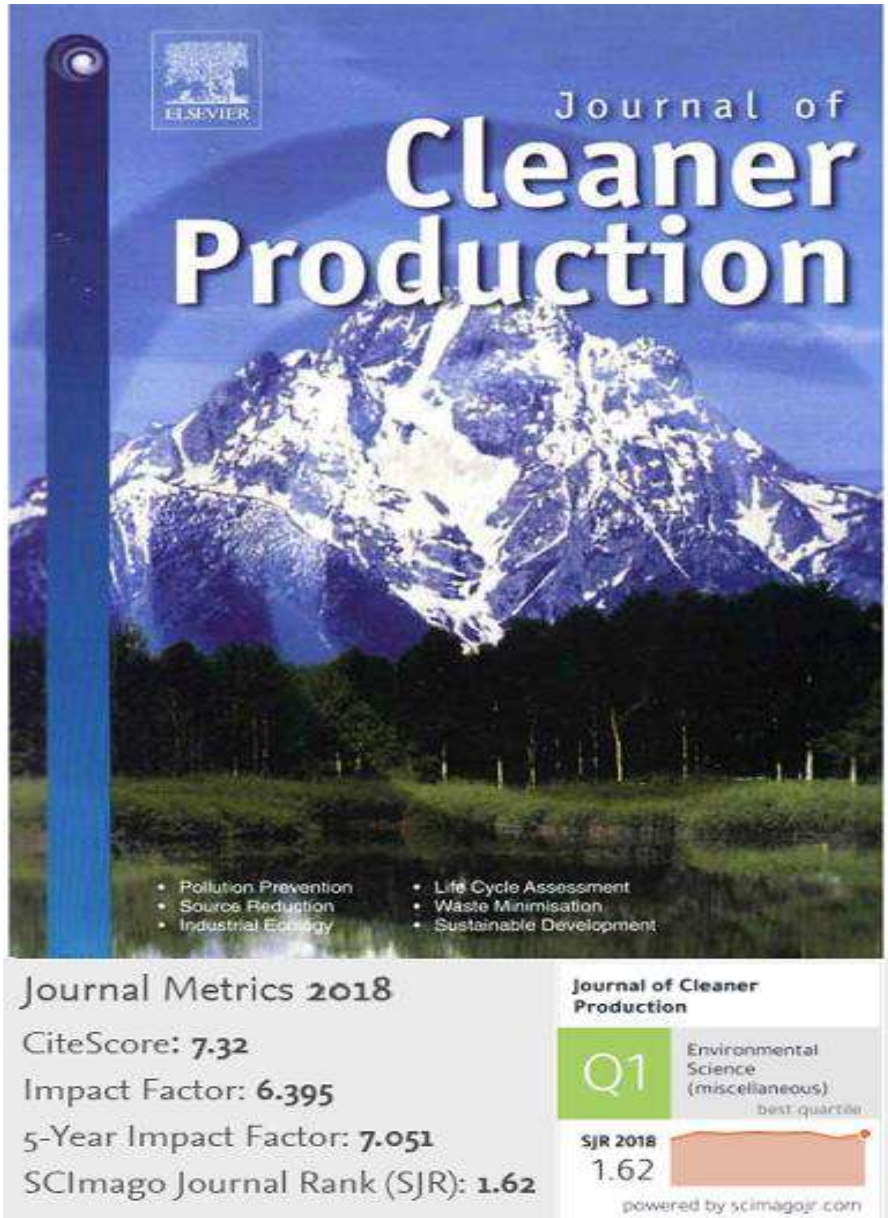
Tiu, B.T.C., Cruz, D.E., 2017. An MILP model for optimizing water exchanges in eco-industrial parks considering water quality. Resour. Conserv. Recycl. 119, 89–96. https://doi.org/10.1016/j.resconrec.2016.06.005.

Vitali, A., Grossi, G., Martino, G., Bernabucci, U., Nardone, A., Lacetera, N., 2018. Carbon footprint of organic beef meat from farm to fork: a case study of short supply chain. J. Sci. Food Agric. 98 (14), 5518–5524. https://doi.org/10.1002/jsfa.9098.

Weber, C.L., Matthews, H.S., 2008. Food-miles and the relative climate impacts of food choices in the United States. Environ. Sci. Technol. 42 (10), 3508–3513. https://doi.org/10.1021/es702969f.

Weiss, F., Leip, A., 2012. Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model. Agric. Ecosyst. Environ. 149 (1), 124–134. https://doi.org/10.1016/j.agee.2011.12.015.

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



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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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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 ≤ & <0.5 moderate; 0.5 ≤ & <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^3) 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^3)
		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.

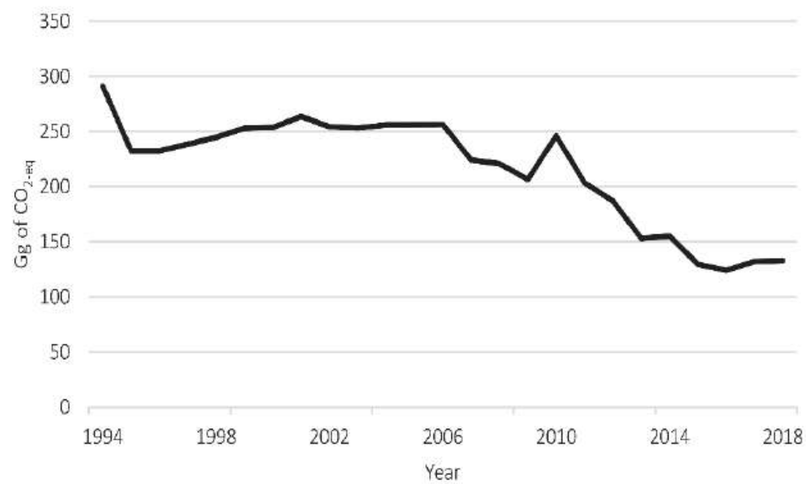

Fig. 1. Dynamic of total methane emissions (CH_4) (Gg of $CO_{2\text{-eq}}$) generated by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018).

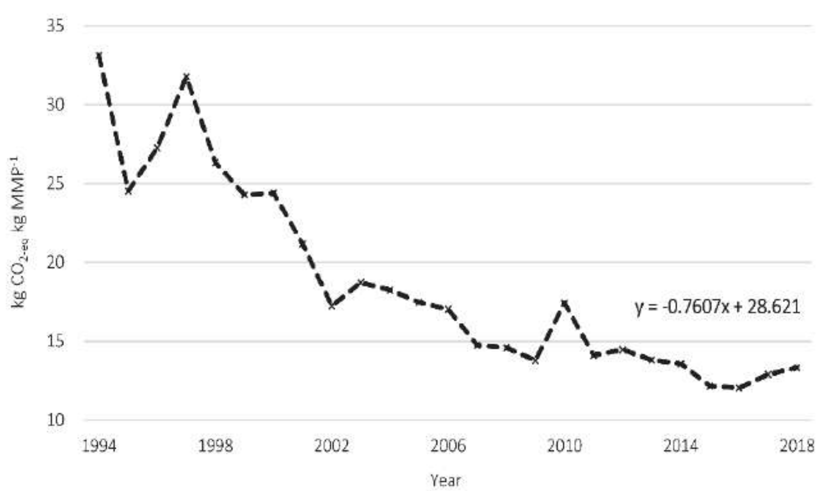

Fig. 2. Total methane emissions (CH_4) in kg $CO_{2\text{-eq}}$ per kg milk-meat protein (kg $CO_{2\text{-eq}}$ kg MMP^{-1}) generated by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018).

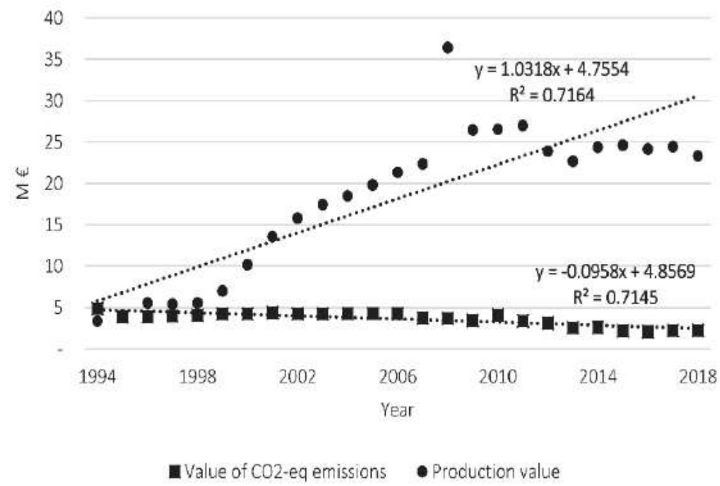

Fig. 3. Comparative analyses between the economic value of milk-meat production and the economic value of greenhouse gas emissions as $CO_{2\text{-eq}}$, generated by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018).

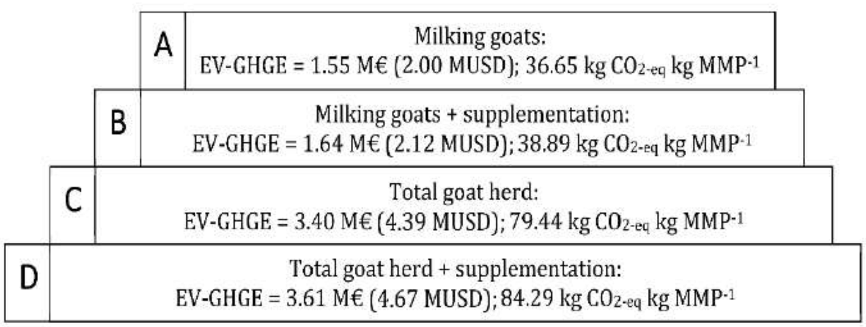

Fig. 4. Average economic value of greenhouse gas emissions [EV-GHGE; M€ (MUSD)] and GHGE per kilogram of milk-meat protein (kg $CO_{2\text{-eq}}$ kg MMP^{-1}) generated by A: Milking goats, B: Milking goats + supplementation, C: Total goat herd, and D: Total goat herd + supplementation by the goat production 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).

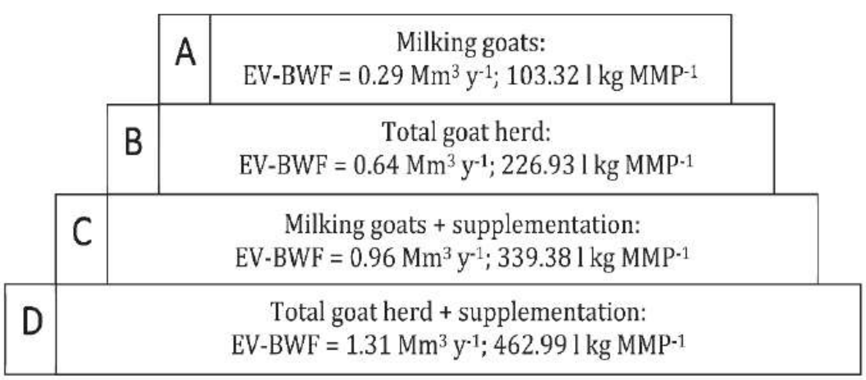

Fig. 5. Annual average value of the blue water footprint (EV-BWF; Mm^3 y^{-1}) and liters per kg of milk-meat protein (l kg MMP^{-1}) generated by A: Milking goats, B: Milking goats + supplementation, C: Total goat herd, and D: Total goat herd – supplementation by the goat production system in the Comarca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

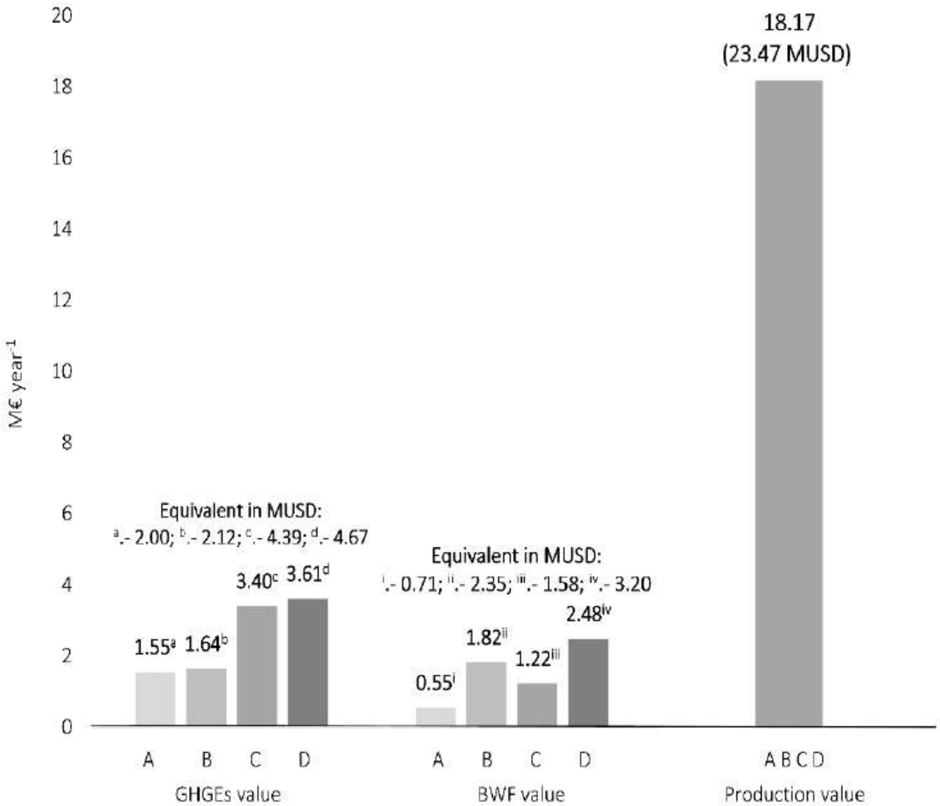

Fig. 6. Annual average economic value of greenhouse gas emissions (GHGE), blue water footprint (BWF) and milk-meat production (M€ year^{-1}) generated by A: Milking goats, B: Milking goats + supplementation, C: Total goat herd and D: Total goat herd + supplementation by the goat production system in 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.)

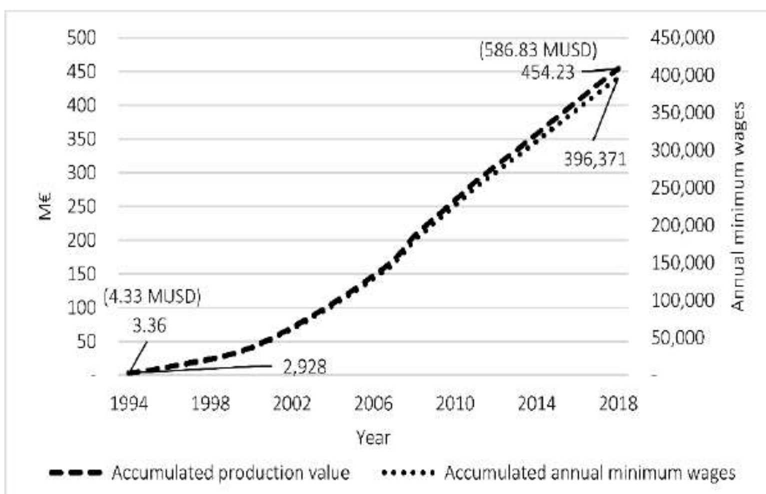

Fig. 7. Accumulated value of milk-meat production, million euros and accumulated annual minimum wages, generated by the goat production system in the Comarca Lagunera, Mexico, across years (1994–2018). Note: This GPS-value of production and this amount of annual minimum wages represent the income of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

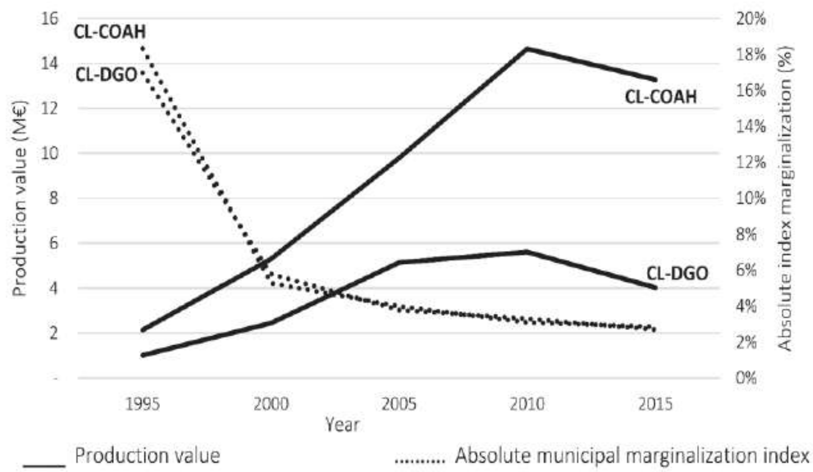

Fig. 8. Average value of goat production (M€) and absolute municipal marginalization index (%) of some municipalities of the Comarca Lagunera of Durango (Lerdo, Mapimi and Tlahualilo) (CL-DGO) and Comarca Lagunera of Coahuila (Francisco I Madero, Matamoros, San Pedro, Viesca) (CL-COAH), Mexico, observed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

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References

Cardoso, L.A., 2012. Environmental and economic impacts of livestock productivity increase in sub-Saharan Africa. Trop. Anim. Health Prod. 44, 1879–1884. https://doi.org/10.1007/s11250-012-0151-z.
Chenyambuga, S.W., Jackson, M., Ndemanisho, E.E., Komwihangilo, D.M., 2014. Profitability and contribution of small-scale dairy goat production to income of smallholder farmers in Babati and Kongwa districts, Tanzania. Livest. Res. Rural Dev. 26, 1–10.
Comisión Nacional del Agua (CONAGUA) - National Water Comission, 2015. Actualization of the annual average water availability in the main aquifer – Comarca Lagunera. Published in the Off. J. Fed. 28. April 20, 2015, Mexico. https://www.gob.mx/cms/uploads/attachment/file/102876/DR_0523.pdf last. (Accessed 15 January 2019). access.
Comisión Nacional de los Salarios Mínimos, National Comission for Minimum Wages, 2011. Minimum wages effective from 1 January 2011. Published by the secretary of labor and social welfare. Mexico. https://www.conasami.gob.mx/pdf/tabla_salarios_minimos/2011/01_01_2011.pdf. (Accessed 25 January 2019). 1, access.
Consejo Nacional de Población (CONAPO), National Population Council, 2013. Absolute Index of Marginalization 2000-2010, p. 119. Mexico, D. F. https://www.conapo.gob.mx/work/models/CONAPO/Resource/1755/1/images/IAM_00-04.pdf. (Accessed 13 March 2019). access.
Consejo Nacional de Población (CONAPO) – National Population Council, 2019. Index of marginalization by municipality 1990 – 2015. Mexico, D. F. Open data from the index of marginalization. https://www.conapo.gob.mx/es/CONAPO/

Datos_ Abiertos_del_Indice_ de_Marginacion last. (Accessed 13 March 2019) access.
Devendra, C., Liang, J.B., 2012. Conference summary of dairy goats in Asia: current status, multifunctional contribution to food security and potential improvements. Small Rumin. Res. 108, 1–11. https://doi.org/10.1016/j.smallrumres.2012.08.012.
Environmental Finance, 2011. Carbon Price. https://www.environmental-finance.com/news/view/1970 last. (Accessed 10 November 2018). access.
Figueroa-Viramontes, U., Delgado, J.A., Cueto-Wong, J.A., Núñez-Hernández, G., Reta-Sánchez, D.G., Barbarick, K.A., 2011. A new Nitrogen Index to evaluate nitrogen losses in intensive forage systems in Mexico. Agric. Ecosyst. Environ. 142, 352–364. https://doi.org/10.1016/j.agee.2011.06.004.
Food and Agriculture Organization of the United (FAO), 2017. Global Livestock Environmental Assessment Model (GLEAM). Rome. http://www.fao.org/gleam/en/. (Accessed 26 July 2019). access.
Food and Agriculture Organization of the United Nations (FAO), 2019. FAOSTAT Statistics Database. Rome. http://www.fao.org/faostat/en/#data/QL last. (Accessed 26 July 2019). access.
García-Bonilla, D.V., Vargas-López, S., Bustamante-González, A., Torres-Hernández, G., Calderón-Sánchez, F., Olvera-Hernández, J.I., 2018. Goat production for meat in the mountain of Guerrero, México. Agricultura, sociedad y desarrollo 15, 1–17.
Gonzalez-Bulnes, A., Meza-Herrera, C.A., Rekik, M., Ben Salem, H., Kridli, R.T., 2011. Limiting factors and strategies for improving reproductive outputs of small ruminants reared in semi-arid environments. In: Degenovine, K.M. (Ed.), Semi-arid Environments: Agriculture, Water Supply and Vegetation. Nova Science Publishers Inc., Hauppauge, NY, USA, pp. 41–60 (Chapter 2), 978-1-61761-541-2.
Herrero, M., Thornton, P.K., Gerber, P., Reid, R.S., 2009. Livestock, livelihoods and the environment: understanding the trade-offs. Curr. Opin. Env. Sus. 1, 111–120. https://doi.org/10.1016/j.cosust.2009.10.003.
Hongmin, D., Mangino, J., Mcallister, T.A., Hatfield, J.L., Johnson, D.E., Lassey, K.R., Aparecida de Lima, M., Romanosvskaya, A., 2006, 10.1-10.87. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Chapter 10: Emissions from Livestock and Manure Management. 2006-IPCC Guidelines for National Greenhouse Gas Inventories, vol 4. Agriculture, Forestry and Other Land Use. Published by the Institute for Global Environmental Strategies (IGES), Hayama, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf. (Accessed 26 July 2019). last access.
Instituto Nacional de Estadística, Geografía e Informatica (INEGI) – National Institute of Statistics, Geography and Informatics, 2013. National household expenditure survey. Press release No. 414/13. Mexico. https://www.inegi.gob.mx./contenidos/programas/engasto/2012/doc/engasto_resultados.pdf. (Accessed 26 July 2019). 14, access.
Intergovernmental Panel on Climate Change (IPCC), 1995. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/. (Accessed 8 December 2019).
Isidro-Requejo, L.M., Meza-Herrera, C.A., Pastor-Lopez, F.J., Maldonado, J.A., Salinas-González, H., 2019. Physicochemical characterization of goat milk produced in the Comarca Lagunera, Mexico. Anim. Sci. J. 90, 563–573. https://doi.org/10.1111/asj.13173.
Kjellsson, J., Liu, S., 2012. Transboundary Waters. http://docplayer.net/32447281-International-water-pricing.html last. (Accessed 26 July 2019). access.
Koluman, N., Silanikove, N., 2018. The advantages of goats for future adaptation to climate change: a conceptual overview. Small Rumin. Res. 163, 34–38. https://doi.org/10.1016/j.smallrumres.2017.04.013.
Leip, A., Weiss, F., Wassenaar, T., Perez, I., Fellmann, T., Loudjani, P., Tubiello, F., Grandgirard, D., Monni, S., Biala, K., 2010. Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS). – final report. European Commission, Joint Research Centre.
Lopes, F.B., Silva, M.C.D., Miyagi, E.S., Fioravanti, M., Facó, O., Guimarães, R.F., Júnior, O.A.C., McManus, C.M., 2012. Spatialization of climate, physical and socioeconomic factors that affect the dairy goat production in Brazil and their impact on animal breeding decisions. Pesqui. Vet. Bras. 32, 1073–1081. https://doi.org/10.1590/S0100-736X2012001100001.
Mekonnen, M.M., Hoekstra, A.Y., 2010. The green, blue and grey water footprint of farm animals and animal products. Main Report. Value of Water. Research Report Series No. 48. https://waterfootprint.org/media/downloads/Report-48-WaterFootprint-AnimalProducts-Vol1.pdf last, 1, access July 26, 2019.
Mellado, M., 2016. Dietary selection by goats and the implications for range management in the Chihuahuan Desert: a review. Rangel. J. 38, 331–341. https://doi.org/10.1071/RJ16002.
Meza-Herrera, C.A., Cano-Villegas, O., Flores-Hernandez, A., Veliz-Deras, F.G., Calderon-Leyva, G., Guillen-Muñoz, J.M., Garcia-De la Peña, C., Rosales-Nieto, C.A., Macias-Cruz, U., Avendaño-Reyes, L., 2017. Reproductive outcomes of anestrous goats supplemented with spineless Opuntia megacantha Salm-Dyck protein enriched cladodes and exposed to the male effect. Trop. Anim. Health Prod. 49, 1511–1516. https://doi.org/10.1007/s11250-017-1356-y.
Meza-Herrera, C.A., Tena-Sempere, M., 2012. Interface between nutrition and reproduction: the very basis of production. In: Astiz, S., Gonzalez-Bulnes, A. (Eds.), Animal Reproduction in Livestock. Eolss Publishers, Oxford, UK. Encyclopedia of Life Support Systems (EOLSS), under the auspices of the UNESCO.
Michael, D., 2011. Carbon Reduction Benchmarks & Strategies: New Animal Products. RIRDC. Publication No. 11/063. https://www.agrifutures.com.au/wp-content/uploads/publications/11-063.pdf. last access August 20, 2018.
Navarrete-Molina, C., Meza-Herrera, C., Ramirez-Flores, J.J., Herrera-Machuca, M.A., Lopez-Villalobos, N., Lopez-Santiago, M.A., Veliz-Deras, F.G., 2019a. Economic evaluation of the environmental impact of a dairy cattle intensive production cluster under arid lands conditions. Animal 1–9. https://doi.org/10.1017/S175173111900048X (in press).
Navarrete-Molina, C., Meza-Herrera, C., Herrera-Machuca, M.A., Lopez-Villalobos, N., Lopez-Santos, A., Veliz-Deras, F.G., 2019b. To beef or not to beef: unveiling the economic environmental impact generated by the intensive beef cattle industry in an arid region. J. Clean. Prod. 231, 1027–1035. https://doi.org/10.1016/j.jclepro.2019.0.5.267.
Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., Vellinga, T., Henderson, B., Steinfeld, H., 2013. Greenhouse Gas Emissions from Ruminant Supply Chains – A Global Life Cycle Assessment. Food and Agriculture Organization of the United Nations (FAO), Rome.
Peacock, C., Sherman, D.M., 2010. Sustainable goat production - some global perspectives. Small Rumin. Res. 89, 70–80. https://doi.org/10.1016/j.smallrumres.2009.12.029.
Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43, 4098–4104. https://doi.org/10.1021/es802423e.
Ridoutt, B.G., Pfister, S., 2013. Towards an integrated family of footprint indicators. J. Ind. Ecol. 17, 337–339. https://doi.org/10.1111/jiec.12026.
Ridoutt, B.G., Pfister, S., 2010. A revised approach to water footprint to make transparent the impacts of consumption and production on global freshwater scarcity. Global Environ. Change 20, 113–120. https://doi.org/10.1016/j.gloenvcha.2009.08.003.
Ríos-Flores, J.L., Rios-Arredondo, B.E., Cantú-Brito, J.E., Rios-Arredondo, H.E., Armendáriz-Erives, S., Chávez-Rivero, J.A., Navarrete-Molina, C., Castro-Franco, R., 2018. Análisis de la eficiencia física, económica y social del agua en espárrago (Asparagus officinalis L.) y uva (Vitis vinífera) de mesa del DR-037 Altar-Pitiquito-Caborca, Sonora, México 2014. Rev. Fac. Cienc. Agrar. 50, 101–122.
Robertson, K., Symes, W., Garnham, M., 2015. Carbon footprint of dairy goat milk production in New Zealand. J. Dairy Sci. 98, 4279–4293. https://doi.org/10.3168/jds.2014-9104.
Salinas-González, H., Valle-Moysen, E.D., de Santiago-Miramontes, M.A., Veliz-Deras, F.G., Maldonado-Jáquez, J.A., Vélez-Monroy, L.I., Torres-Hernández, D., Isidro-Requejo, L.M., Figueroa-Viramontes, U., 2016. Descriptive analysis of goat units in the southwest of the Comarca Lagunera, Mexico. Interciencia 41, 11.
Santos-Lavalle, R., Flores-Verduzco, J.J., Cervantes-Escoto, F., Salas-González, J.M., Sagarnaga-Villegas, L.M., 2018. Opportunities for goat producers from Guanajuato, Mexico, in the marketing of fine cheese. Revista Mexicana de Ciencias Pecuarias 9, 601–613.
Servicio de Información Agroalimentaria y Pesquera (SIAP) - Agrifood and Fishery Information System, 2019. Livestock production yearbook. access. http://infosiap.siap.gob.mx/repoAvance_siap_gb/pecAvanceEdo.jsp last. (Accessed 26 July 2019).
Silanikove, N., Leitner, G., Merin, U., Prosser, C.G., 2010. Recent advances in exploiting goat's milk: quality, safety and production aspects. Small Rumin. Res. 89, 110–124. https://doi.org/10.1016/j.smallrumres.2009.12.033.
Silanikove, N., Koluman, N., 2015. Impact of climate change on the dairy industry in temperate zones: predications on the overall negative impact and on the positive role of dairy goats in adaptation to earth warming. Small Rumin. Res. 123, 27–34. https://doi.org/10.1016/j.smallrumres.2014.11.005.
Livestock in a changing landscape. In: Steinfeld, H., Mooney, H.A., Schneider, F., Neville, L.E. (Eds.), 2013. Drivers, Consequences, and Responses, vol 1. Island Press.
Thompson Reuters, 2011. Point Carbon. http://pointcarbon.com/aboutus/pressroom. last access November 10, 2019.
Thornton, P.K., 2010. Livestock production: recent trends, future prospects. Philos. Trans. R. Soc. Lond. B Biol. Sci. 365, 2853–2867. https://doi.org/10.1098/rstb.2010.0134.
Tiu, B.T.C., Cruz, D.E., 2017. An MILP model for optimizing water exchanges in eco-industrial parks considering water quality. Resour. Conserv. Recycl. 119, 89–96. https://doi.org/10.1016/j.resconrec.2016.06.005.
Urieta, L.F., Urieta, D.F., de la Salud Rubio Lozano, M., Medina, R.D.M., García, A.M.T., 2001. Comparative analysis of meat and meat products from French-Alpine, ¾ French-Alpine (1/4) Boer goats. Revista Mexicana de Ciencias Pecuarias 39, 237–244.
Weiss, F., Leip, A., 2012. Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model. Agric. Ecosyst. Environ. 149, 124–134. https://doi.org/10.1016/j.agee.2011.12.015.

UNIVERSIDAD AUTÓNOMA CHAPINGO
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THESIS IN JOINT SUPERVISION
WITH INTERNATIONAL MENTION

THE RUMINANT PRODUCTION SYSTEMS IN THE COMARCA LAGUNERA, MEXICO: ENVIRONMENTAL IMPACT, PRODUCTIVE TRENDS, AND MITIGATION STRATEGIES

VI. POTENTIAL STRATEGIES TO MITIGATE THE ECOLOGICAL FOOTPRINT OF RUMINANT PRODUCTION SYSTEMS IN THE COMARCA LAGUNERA, MEXICO

Doctorado en ciencias en recursos naturales y medio ambiente en zonas áridas

Doctorado en recursos naturales y gestión sostenible

Based on the available scientific information, which point to a higher EI in animal foods production, especially those from ruminant species, one of the most common strategies proposed to reduce the CF and WF, is without a doubt, to reduce the consumption of food of animal origin (Hoekstra, 2012; Legesse, et al., 2017; Mekonnen & Hoekstra, 2012; Vanham et al., 2013). Another strategy related and directed to consumers is to select products of animal origin based on their EF (Ercin et al., 2012). Due to differences in feed conversion efficiencies, the EGHG and water use blue per kilogram is generally higher for beef cattle than for poultry or pork (Gerbens-Leenes et al., 2013).

Such differences of conversion are not applicable to all ruminant species, because, for example, in Middle East and Africa, animal protein goats require considerably less water than a mixture of maize and pea (Damerau et al., 2016). A similar situation is observed in the CL when comparing with the protein of bovine origin. Besides, in many regions of the world and the CL, goat production seems to be the only sustainable livestock activity due to climatic, edaphological and socioeconomic factors. Nonetheless, we need to take into account both pros and conts of every livestock activity in a defined region to take the best productive options. If we do not recognize the specific situation of different animal production systems, in special their eological and socioeconomical footprint, can lead to unsustainable and counterproductive results (Legesse, et al., 2017).

6.1. Carbon footprint

The proposed strategies to reduce the EI of livestock production should be based on technologies and practices that help improve herd-level efficiency. There is a growing demand to produce livestock products more efficiently per unit of methane, as well as per liter of water. In the case of CL, it is proposed to include the use of better-quality balanced foods, in such a way that they help to reduce the EGHG at the enteric level and at the manure management level (Herrero et al., 2012; Gerber et al., 2013; Moate et al., 2016). In this sense, would help the adoption of management practices manure ensured both the recovery and the recycling of nutrients and energy, parallel to improving the efficiency of energy use along the chain of supplements, Previously, it would help to potentiate the mitigation efforts of the CF of ruminant cattle in CL (Gerber et al., 2013).

Some other technologies applicable in the CL, are the improvement of the quality of the forages and the use of food additives that include bioactive compounds, fats, ionophores/antibiotics, propionate reinforcements, archaebacterial inhibitors, nitrates and sulfate supplements, along with vaccine development and genetic selection methods. Because all the above has a great potential to reduce EGHG and, therefore, should be considered as viable options as short-term mitigation strategies (Herrero et al., 2012; Gerber et al., 2013;Moate et al., 2016; Smith et al., 2014).

Other mitigation strategies, applicable to CL, include the use of genetically improved animals that have a higher production efficiency with a lower EGHG per unit of product, or those with a better potential to reduce enteric fermentation emissions. Microbial technologies to develop vaccines, methanotrophic microorganisms, rumen defaunation, bacteriophages and the use of probiotics to improve reproductive efficiency are medium-term options to expand mitigation schemes (Smith et al., 2014). Genomic selection aligned with direct measurements of methane emissions, as well as with the efficiency of food conversion, would promote reductions with respect to the intensity of methane emissions (Herrero et al., 2012; Moate et al., 2016). In addition, to reduce the emissions of N_2O, in the ruminants in the CL, apply the strategies proposed by Smith et al. (2014) that include dietary manipulation to decrease fecal N, dietary nitrification inhibitors, urease inhibitors, the best selection of fertilizers and the use of best manure management practices incorporated into floors. Likewise, and although not yet tested for CL, it is proposed achieve up to 30% reduction of emissions from manure through the adoption of technologies manure management, generated and validated in Europe (Oenema et al., 2007). In addition, policy makers and professionals involved in the agricultural management sector must be able to implement different strategies to mitigate the impact on ecosystem services (De Groot et al., 2002). When considering strategies to mitigate the EGHG by ruminant production systems, bioenergy is an interesting alternative, however, it is important to consider different issues such as the implementation of practices to improve sustainability, as well as the efficiency of bioenergy systems (Smith et al., 2014).

In the case of CL, the technology currently used in many ruminant production units is the use of biodigesters, which is an integral technology, since it contributes to reducing EGHG, produces bioenergy and organic biofertilizers while helping to clean the waters gray. However, special attention should be given to the biological treatment that is given to the microbial population and, consequently, to the C/N ratio, which will help to improve the treatment of wastewater, to mitigate the wear and function of the biodigester membrane, as demonstrated by Sepehri and Sarrafzadeh (2018).

6.2. Water footprint

It should be recognized that in the CL, several parts of the rural and urban sectors depend economically, directly or indirectly, on both dairy and beef cattle production systems. That is why instead of proposing radical actions to reduce or even eliminate these economically important production systems, smart alternatives should be proposed to reduce the EI generated by them.

Considering that ruminant livestock farming in the CL is carried out in extremely arid conditions, with an annual rainfall <240 mm, the search for technological protocols and regulatory policies to promote rational water use should be considered. As the major impact of ruminant production systems is due to the production and handling of animal feed, it seems plausible, as a short-term strategy, to stimulate the stratification of the links in the ruminant production chains; this could easily be done by promoting the production of fodder and grain in a more appropriate geographical region to sustain said production without compromising its hydrological balance. In addition, it is of particularly importance to promote the use of more technified and efficient irrigation systems in the agricultural area of the CL.

It is of utmost importance to stop the environmental deterioration of the Durango mountain range by proposing a healthy, efficient and sensible management of the upper Nazas river basin, because it is the main source of fluid and underground water supply, for the development of agricultural activities in the CL. Said WF mitigation strategy should favor management practices to promote the supply of a larger volume of water to the lower river basin located in the CL. In addition to this strategy, payment promotion should be seriously considered. For environmental services to the inhabitants of the upper basin, not only to stop the deterioration of the forest, but also to support its conservation and improve the collection of water and carbon sequestration, which will not only mitigate the WF but in parallel the CF.

Another proposal for mitigation of WF, applicable to CL, is the use of other animal genotypes, which are more efficient in terms of the use of energy and water with reasonably favorable results for the dairy and meat industry. Despite a possible reduction in the volume of production, the use of these genotypes can compensate for the losses that occur with this strategy due to the increase in the total solid content of solid milk and a greater daily weight gain, especially in fat and protein content.

Without a doubt, such potential mitigation proposals would only be viable with the participation and commitment of the different entities involved in these complex production systems, especially the producers themselves. Certainly, both methodologies and logistics must be carefully planned to achieve these objectives to mitigate the impacts of the animal industry on both the environment and natural resources. For this reason, the information generated and presented in this thesis report must be useful for decision-making bodies, whose main objective should be to maintain the overall sustainability of agricultural activity in a harmonious balance with the productive, economic, biological sectors and social aspects of CL (Rios-Flores et al., 2018).

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THESIS IN JOINT SUPERVISION
WITH INTERNATIONAL MENTION

THE RUMINANT PRODUCTION SYSTEMS IN THE COMARCA LAGUNERA, MEXICO: ENVIRONMENTAL IMPACT, PRODUCTIVE TRENDS, AND MITIGATION STRATEGIES

VII. CONCLUSIONS

Doctorado en ciencias en recursos naturales y medio ambiente en zonas áridas

Doctorado en recursos naturales y gestión sostenible

In order to homogenize the analysis periods, the required calculations to determine the EI of the dairy cattle production system in the CL, were economically quantified during the period from 1994 to 2018 (Appendix 1). When comparing the EI with the EV of the milk production, a zero profitability of the system is observed since the EV of the milk production represented only 4.96% of the environmental costs. Undoubtedly, the dairy cattle industry is responsible for a significant anthropogenic EI in CL. The highest environmental and economic cost of the bovine milk production system in the CL is generated by the water footprint. Water is an extremely limited and scarce natural resource in this warm-arid region, coupled with the presence of an endorheic basin, which presents an alarming water deficit.

Regarding beef cattle, our study demonstrates a clear and long-term information base (1994-2018) that the EI and EcI WF and CF generated by the system of intensive fattening cattle in the CL it is significantly greater than and EV generated by this activity in the region. Contrasting the EI with EV of intensive meat bovine, the result is a null return; EV meat production bovine represented only 3.67% of environmental costs (Appendix 1). Like the production of bovine milk, the main environmental and economic cost was that associated with WF. Without a doubt, the trends observed in the last 25 years require an immediate application of measures and policies aimed at mitigating the EF of this production system. Therefore, it is fundamental and essential to promote actions that foster a bovine fattening system based on a responsibility, not only environmental but also social, in order to form a more efficient, rational and sustainable production process, which at the same time reduces the anthropogenic impact.

On the other hand, the results obtained in the case of the goat meat-milk production system in the CL clearly demonstrate that the long-term economic benefit (1994-2018) is greater than its EI. Because its EV is 275.72% higher, than the EVEI (Appendix 1). The results show that it is an eco-efficient system when comparing its results with those observed worldwide, both for CF and for the transformation of blue water into animal protein with an indisputable biological value. The need for measures to improve the availability and quality of products and services for the benefit not only of goats, but also of the goat keepers and his family is emphasized. In addition, to promote the sustainability of goat production will contribute to improving the socioeconomic conditions of the people involved in this livestock. In the same way, it was shown that the greater the economic and productive system efficiency goat production, the better the socioeconomic conditions of farmers and their families, with a concomitant decrease in both the index and the degree of marginalization of families and municipalities where this activity takes place.

By adding the EV of the EI of the systems analyzed here and by contrasting them with the EV generated by them in the CL, it is clearly demonstrated that the economic benefit in the years studied (1994-2018) of these systems is less than their EI. However, it is essential to highlight the exception that represents the goat meat-milk production system, where this relationship shows an inverse trend. However, by adding the values obtained, the EV of ruminant livestock in the CL, represents only 4.85%, with respect to the EV of its EI. So same, the EV of CF represent only 2.77% of environmental costs, while the remaining 97.23% of those costs to WF (Appendix 1).

The implementation of mitigation measures should prioritize the rational use of resources, employment generation and regional economic benefits as part of a more efficient and sustainable production process. A very strict policy to mitigate this impact would be the establishment of a differential or tax payment scheme. This could be done considering both the amount of water used and the amount of GHG emitted, where the proposal would be to consider international prices for both tracks. Future studies are required complementary to quantify the social and economic benefit of ruminant production systems in the CL where different mitigation strategies are evaluated.

Finally, ignoring this complex situation endangers the viability and sustainability of not only ruminant production systems, but also works against productive, economic, biological and social sustainability of the CL itself. In addition, the multidimensional nature of the sustainability of goat production in marginal contexts should be considered, because its refined and sophisticated ethological, adaptive and physiological plasticity was demonstrated. Certainly, not all ruminants were created equal.

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VIII. REFERENCES

Doctorado en ciencias en recursos naturales y medio ambiente en zonas áridas

Doctorado en recursos naturales y gestión sostenible

AgroDer. 2012. Huella hídrica en México en el contexto de Norteamérica. WWF México y AgroDer. México DF. 46 pp. Available in http://www.huellahidrica.org/Reports/AgroDer,%202012.%20Huella%20h%C3%ADdrica%20en%20M%C3%A9xico.pdf. Accessed June 16, 2019.

Alemu, A. W., Dijkstra, J., Bannink, A., France, J., & Kebreab, E. (2011). Rumen stoichiometric models and their contribution and challenges in predicting enteric methane production. *Animal Feed Science and Technology, 166,* 761-778. https://doi.org/10.1016/j.anifeedsci.2011.04.054.

Allan, J. A. (2006). Virtual Water, Part of an invisible synergy that ameliorates water scarcity. In: *Water Crisis: myth or reality?* Rogers, P., Llamas, M., & Martinez-Cortina, L. Pp. 131-150. Balkema, Rotterdam: FAO. ISBN 13: 9-78-0-415-36438-6.

Amend, T., Barbeau, B., Beyers, B., Burns, S., Eißing, S., Fleischhauer, A., Kus, B., & Poblete. P. (2011). *¿Un pie grande en un planeta pequeño? Haciendo cuentas con la huella ecológica*. Colección La sostenibilidad tiene muchos rostros. Alemania: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) / Global Footprint Network.

Banco de Mexico – Bank of Mexico (Banxico). (2019). *Mercado cambiario (Tipos de cambio).* Available in http://www.anterior.banxico.org.mx/portal-mercado-cambiario/. Accessed June 25, 2019.

Beckett, J. L., & Oltjen, J. W. (1993). Estimation of the water requirement for beef production in the United States. *Journal of animal science, 71*(4), 818-826. https://doi.org/10.2527/1993.714818x.

Benavides Ballesteros, H. O., & León Aristizabal, G. E. (2007). Información técnica sobre Gases de Efecto Invernadero y el cambio climático. Nota técnica del IDEAM. *Ideam,* 1–102. DOI: IDEAM–METEO/008-2007.

Bosire, C. K., Krol, M. S., Mekonnen, M. M., Ogutu, J. O., de Leeuw, J., Lannerstad, M., & Hoekstra, A. Y. (2016). Meat and milk production scenarios and the associated land footprint in Kenya. *Agricultural Systems, 145,* 64-75. https://doi.org/10.1016/j.agsy.2016.03.003.

Bragaglio, A., Napolitano, F., Pacelli, C., Pirlo, G., Sabia, E., Serrapica, F., Serrapica, M., & Braghieri, A. (2018). Environmental impacts of Italian beef production: A comparison between different systems. *Journal of Cleaner Production, 172,* 4033-4043. https://doi.org/10.1016/j.jclepro.2017.03.078.

Browne, D., O'Regan, B., & Moles, R. (2009). Use of carbon footprinting to explore alternative household waste policy scenarios in an Irish city - region. *Resources, Conservation and Recycling, 54,* 113–122.

Busscher, W. (2012). Spending our water and soils for food security. *Journal of Soil and Water Conservation, 67*(3), 228-234. https://doi.org/10.2489/jswc.67.3.228.

Capper, J. L. (2011). The environmental impact of beef production in the United States: 1977 compared with 2007. *Journal of animal science, 89*(12), 4249-4261. https://doi.org/10.2527/jas.2010-3784.

Carrasco, J. F., Casassa, G., & Quintana, J. (2005). Changes of the 0 C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century. *Hydrological Sciences Journal, 50*(6), 933–948. https://doi.org/10.1623/hysj.2005.50.6.933.

Cardoso, A. S., Berndt, A., Leytem, A., Alves, B. J., de Carvalho, I. D. N., de Barros Soares, L. H., Urquiaga, S., & Boddey, R. M. (2016). Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. *Agricultural Systems, 143,* 86-96. https://doi.org/10.1016/j.agsy.2015.12.007.

Cardoso, L. A. (2012). Environmental and economic impacts of livestock productivity increase in sub-Saharan Africa. *Tropical animal health and production, 44*(8), 1879-1884. https://doi.org/10.1007/s11250-012-0151-z.

Chapagain, A. K., & Hoekstra, A. Y. (2003). *Virtual water flows between nations in relation to trade in livestock and livestock products*. Value of Water Research Report Series No. 13. UNESCO-IHE, Delft, the Netherlands. 202 pp. Available in https://waterfootprint.org/media/downloads/Report13.pdf. Accessed June 07, 2019.

Chapagain, A. K. & Orr, S. (2009). An improved water footprint methodology to link global consumption to local water resources: A case study of Spanish tomato consumption. *Journal of Environmental Management. 90,* 1219–1228. https://doi.org/10.1016/j.jenvman.2008.1006.1006.

Chukwuocha, A. C., Ogbuagu, D. H., & Okoro, V. O. (2011). A Comparative Analysis of Emission of Methane from Livestock Farms in Enugu, Eastern Nigeria. *Journal of Agricultural Science and Technology A, 1,* 908-912. ISSN 1939-1250.

Comisión Económica para América Latina y el Caribe (CEPAL). (2014). *La economía del cambio climático en América Latina y el Caribe: Paradojas y desafíos del desarrollo sostenible. Vitacura, Santiago de Chile.* 98 pp. Available in https://repositorio.cepal.org/bitstream/handle/11362/37310/S1420656_es.pdf. Accessed May 25, 2019.

Cook, S. E., Andersson, M. S., & Fisher, M. J. (2009). Assessing the importance of livestock water use in basins. *The Rangeland Journal, 31*(2), 195-205. https://doi.org/10.1071/RJ09007.

Courchene, T. J., & Allan, J. R. (2008). Climate change: The case of carbon tariff/tax. *Policy Options, 3,* 59–64.

Damerau, K., Patt, A. G., & van Vliet, O. P. (2016). Water saving potentials and possible trade-offs for future food and energy supply. *Global environmental change, 39,* 15-25. https://doi.org/10.1016/j.gloenvcha.2016.03.014.

De Boer, I. J., Hoving, I. E., Vellinga, T. V., Van de Ven, G. W., Leffelaar, P. A., & Gerber, P. J. (2013). Assessing environmental impacts associated with freshwater consumption along the life cycle of animal products: the case of Dutch milk production in Noord-Brabant. *The International Journal of Life Cycle Assessment, 18*(1), 193-203. https://doi.org/10.1007/s11367-012-0446-3.

De Groot, R. S., Wilson, M. A., & Boumans, R. M. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological economics, 41*(3), 393-408. https://doi.org/10.1016/S0921-8009(02)00089-7.

De la Cruz, E., Gutiérrez, E., Palomo, A., & Rodríguez, S. (2003). Aptitud combinatoria y heterosis de líneas de maíz en la Comarca Lagunera. *Revista Fitotecnia Mexicana, 26*(4), 279-284. ISSN: 0187-7380.

De Miguel, Á., Hoekstra, A. Y., & García-Calvo, E. (2015). Sustainability of the water footprint of the Spanish pork industry. *Ecological Indicators, 57,* 465-474. https://doi.org/10.1016/j.ecolind.2015.05.023.

Delgado, C. (2005) Rising demand for meat and milk in developing countries: implications for grasslands-based livestock production. In *Grassland: a global resource.* McGilloway, D. A. (Ed). pp. 29 – 39. The Netherlands: Wageningen Academic Publishers.

Delgado, C. L. (2003). Rising consumption of meat and milk in developing countries has created a new food revolution. *The Journal of nutrition, 133*(11), 3907S-3910S. https://doi.org/10.1093/jn/133.11.3907S.

Delgado, J. A., & Follett, R. F. (2010). Advances in nitrogen management for water quality. *Soil and water conservation society, Ankeny, IA,* 1-424.

Delgado C, Rosegrant M, Meijer S. 2001. Livestock to 2020: The revolution continues. *International Agricultural Trade Research Consortium (IATRC),* 1–38. Available in http://ageconsearch.umn.edu/bitstream/14560/1/cp01de01.pdf. Accessed June 13, 2019.

Del Valle Melendo, J. (2014). El cambio climático: reflexiones tras la cumbre de Varsovia. *Boletín Electrónico del Instituto Español de Estudios Estratégicos. Enero,* 1-22. Available in http://www.ieee.es/Galerias/fichero/docs_opinion/2014/DIEEEO07-2014_CambioClimatico_JavierdelValle.pdf. Accessed May 24, 2019.

Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P. L., Wofsy, S. C., & Zhang, X. (2007). Couplings between changes in the climate system and biogeochemistry. pp. 499-587. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (eds.). Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA. Available in https://www.globalcarbonproject.org/global/pdf/AR4WG1_Pub_Ch07.pdf. Accessed May 27, 2019.

Department for Business Innovation & Skills (DBSI). (2011). *Specifi cation for the assessment of the life cycle greenhouse gas emissions of goods and services.* London, United Kingdom. 45 pp. ISBN 978-0-580-71382-8. Available in http://shop.bsigroup.com/upload/shop/download/pas/pas2050.pdf. Accessed May 26, 2019.

Deutsch, L., Falkenmark, M., Gordon, L., Rockstrom, J., & Folke, C. (2010). Water-mediated ecological consequences of intensification and expansion of livestock production. In *Livestock in a Changing Landscape: Drivers, Consequences, and Responses. Volume 1.* Steinfeld, H., Mooney, H. A., Schneider, F., & Neville, L. E. (Eds.). Published by Island Press 2010. Pp 97-110. ISBN 978-1-59726-671-0.

Diario Oficial de la Federación - Official Journal of the Federation (DOF). (2013). *Decreto por el que se aprueba el Programa Sectorial de Desarrollo Agropecuario, Pesquero y Alimentario 2013-2018.* Diario Oficial de la Federación, México. De fecha 13 de diciembre del 2013. 50, 132–174.

Drastig, K., Prochnow, A., Kraatz, S., Klauss, H., & Plöchl, M. (2010). Water footprint analysis for the assessment of milk production in Brandenburg (Germany). *Advances in Geosciences, 27,* 65-70. https://doi.org/10.5194/adgeo-27-65-2010.

Eady, S., Viner, J., & MacDonnell, J. (2011). On-farm greenhouse gas emissions and water use: case studies in the Queensland beef industry. *Animal Production Science, 51*(8), 667-681. https://doi.org/10.1071/AN11030.

East, A. J. (2008).What is a carbon footprint? An overview of definitions and methodologies. In *Vegetable industry carbon footprint scoping study—Discussion papers and workshop*, 26 September 2008. Sydney: Horticulture Australia Limited.

EBLEX. (2010). Testing the water. The English beef and sheep production environmental roadmap, phase 2. Kenilworth, Warwickshire, United Kingdom. 48 pp. Available in http://beefandlamb.ahdb.org.uk/wp/wp-content/uploads/2013/06/Testing-the-Water.pdf. Accessed June 10, 2019.

Edgar, G. H., & Peters, G. P. (2009). Carbon footprint of nations: A global, trade linked analysis. *Environmental Science and Technology, 43,* 6414–6420.

Enishi, O. (2007). Greenhouse gas emissions caused from livestock in Japan. In *Proceedings of the 4th Workshop on Greenhouse Gas Inventories in Asia*. Jakarta, (GGIAJ' 07), National Institute for Environmental Studies, Japan.

Environmental Finance. (2011). *Carbon Price.* Available in http://www.environmental-finance.com/news/view/1970. Accessed November 10, 2012.

Environmental Protection Agency – United States (EPA). (2017). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015.* United States Environmental Protection Agency. 633 pp. Available in https://www.epa.gov/sites/production/files/2017-02/documents/2017_complete_report.pdf. Accessed May 27, 2019.

Ercin, A. E., Aldaya, M. M., & Hoekstra, A. Y. (2012). The water footprint of soy milk and soy burger and equivalent animal products. *Ecological indicators, 18,* 392-402. https://doi.org/10.1016/j.ecolind.2011.12.009.

Eshel, G., & Martin, P. A. (2006). Diet, energy and global warming, University of Chicago study. *Earth Interactions, 10*(9), 1-17.

Falkenmark, M. & Rockström, J. (2006). The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. *Journal of Water Resources Planning and Management, 132*(3), 129-132.

Falkenmark, M. & Rockström J. (2004). *Balancing Water for Humans and Nature: The New Approach in Eco-hydrology*. London: Routledge. 248 pp. ISBN: 1-85383-926-4. https://doi.org/10.4324/9781849770521.

Ferris, L., Best, J., Scholefield, H., Marques, J., Sawada, B., & Nemetz, P. (2007). *Carbon neutrality and University of British Colombia: A f irst glance*. Colombia: University of British Colombia. 48 pp.

Finkbeiner, M. (2009). Carbon footprinting – Opportunities and threats. *International Journal of Life Cycle Assessment, 14*, 91–94.

Flückiger, J., Blunier, T., Stauffer, B., Chappellaz, J., Spahni, R., Kawamura, K., Schwander, J., Stocker, T. F., & Dahl-Jensen, D. (2004). N_2O and CH_4 variations during the last glacial epoch: Insight into global processes. *Global Biogeochemical Cycles, 18*(1). https://doi.org/10.1029/2003GB002122.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., & Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature, 478*(7369), 337. https://doi.org/10. 10.1038/nature10452.

Food and Agriculture Organization of the United Nations (FAO). (2019). *FAOSTAT statistics database.* Rome. Available in http://www.fao.org/faostat/en/#data. Accessed June 11, 2019.

Food and Agriculture Organization of the United Nations (FAO). (2018). *Water use of livestock production systems and supply chains – Guidelines for assessment (Draft for public review).* Livestock Environmental Assessment and Performance (LEAP) Partnership. FAO, Rome, Italy. 106 pp. Available in http://www.fao.org/3/I9692EN/i9692en.pdf. Accessed June 08, 2019.

Food and Agriculture Organization of the United Nations (FAO). (2012). *Livestock sector development for poverty reduction: an economic and policy perspective – Livestock's many virtues*. By Otte, J., Costales, A., Dijkman, J., Pica-Ciamarra, U., Robinson, T., Ahuja, V., Ly, C., & Roland-Holst, D. Rome, FAO. 161 pp. ISBN 978-92-5-107242-4. Available in http://www.fao.org/3/i2744e/i2744e00.pdf. Accessed June 11, 2019.

Food and Agriculture Organization of the United Nations (FAO). (2011). *World Livestock 2011 – Livestock in food security.* Rome, Italy. 130 pp. ISBN 978-92-5-107013-0. Available in http://www.fao.org/3/i2373e/i2373e.pdf. Accessed May 24, 2019.

Food and Agriculture Organization of the United Nations (FAO). (2009). *The state of food and agriculture: Livestock in the balance.* Rome, FAO. 180 pp. ISBN 978-92-5-

106215-9. Available in http://www.fao.org/3/i0680e/i0680e.pdf. Accessed June 11, 2019.

Food and Agriculture Organization of the United Nations (FAO). (2017). *Sustainable livestock farming and climate change in Latin America and the Caribbean.* Available in http://www.fao.org/americas/prioridades/ganaderia-sostenible/en/. Accessed June 13, 2019.

Food and Agriculture Organization of the United Nations (FAO). (2006). *The impacts of livestock on the environment*. Magazine focus. Rome, Italy. Available in http://www.fao.org/ag/magazine/0612sp1.htm. Accessed June 13, 2019.

Fulton, J., Cooley, H., & Gleick, P. H. (2014). Water footprint outcomes and policy relevance change with scale considered: evidence from California. *Water resources management, 28*(11), 3637-3649. https://doi.org/10.1007/s11269-014-0692-1.

García, E. (1973). *Modificaciones al sistema de clasificación climática de Köppen para adaptarlo a las condiciones de la república mexicana*. UNAM. México, DF. 246 pp.

García, H. J., & Jurado, E. (2008). Caracterización del matorral con condiciones prístinas en Linares NL, México. *Ra Ximhai: revista científica de sociedad, cultura y desarrollo sostenible, 4*(1), 1-22. ISSN: 1665-0441.

Garg, S., & Dornfeld, D. (2008). *An indigenous application for estimating carbon footprint of academia library based on life cycle assessment.* University of California, Berkeley: Laboratory for Manufacturing and Sustainability. Available in http://escholarship.org/uc/item/8zp825mq. Accessed May 26, 2019.

Gao, H., Wei, T., Lou, I., Yang, Z., Shen, Z., & Li, Y. (2014). Water saving effect on integrated water resource management. *Resources, Conservation and Recycling, 93,* 50-58. https://doi.org/10.1016/j.resconrec.2014.09.009.

Gebreselassie, S., Peden, D., Haileslassie, A., & Mpairwe, D. (2009). Factors affecting livestock water productivity: animal scale analysis using previous cattle feeding trials in Ethiopia. *The Rangeland Journal, 31*(2), 251-258. https://doi.org/10.1071/RJ09011.

Gerbens-Leenes, P. W., Mekonnen, M. M., & Hoekstra, A. Y. (2013). The water footprint of poultry, pork and beef: A comparative study in different countries and production systems. *Water Resources and Industry, 1,* 25-36. https://doi.org/10.1016/j.wri.2013.03.001.

Gerbens-Leenes, P. W., Mekonnen, M. M., & Hoekstra, A. Y. (2011). A comparative study on the water footprint of poultry, pork and beef in different countries and production systems. Value of Water Research Report Series No. 55. UNESCO-IHE, Delft, the Netherlands. 42 pp. Available in https://waterfootprint.org/media/downloads/Report55_1.pdf. Accessed June 07, 2019.

Gerber, P. J., Mottet, A., Opio, C. I., Falcucci, A., & Teillard, F. (2015). Environmental impacts of beef production: Review of challenges and perspectives for durability. *Meat Science, 109,* 2-12. https://doi.org/10.1016/j.meatsci.2015.05.013.

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. (2013). *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. 139 pp. ISBN 978-92-5-107921-8. Available in http://www.fao.org/3/a-i3437e.pdf. Accessed May 25, 2019.

Global Research Alliance on Agricultural Greenhouse Gases & The Sustainable Agriculture Initiative (GRA & SAI). (2015). *Reducing greenhouse gas emissions from livestock: Best practice and emerging options.* New Zealand Agricultural Greenhouse Gas Research Centre. 46 pp. ISBN 978-0-473-30433-1. Available in

https://ccacoalition.org/es/resources/reducing-greenhouse-gas-emissions-livestock-best-practice-and-emerging-options. Accessed May 29, 2019.
Good Company. (2008). *The City of Vancouver, Washington: Corporate greenhouse gas emissions inventory for calendar years 2006 and 2007 report and analysis.* Oregon: Good Company. 8 pp. Available in https://www.cityofvancouver.us/sites/default/files/fileattachments/public_works/page/1120/cov_ghgcorp_execsumm_092608.pdf. Accessed May 26, 2019.
Grey, D., & Sadoff, C. W. (2007). Sink or swim? Water security for growth and development. *Water policy, 9*(6), 545-571. https://doi.org/10.2166/wp.2007.021.
Guyader, J., Janzen, H. H., Kroebel, R., & Beauchemin, K. A. (2016). Forage use to improve environmental sustainability of ruminant production. *Journal of animal science, 94*(8), 3147-3158. https://doi.org/10.2527/jas.2015-0141.
Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z., Wada, Y. & Wisser D. (2014). Global water resources affected by human interventions and climate change. *Proceedings of the National Academy of Sciences, 111*(9), 3251-3256. https://doi.org/10.1073/pnas.1222475110.
Hamerschlag, K., & Venkat, K. (2011). *Meat Eater's Guide to Climate Change+ Health: Lifecycle Assessments: Methodology and Results 2011*. Environmental Working Group. Washington, DC. 63 pp. Available in https://static.ewg.org/reports/2011/meateaters/pdf/methodology_ewg_meat_eaters_guide_to_health_and_climate_2011.pdf. Accessed June 16, 2019.
Hammond, G. (2007). Time to give due weight to the 'carbon footprint' issue. *Nature, 445*(7125), 256.
Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., Takahashi, K. & Kanae, S. (2013). A global water scarcity assessment under Shared Socio-economic Pathways–Part 1: Water use. *Hydrology and Earth System Sciences, 17*(7), 2375-2391. https://doi.org/10.5194/hess-17-2375-2013.
Hermansen, J. E., & Kristensen, T. (2011). *Management options to reduce the carbon footprint of livestock products*. University of Aarhus, Faculty of Agricultural Sciences, Department of Agroecology and Environment, Research Centre Foulum, PO Box 50, DK-8830 Tjele, Denmark.
Herrero, M., Grace, D., Njuki, J., Johnson, N., Enahoro, D., Silvestri, S., & Rufino, M. C. (2013). The roles of livestock in developing countries. *Animal, 7*(s1), 3-18. https://doi.org/10.1017/S1751731112001954.
Herrero, M., Thornton, P. K., Notenbaert, A., Msangi, S., Wood, S., Kruska, R., Dixon, J., Bossio, D., van de Steeg, J., Freeman, H. A., Li, X., & Rao, P. P. (2012). Drivers of change in crop–livestock systems and their potential impacts on agro-ecosystems services and human wellbeing to 2030: A study commissioned by the CGIAR Systemwide Livestock Programme. Nairobi, Kenya: ILRI. 114 pp. ISBN 92–9146–285–3. Available in https://cgspace.cgiar.org/bitstream/handle/10568/3020/SLP%20drivers%20study%20final%20draft.pdf. Accessed June 11, 2019.
Hoekstra, A. Y. (2013). *The Water Footprint of Modern Consumer Society*. 224 pp. London: Routledge. https://doi.org/10.4324/9780203126585.
Hoekstra, A. Y. (2012). The hidden water resource use behind meat and dairy. *Animal frontiers, 2*(2), 3-8. https://doi.org/10.2527/af.2012-0038.
Hoekstra, A.Y. (2010a) The water footprint: water in the supply chain. *The Environmentalist. 93,* 12-13.

Hoekstra, A.Y. (2010b) *The relation between international trade and freshwater scarcity*. WTO Staff Working Paper. No. ERSD-2010-05, World Trade Organization (WTO), Geneva. http://dx.doi.org/10.30875/3563958d-en.

Hoekstra, A. Y. (2010c). The water footprint of animal products. In The meat crisis: Developing more sustanable production and consumption. D'Silva J, Webster J (eds). Earthscan, London, UK. pp. 22-33.

Hoekstra, A. Y., & Chapagain, A. K. (2007). Water footprints of nations: water use by people as a function of their consumption pattern. *Water Resources Management 21*(1):35–48. http://dx.doi.org/10.1007/s11269-006-9039-x.

Hoekstra, A. Y.; Chapagain, A. K. & Zhang, G. P. (2016). Water footprints and sustainable water allocation. *Sustainability, 8*(20), 1-6. http://dx.doi.org/10.3390/su8010020.

Hoekstra, A. Y., & Hung, P. Q. (2002) *Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade.* Value of Water Research Report Series No. 11. Delft, The Netherlands. 120 pp.

Hoekstra, A. Y. & Hung, P. Q. (2005). Globalization of water resources: International virtual water flows in relation to crop trade. Global *Environmental Change, 15*(5), 45–56. http://dx.doi.org/10.1016/j.gloenvcha.2004.06.004.

Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., Richter, B. D. (2012). Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability. *PLoS ONE, 7*(2), e32688. https://doi.org/10.1371/journal.pone.0032688.

Hoff, H., Falkenmark, M., Gerten, D., Gordon, L., Karlberg, L., & Rockström, J. (2010). Greening the global water system. *Journal of Hydrology, 384*(3-4), 177-186. https://doi.org/10.1016/j.jhydrol.2009.06.026.

Hongmin, D., Mangino, J., Mcallister, T. A., Hatfield, J. L., Johnson, D. E., Lassey, K. R., Aparecida de Lima, M., & Romanosvskaya, A. (2006). Chapter 10: Emissions from livestock and manure management. In *2006-IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use*. Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. 10.1-10.87 pp. Published by the Institute for Global Environmental Strategies (IGES), Hayama, Japan. Available in http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf. Accessed May 27, 2019.

Hu, Z., Chen, Y., Yao, L., Wei, C., & Li, C. (2016). Optimal allocation of regional water resources: From a perspective of equity–efficiency tradeoff. *Resources, Conservation and Recycling, 109*, 102-113. https://doi.org/10.1016/j.resconrec.2016.02.001.

Huang, J., Xu, C. C., Ridoutt, B. G., Liu, J. J., Zhang, H. L., Chen, F., & Li, Y. (2014). Water availability footprint of milk and milk products from large-scale dairy production systems in Northeast China. *Journal of cleaner production, 79*, 91-97. https://doi.org/10.1016/j.jclepro.2014.05.043.

Huerta, A. R., Güereca, L. P., & Lozano, M. D. L. S. R. (2016). Environmental impact of beef production in Mexico through life cycle assessment. *Resources, Conservation and Recycling, 109,* 44-53. https://doi.org/10.1016/j.resconrec.2016.01.020.

Instituto Nacional de Estadística, Geografía e Informatica - National Institute of Statistics, Geography and Informatics (INEGI). (2019). PIB y cuentas nacionales - Por actividad económica. Available in https://www.inegi.org.mx/temas/pib/. Accessed June 15, 2019.

Insituto Nacional de Estadistica, Geografia e Informatica - National Institute of Statistics, Geography and Informatics (INEGI). (2016). *Resultados de la Actualización del Marco Censal Agropecuario 2016.* Ciudad de México. 37 pp. Available in

https://www.inegi.org.mx/contenidos/programas/amca/2016/doc/pr_amca2016.pdf. Accessed June 13, 2019.
Intergovernmental Panel on Climate Change (IPCC). (2014a). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R., & White, L. L. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 1132 pp. ISBN 978-84-00-08452-3. Available in https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartA_FINAL.pdf. Accessed May 24, 2019.
Intergovernmental Panel on Climate Change (IPCC). (2014b). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Barros, V .R., Field, C. B., Dokken, D. J., Mastrandrea, M. D., Mach, K. J., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R. & White L. L. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp. ISBN 978-1-107-68386-0. Available in https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartB_FINAL.pdf. Accessed May 25, 2019.
Intergovernmental Panel on Climate Change (IPCC). (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex V., & Midgley, P. M. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. ISBN 978-1-107-66182-0. Available in http://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf. Accessed May 25, 2019.
Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., & Hanson, C. E. (Eds.). Cambridge University Press, Cambridge, UK, 976 pp. ISBN 978 0521 70597-4. Available in https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf. Accessed May 26, 2019.
Intergovernmental Panel on Climate Change (IPCC). (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H. S., Buendia L., Miwa K., Ngara T. & Tanabe K. (eds). Published: IGES, Japan. ISBN 4-88788-032-4. Available in https://www.ipcc-nggip.iges.or.jp/public/2006gl/. Accessed May 27, 2019.
Jaramillo-Villalobos, V. 1994. *Revegetación y reforestación de las áreas ganaderas de las zonas áridas y semiáridas de México.* Comisión Técnica Consultiva de Coeficientes de Agostaderos (COTECOCA). Subsecretaría de Ganadería. Secretaría de Agricultura y Recursos Hidráulicos (SARH). México, D. F. 48 pp. ISBN: 968800376X, 9789688003763.
Jarvis, P. (2007). Never mind the footprints, get the mass right. *Nature, 446,* 24.

Johnson, E. (2008). Disagreement over carbon footprints: A comparison of electric and LPG forklifts. *Energy Policy, 36*(4), 1569-1573. https://doi.org/10.1016/j.enpol.2008.01.014.

Jungbluth, T., Hartung, E., & Brose, G. (2001). Greenhouse gas emissions from animal houses and manure stores. *Nutrient cycling in Agroecosystems, 60*(1-3), 133-145. https://doi.org/10.1023/A:1012621627268.

Kjellsson, J., & Liu, S. (2012). *Transboundary Waters.* 8 pp. Available in http://docplayer.net/32447281-International-water-pricing.html. Accessed June 10, 2019.

Konar, M., Dalin, C., Suweis, S., Hanasaki, N., Rinaldo, A., & Rodriguez-Iturbe, I. (2011). Water for food: The global virtual water trade network. *Water Resources Research, 47*(5), 1-17. https://doi.org/10.1029/2010WR010307.

Kossoy, A., Peszko, G., Oppermann, K., Prytz, N., Gilbert, A., Klein, N., Lam, L., & Wong, L. (2015). *Carbon pricing watch 2015 (No. 21986)*. Washington, DC. World Bank. https://doi.org/10.1596/978-1-4648-0268-3.

Krauß, M., Drastig, K., Prochnow, A., Rose-Meierhöfer, S., & Kraatz, S. (2016). Drinking and cleaning water use in a dairy cow barn. *Water, 8*(7), 302. https://doi.org/10.3390/w8070302.

Krauß, M., Kraatz, S., Drastig, K., & Prochnow, A. (2015). The influence of dairy management strategies on water productivity of milk production. *Agricultural water management, 147,* 175-186. https://doi.org/10.1016/j.agwat.2014.07.015

Legesse, G., Ominski, K. H., Beauchemin, K. A., Pfister, S., Martel, M., McGeough, E. J., Hoekstra, A. Y., Kroebel, R., Cordeiro, M. R. C., & McAllister, T. A. (2017). BOARD-INVITED REVIEW: Quantifying water use in ruminant production. *Journal of animal science, 95*(5), 2001-2018. https://doi.org/10.2527/jas.2017.1439.

Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco,J., Seto, K., Gleick, P., Kremen, C. & Li, S. (2015). Systems integration for global sustainability. *Science, 347*(6225), 1258832. http://dx.doi.org/10.1126/science.1258832.

Liu, J. G. (2009). A gis-based tool for modelling large-scale crop-water relations. *Environmental Model Software, 24*(4), 411–422. https://doi.org/10.1016/j.envsoft.2008.08.004.

Liu, C., Kroeze, C., Hoekstra, A. Y., & Gerbens-Leenes, W. (2012). Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers. *Ecological indicators, 18*, 42-49. https://doi.org/10.1016/j.ecolind.2011.10.005.

López Feldman, A. J., & Hernández Cortés, D. (2016). Cambio climático y agricultura: una revisión de la literatura con énfasis en América Latina. *El trimestre económico, 83*(332), 459-496. http://dx.doi.org/10.20430/ete.v83i332.231.

Lopez Santos, A., Pinto Espinoza, J., Esquivel Arriaga, G., Randeles Reyes, V.H. & Bueno Hurtado, P. (2015). *Escenarios climáticos locales basados en los MGCG del IPCC.* 1ra ed. Universidad Autónoma Chapingo, Durango, México. 128 pp. ISBN: 978-607-12-0403-5.

Lynas, M. (2007). *Carbon counter*. Glasgow: Harper Collins Publishers.

Madrid de Mejía, F. M. (2015). Cambio climático y huella ecológica. *Revista de Ciencias*, XI, 105-112. https://doi.org/10.31381/revista_ciencias.v11i0.573.

Malghan, D. (2010). On the relationship between scale, allocation, and distribution. *Ecological Economics, 69*(11), 2261-2270. https://doi.org/10.1016/j.ecolecon.2010.06.015.

Martínez-Austria, P. F. (2013). Los retos de la seguridad hídrica. *Tecnología y ciencias del agua, 4*(5), 165-180. ISSN: 0187-8336.

Martínez Castillo, R. (2007). Algunos aspectos de la huella ecológica. *InterSedes: Revista de las Sedes Regionales, VIII*(14), 11-25.
Mays, K. L., Shepson, P. B., Stirm, B. H., Karion, A., Sweeney, C., & Gurney, K. R. (2009). Aircraft-based measurements of the carbon footprint of Indianapolis. *Environmental Science & Technology, 43*(20), 7816-7823. https://doi.org/10.1021/es901326b.
Mekonnen, M. M., & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. *Ecosystems, 15*(3), 401-415. https://doi.org/10.1007/s10021-011-9517-8
Mekonnen, M. M., & Hoekstra, A. Y. (2010). *The green, blue and grey water footprint of farm animals and animal product Volume 2: Appendices.* Value of Water Research Report Series No. 48. UNESCO-IHE, Delft, the Netherlands. 122 pp. Available in https://waterfootprint.org/media/downloads/Report-48-WaterFootprint-AnimalProducts-Vol2_1.pdf. Accessed June 16, 2019.
Mekonnen, M., Pahlow, M., Aldaya, M., Zarate, E., & Hoekstra, A. (2015). Sustainability, efficiency and equitability of water consumption and pollution in Latin America and the Caribbean. *Sustainability, 7*(2), 2086-2112. https://doi.org/10.3390/su7022086.
Meza-Herrera, C. A., Ramirez-Flores, J. J., Lopez-Villalobos, N., Silanikove, N., Garcia-Martinez, A., & Veliz-Deras, F. G. (2016). Economic costs of greenhouse gas emissions and water footprint of the intensive milk production system in the arid lands of northern Mexico. In *Steps to sustainable livestock – International Conference*. University of Bristol, CABOT Institute, 12-15 January 2016, Bristol, UK, p. 109.
Meza-Herrera, C. A., Ramirez-Flores, J. J., Lopez-Villalobos, N., Garcia-Martinez, A., Veliz-Deras, F. G., & Lopez-Santiago, M. A. (2015). Unveiling the economic costs of the environmental impact and the water footprint of the Holstein intensive production system in the arid lands of northern Mexico. In *CoBo-Congress-controversies & consensus in bovine health, industry& economics*, 27-30 August 2015, Berlin, Germany, PL01- p. 68.
Millennium Ecosystem Assessment (MEA). (2005). *Ecosystems and Human Well-being: Biodiversity Synthesis.* World Resources Institute, Island Press, Washington, DC. 155 pp. Washington, DC. ISBN 1-59726-040-1. Available in https://www.millenniumassessment.org/documents/document.356.aspx.pdf. Accessed June 13, 2019.
Moate, P. J., Deighton, M. H., Williams, S. R. O., Pryce, J. E., Hayes, B. J., Jacobs, J. L., Eckard, R. J., Hannah, M. C., & Wales, W. J. (2016). Reducing the carbon footprint of Australian milk production by mitigation of enteric methane emissions. *Animal Production Science, 56*(7), 1017-1034. https://doi.org/10.1071/AN15222.
Mogensen, L., Kristensen, T., Nguyen, T. L. T., Knudsen, M. T., & Hermansen, J. E. (2014). Method for calculating carbon footprint of cattle feeds–including contribution from soil carbon changes and use of cattle manure. *Journal of Cleaner Production, 73,* 40-51. https://doi.org/10.1016/j.jclepro.2014.02.023.
Mogensen, L., Nguyen, T. L. T., Madsen, N. T., Pontoppidan, O., Preda, T., & Hermansen, J. E. (2016). Environmental impact of beef sourced from different production systems-focus on the slaughtering stage: input and output. *Journal of Cleaner Production, 133,* 284-293. https://doi.org/10.1016/j.jclepro.2016.05.105.
Montzka, S. A., Dlugokencky, E. J. & Butler, J. H. (2011). Non-CO_2 greenhouse gases and climate change. *Nature 476*, 43–50.
Moore, P. (2017). *The Positive Impact of Human CO_2 Emissions on the Survival of Life on Earth*. Frontier Centre for Public Policy. 28 pp. ISBN: 978-0-9686404-1-8.
Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., & Van Cleemput, O. (1998). Closing the global N_2O budget: nitrous oxide emissions through the

agricultural nitrogen cycle. *Nutrient cycling in Agroecosystems, 52*(2-3), 225-248. https://doi.org/10.1023/A:1009740530221.
Nana, E., Corbari, C., & Bocchiola, D. (2014). A model for crop yield and water footprint assessment: Study of maize in the Po valley. *Agricultural Systems, 127,* 139-149. https://doi.org/10.1016/j.agsy.2014.03.006.
Nilsson, A., & Pettersson, L. G. (2015). The structural origin of anomalous properties of liquid water. *Nature communications, 6,* 1-11. https://doi.org/10.1038/ncomms9998.
Oenema, O., Oudendag, D., & Velthof, G. L. (2007). Nutrient losses from manure management in the European Union. *Livestock science, 112*(3), 261-272. https://doi.org/10.1016/j.livsci.2007.09.007.
Ogino, A., Sommart, K., Subepang, S., Mitsumori, M., Hayashi, K., Yamashita, T., & Tanaka, Y. (2016). Environmental impacts of extensive and intensive beef production systems in Thailand evaluated by life cycle assessment. *Journal of Cleaner Production, 112,* 22-31. https://doi.org/10.1016/j.jclepro.2015.08.110.
Opio, C., Gerber, P., & Steinfeld, H. (2012). Livestock and the environment: addressing the consequences of livestock sector growth. *Advances in Animal Biosciences, 2*(3), 601-607. https://doi.org/10.1017/S204047001100286X.
Organisation for Economic Co-operation and Development (OECD). (2012). *Farmer Behaviour, Agricultural Management and Climate Change*. OECD Publishing. 87 pp. http://dx.doi.org/10.1787/9789264167650-en.
Pandey, D., Agrawal, M., & Pandey, J. S. (2011). Carbon footprint: current methods of estimation*. Environmental monitoring and assessment, 178*(1-4), 135-160. https://doi.org/10.1007/s10661-010-1678-y.
Pérez Espejo, R. (2008). El lado oscuro de la ganadería. *Problemas del desarrollo, 39*(154), 217-227. ISSN 0301-7036.
Peters, G. P. (2010). Carbon footprints and embodied carbon at multiple scales. *Current Opinion in Environmental Sustainability, 2*(4), 245-250. https://doi.org/10.1016/j.cosust.2010.05.004.
Peters, G. M., Wiedemann, S. G., Rowley, H. V., & Tucker, R. W. (2010). Accounting for water use in Australian red meat production. *The International Journal of Life Cycle Assessment, 15*(3), 311-320. https://doi.org/10.1007/s11367-010-0161-x.
Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Clark, S., Poon, E., Abbett, E., & Nandagopal, S. (2004). Water resources: agricultural and environmental issues. *BioScience, 54*(10), 909-918. https://doi.org/10.1641/0006-3568(2004)054[0909:WRAAEI]2.0.CO;2.
Pimentel, D., Houser, J., Preiss, E., White, O., Fang, H., Mesnick, L., Barsky, T., Tariche, S., Schreck, J., & Alpert, S. (1997). Water resources: Agriculture, the environment, and society: An assessment of the status of water resources. *Bioscience 47*(2), 97–106. https://doi.org/10.2307/131302.
Pingali, P., & McCullough, E. (2010). Drivers of change in global agriculture and livestock systems. In *Livestock in a changing landscape, Volume 1: drivers, consequences and responses.* Steinfeld, H., Mooney, H. A., Schneider, F., & Neville, L. E. (Eds). Washington, D.C. Island Press. pp 5-10. ISBN: 9781597266710.
Rees, W. E., & Wackernagel, M. (2000). Ecological footprint: merits and brickbats. *Ecological Economics, 32*(3): 371-374.
Ridoutt, B. G., & Pfister, S. (2013). Towards an integrated family of footprint indicators. *Journal of Industrial Ecology, 17*(3), 337-339. https://doi.org/10.1111/jiec.12026.
Ridoutt, B. G., Page, G., Opie, K., Huang, J., & Bellotti, W. (2014). Carbon, water and land use footprints of beef cattle production systems in southern Australia*. Journal of Cleaner Production, 73,* 24-30. https://doi.org/10.1016/j.jclepro.2013.08.012.

Ridoutt, B. G., Sanguansri, P., Nolan, M., & Marks, N. (2012a). Meat consumption and water scarcity: beware of generalizations. *Journal of Cleaner Production, 28,* 127-133. https://doi.org/10.1016/j.jclepro.2011.10.027.

Ridoutt, B. G., Sanguansri, P., Freer, M., & Harper, G. S. (2012b). Water footprint of livestock: comparison of six geographically defined beef production systems. *The International Journal of Life Cycle Assessment, 17*(2), 165-175. https://doi.org/10.1007/s11367-011-0346-y.

Ridoutt, B. G., Sanguansri, P., & Harper, G. S. (2011). Comparing carbon and water footprints for beef cattle production in Southern Australia. *Sustainability, 3*(12), 2443-2455. https://doi.org/10.3390/su3122443.

Ridoutt, B. G., Williams, S. R. O., Baud, S., Fraval, S., & Marks, N. (2010). The water footprint of dairy products: Case study involving skim milk powder. *Journal of dairy science, 93*(11), 5114-5117. https://doi.org/10.3168/jds.2010-3546.

Ríos-Flores, J. L., Rios-Arredondo, B. E., Cantú-Brito, J. E.,Rios-Arredondo, E. H., Armendáriz-Erives, S., Chavez-Rivero, J. A., Navarrete-Molina, C., & Castro-Franco, R. (2018). Análisis de la eficiencia física, económica y social del agua en espárrago (Asparagus officinalis L.) y uva (Vitis vinífera) de mesa del DR-037 Altar-Pitiquito-Caborca, Sonora, Mexico 2014. *Revista de la Facultad de Ciencias Agrarias. Universidad Nacional de Cuyo, 50*(1), 101-122.

Ripple, W. J., Smith, P., Haberl, H., Montzka, S. A., McAlpine, C., & Boucher, D. H. (2013). Ruminants, climate change and climate policy. *Nature Climate Change, 4*(1), 2. https://doi.org/10.1038/nclimate2081.

Robertson, G. P. (2004). Abatement of nitrous oxide, methane, and the other non-CO_2 greenhouse gases: the need for a systems approach. In *The global carbon cycle Integrating Humans, Climate, and the Nature World*. Field, C.B., & Raupach M.R. (Eds.). (pp. 493–506). Washington, DC, USA.: Island Press.

Rodriguez Casado, R., Garrido Colmenero, A., Llamas Madurga, M. R., & Varela Ortega, C. (2008*). La huella hidrológica de la agricultura española.* Papeles de Agua virtual, (2), 1-38. ISBN: 978-84-96655-23-2.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., & Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 C. *Nature, 534*(7609), 631.

Rota, A., & Sidahmed, A. (2010). *Livestock planning, challenges and strategies for livestock development in IFAD*. IFAD's Livestock Position Paper. Ed IFAD, Rome. 26 pp. Available in https://fcrn.org.uk/sites/default/files/IFAD_LivestockPaper.pdf. Accessed May 27, 2019.

Ruano, J. C. (2016). La huella socioecológica de la globalización. *Sociedad y Ambiente,* (11), 92-121. ISSN: 2007-6576.

Schlink, A. C., Nguyen, M. L., & Viljoen, G. J. (2010). Water requirements for livestock production: a global perspective. *Scientific and Technical Review of the Office International des Epizooties, 29*(3), 603-619.

Scientific Comittee on Problems of the Environment (SCOPE). (2010). *Livestock in a Changing Landscape: Drivers, Consequences, and Responses. Volume 1.* Steinfeld, H., Mooney, H. A., Schneider, F., & Neville, L. E. (Eds.). Published by Island Press 2010. 401 pp. ISBN 978-1-59726-671-0.

Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación - Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA). (2018). *6to Informe de labores 2017-2018 de la Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación.* México, D.F. 168 pp. Available in http://gaceta.diputados.gob.mx/Gaceta/64/2018/sep/Sagarpa-20180904.pdf. Accessed June 13, 2019.

Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación - Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA). (2014). *Anuario Estadístico de la Producción Agropecuaria*. Delegación en la Región Lagunera – SAGARPA. Cd. Lerdo, Durango. México. 167 pp.

Secretaría de Medio Ambiente y Recursos Naturales - Ministry of Environment and Natural Resources (SEMARNAT). (2013). Inventario Nacional de Emisiones de Gases de Efecto Invernadero 1990-2010. Mexico, D.F. 412 pp. ISBN: 978-607-8246-63-2 Available in https://www.gob.mx/cms/uploads/attachment/file/162773/CGCCDBC_2013_INEGEI_1990_2010.pdf. Accessed June 15, 2019.

Secretaría de Medio Ambiente y Recursos Naturales - Ministry of Environment and Natural Resources (SEMARNAT). (2012). *Huella ecológica, datos y rostros.* Cuadernos de divulgación ambiental. Mexico, D.F. 28 pp. ISBN: 978-607-8246-18-2. Available in https://www.sema.gob.mx/descargas/manuales/HuellaEcologica_SEMARNAT.pdf. Accessed May 25, 2019.

Sepehri, A., & Sarrafzadeh, M. H. (2018). Effect of nitrifiers community on fouling mitigation and nitrification efficiency in a membrane bioreactor. *Chemical Engineering and Processing-Process Intensification, 128,* 10-18. https://doi.org/10.1016/j.cep.2018.04.006.

Servicio de Información Agroalimentaria y Pesquera - Agrifood and Fishery Information System. (SIAP). (2019). *Avance acumulado de la producción pecuaria.* Available in http://infosiap.siap.gob.mx/repoAvance_siap_gb/pecResumen.jsp. Accessed June 13, 2019.

Servicio de Información Agroalimentaria y Pesquera - Agrifood and Fishery Information System. (SIAP). (2018). *Atlas Agroalimentario 2012-2018.* Publicado por la SAGARPA. 222 pp. Available in https://nube.siap.gob.mx/gobmx_publicaciones_siap/pag/2018/Atlas-Agroalimentario-2018. Accessed June 13, 2019.

Siebert, S., & Döll, P. (2010). Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology,* 384(3-4), 198-217. https://doi.org/10.1016/j.jhydrol.2009.07.031.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N. H., Rice, C. W., Robledo-Abad, C., Romanovskaya, A., Sperling, F., & Tubiello, F. N. (2014). Agriculture, forestry and other land use (AFOLU). *In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., & Minx, J.C. (Eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 811e922. Available: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf.

Smith, J., Sones, K., Grace, D., MacMillan, S., Tarawali, S., & Herrero, M. (2013). Beyond milk, meat, and eggs: Role of livestock in food and nutrition security. *Animal Frontiers, 3*(1), 6-13. https://doi.org/10.2527/af.2013-0002.

Smith, P., Gregory, P. J., Van Vuuren, D., Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., & Bellarby, J. (2010). Competition for land. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1554), 2941-2957. https://doi.org/10.1098/rstb.2010.0127.

Stehfest, E., Bouwman, L., Van Vuuren, D. P., Den Elzen, M. G., Eickhout, B., & Kabat, P. (2009). Climate benefits of changing diet. *Climatic change, 95*(1-2), 83-102. https://doi.org/10.1007/s10584-008-9534-6.

Steinfeld, H., Gerber, P., Wassenaar, T. D., Castel, V., Rosales, M., & de Haan, C. (2006). *Livestock's long shadow. Environmental issues and options*. Edit FAO Rome, Italy. 416 pp. ISBN: 978-92-5-105571-7. Available in http://www.fao.org/3/a-a0701e.pdf. Accessed June 11, 2019.

Sultana, M. N., Uddin, M. M., Ridoutt, B., Hemme, T., & Peters, K. (2015). Benchmarking consumptive water use of bovine milk production systems for 60 geographical regions: An implication for Global Food Security. *Global Food Security, 4,* 56-68. https://doi.org/10.1016/j.gfs.2014.08.006.

Sultana, M. N., Uddin, M. M., Ridoutt, B. G., & Peters, K. J. (2014). Comparison of water use in global milk production for different typical farms. *Agricultural Systems, 129,* 9-21. https://doi.org/10.1016/j.agsy.2014.05.002.

Thiaw, I., Kumar, P., Yashiro, M., & Molinero, C. (2011). Food and ecological security: identifying synergy and trade-offs. *UNEP Policy Series: Ecosystem Management, 4*, 1-12.

Thomas, G. W. (1987). Water: critical and evasive resource on semiarid lands. In *Conference on Water and Water Policy in World Food Supplies*. Jordan, W. R. (ed). Texas A&M Univ. Press, College Station, Texas (USA). pp 83-90.

Thompson Reuters. (2011). *Point Carbon*. Available in http://pointcarbon.com/aboutus/pressroom. Accessed November 10, 2011.

Thornton, P. K. (2010). Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1554), 2853-2867. https://doi.org/10.1098/rstb.2010.0134.

Toro-Mujica, P., Aguilar, C., Vera, R., & Cornejo, K. (2016). A simulation-based approach for evaluating the effects of farm type, management, and rainfall on the water footprint of sheep grazing systems in a semi-arid environment. *Agricultural Systems, 148,* 75-85. https://doi.org/10.1016/j.agsy.2016.07.011.

United Nations (UN). (2014). *Concise Report on the World Population Situation in 2014.* Population Division, Department of Economic and Social Affairs, United Nations. New York, NY, USA. 38 pp. ISBN 978-92-1-151518-3. Available in https://www.un.org/en/development/desa/population/publications/pdf/trends/Concise%20Report%20on%20the%20World%20Population%20Situation%202014/en.pdf. Accessed May 24, 2019.

United Nations System Standing Committee on Nutrition (SCN). (2005). *Overweight and Obesity: A New Nutrition Emergency?* SCN News No. 29. 76 pp. ISSN 1564-3743. Available in https://www.unscn.org/web/archives_resources/files/scnnews29.pdf. Accessed June 11, 2019.

Vanham, D., Hoekstra, A. Y., & Bidoglio, G. (2013). Potential water saving through changes in European diets. *Environment international, 61,* 45-56. https://doi.org/10.1016/j.envint.2013.09.011.

Wackernagel, M., & Rees, W. E. (1999). *Nuestra Huella Ecológica: reduciendo el Impacto Humano sobre la Tierra.* Santiago de Chile: Colección Ecológica & Medio Ambiente, Lom Ediciones.

Wackernagel, M., Schulz, N. B., Deumling, D., Linares, A. C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., & Randers, J. (2002). Tracking the ecological overshoot of the human economy. *Proceedings of the national Academy of Sciences, 99*(14), 9266-9271. https://doi.org/10.1073pnas.142033699.

Wang, X. J., Zhang, J. Y., Shahid, S., Guan, E. H., Wu, Y. X., Gao, J., & He, R. M. (2016). Adaptation to climate change impacts on water demand. *Mitigation and Adaptation*

Strategies for Global Change, 21(1), 81-99. https://doi.org/10.1007/s11027-014-9571-6.

Wiedemann, S. G., Yan, M. J., & Murphy, C. M. (2016). Resource use and environmental impacts from Australian export lamb production: a life cycle assessment. *Animal Production Science, 56*(7), 1070-1080. https://doi.org/10.1071/AN14647.

Wiedmann, T., & Minx, J. (2008). A Definition of 'Carbon Footprint'. In: *C. C. Pertsova, Ecological Economics Research Trends: Chapter 1,* pp. 1-11, Nova Science Publishers, Hauppauge NY, USA. Available in http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.467.6821&rep=rep1&type=pdf. Accessed May 26, 2019. https://www.novapublishers.com/catalog/product_info.php?products_id=5999.

World Bank. (2019). *Population total.* Available in https://data.worldbank.org/indicator/SP.POP.TOTL?end=2017&start=1960&view=chart. Accessed June 15, 2019.

World Bank. (2012). *A Synthesis Report of the Economics of Adaptation to Climate Change.* Washington, DC. 84 pp. Available in https://siteresources.worldbank.org/EXTCC/Resources/EACC_FinalSynthesisReport0803_2010.pdf. Accessed May 26, 2019.

World Bank. (2009). *Minding the stock: bringing public policy to bear on livestock sector development.* Report no. 44010-GLB.Washington, DC. 92 pp. Available in http://siteresources.worldbank.org/INTARD/Resources/FinalMindingtheStock.pdf. Accessed May 27, 2019.

World Water Assessment Programme (WWAP). (2006). *The United Nations World Water Development Report 2. Water: A Shared Responsibility*. Paris: United Nations Educational, Scientific, and Cultural Organization, and New York: Berghahn Books.

Weindl, I., Bodirsky, B. L., Rolinski, S., Biewald, A., Lotze-Campen, H., Müller, C., Dietrich, J. P., Humpenöder, F., Stevanović, M., Schaphoff, S., & Popp, A. (2017). Livestock production and the water challenge of future food supply: Implications of agricultural management and dietary choices. *Global environmental change, 47,* 121-132. https://doi.org/10.1016/j.gloenvcha.2017.09.010.

Zonderland-Thomassen, M. A., & Ledgard, S. F. (2012). Water footprinting–A comparison of methods using New Zealand dairy farming as a case study. *Agricultural Systems, 110,* 30-40. https://doi.org/10.1016/j.agsy.2012.03.006.

Zonderland-Thomassen, M. A., Lieffering, M., & Ledgard, S. F. (2014). Water footprint of beef cattle and sheep produced in New Zealand: water scarcity and eutrophication impacts. *Journal of Cleaner Production, 73,* 253-262. https://doi.org/10.1016/j.jclepro.2013.12.025.

UNIVERSIDAD AUTÓNOMA CHAPINGO

UNIDAD REGIONAL UNIVERSITARIA DE ZONAS ÁRIDAS

UNIVERSIDAD DE CÓRDOBA

INSTITUTO DE ESTUDIOS DE POSGRADO

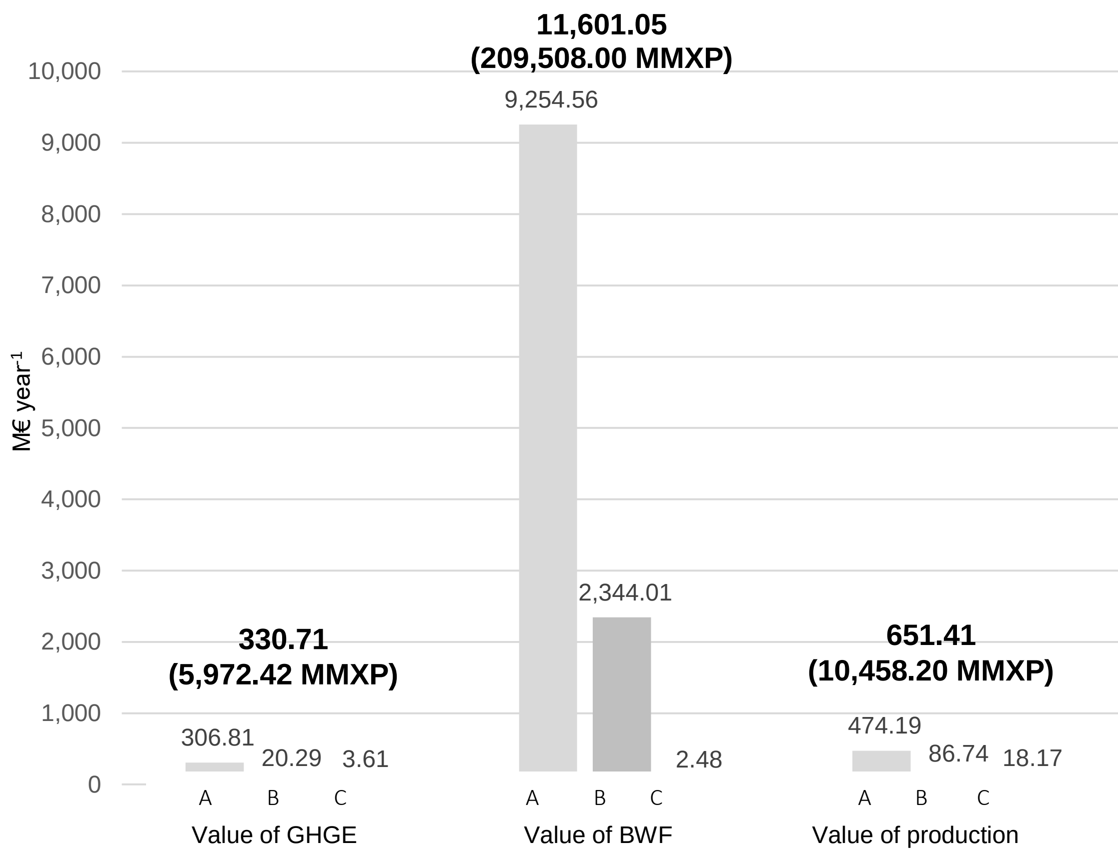
THESIS IN JOINT SUPERVISION
WITH INTERNATIONAL MENTION

THE RUMINANT PRODUCTION SYSTEMS IN THE COMARCA LAGUNERA, MEXICO: ENVIRONMENTAL IMPACT, PRODUCTIVE TRENDS, AND MITIGATION STRATEGIES

IX. APPENDIX

Doctorado en ciencias en recursos naturales y medio ambiente en zonas áridas

Doctorado en recursos naturales y gestión sostenible



Appendix 1. Annual average economic value of greenhouse gas emissions (GHGE) and blue water footprint (BWF) and the value milk-meat production (M€ year^{-1}) generated by A: Dairy Cow Production Systems, B: Intensive Beef Cattle Fattening Industry and C: Goat Milk-meat Production System in the Comarca Lagunera, Mexico, across years (1994 - 2018).