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Small ruminants and sustainability in Latin America & the Caribbean: Regionalization, main production systems, and a combined productive, socio-economic & ecological footprint quantification

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ABSTRACT

A comprehensive evaluation of the sustainability of the Small Ruminant Production Systems (SRPS) in Latin America and the Caribbean (LAC) is crucial to better understand their main distinctive characteristics and to propose a methodological analysis to quantify the ecological, economic and social footprint of small ruminants in the LAC region; this study aims to address such issues. Although it is complex to achieve a classification of systems integrating all the different SRPS existing in the LAC region, four main systems were proposed: *Silvopastoral, Extensive Agrosilvopastoral, Intensve Agrosilvopastoral, & Intensive-Industrial.* During 1998–2018, the LAC-goat-sheep annual average (AA) regarding inventory was 113.7 M heads. While sheep represented 70% of LAC inventory showing an overall decrease (−8%; 316,126 sheep yr^{-1}), goats accounted 30%, with a global 18% rise (142,744 goats yr^{-1}). Eight countries concentrated 90% of such census, highlighting Brazil 23% (25.87 M), Argentina 16% (18.78 M), Mexico 14% (16.43 M), & Peru 14% (15.49 M). The SRPS generated an AA of milk-meat-wool protein (MMWP) of 204.5 Mt, observing a decreased trend (−18%) mainly related to a reduction in raw wool (−45%) with concomitant increases for goat meat (7%), goat milk (27%), sheep meat (15%) & sheep milk (15%). While the SRPS-LAC-AA gross economic value of production was 1772.0 MUSD, 10 countries concentrated 95% of such value, notably Argentina 452.56 MUSD (26%), Mexico 369.11 MUSD (21%), & Brazil 328.0 MUSD (19%). Regarding the environmental impact for said period, the SRPS generated AA values of 585.5 Gg-CH_4, 14,649 CH_4.CO_{2eq}, 1.73 Gg N_2O, 514.1 N_2O-CO_{2eq}, 15,164.3 Total Emissions- CO_{2eq}, & an AA-BWF of 264.3 Mm^3. Regarding the DGHGE (Gg of CO_{2eq}) emissions, 75% were generated by five countries, highlighting Brazil (3445; 23%), Argentina (2477; 16%), & Mexico (2196; 14%). While the global EV of production by the SRPS-LAC was 37,212 MUSD, the total economic cost of the DGHGE was 6516 MUSD; such cost represented 18% of the EVP-SRPS-LAC. The BWF-SRPS-LAC increased by 12%, from 246.36 Mm^3 in 1998–275.58 Mm^3 in 2018; the main countries were Mexico (71.73 Mm^3; 27%), Brazil (46.62 Mm^3; 18%), & Argentina (43.81 Mm^3; 16%). Interestingly, the BWF in m^3 kg^{-1} $MMWP^{-1}$ yr^{-1}, registered an overall increase of 36%, going from 1.11 in 1998–1.51 in 2018. When breaking down the percentage contributions of the EV-Ecological Footprint (EF), 79% corresponds to the EV-BWF and the remaining 21% to the EV-CF. The less water-efficient countries were Guatemala, Bahamas & Guyana, with respective EV-BWF values of 386%, 356% & 316%. Regarding the socioeconomic impact, when transforming the EVP-SRPS-LAC into minimum wages, a global growth of 139% was observed; from 200,000 (1998) to 478,000 (2018) annual minimum wages (AMW). Mexico displayed the highest growth while the largest AMW-contribution across years, with 172,587 AMW, an AA increase of 7243 MW and a grand total MW-contribution (GTMWC) of 3,624,307 MW across years. Our methodological approach

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demonstrate that the SRPS-LAC are an eco-friendly while sustainable option in the face of climate change. However, this sustainability is not homogeneous throughout the study region; further studies must address this type of environmental impact by the SRPS-LAC in a regionalized fashion within the LAC-region; it is certainly a pending assignment. According to our results, it is fundamental to generate transformation and revaluation strategies based on a circular bio-economy perspective, to better understand how these various SRPS products and services benefit the environment, the producer and his family.

1. Introduction

One of the great opportunities that animal production systems (APS) offer to humanity is the possibility of converting into protein of high nutritional value, resources that are not naturally usable for human consumption. Among these APSs, those related to the production of ruminants stand out, which by housing a specialized microbiome in their digestive system, have the ability to transform structural carbohydrates from plant biomass (i.e. cellulose, hemicellulose, lignin) into high biological quality protein. (i.e. meat & milk) available for human consumption (Derner et al., 2017). Globally, grasslands provide 70% of the forage for ruminants (Holechek, 2013), while close to 50% of the land surface is used for grazing domesticated ruminants (i.e. cattle, sheep & goats; CSG) (Holechek et al., 2011). In general, these areas are not suitable for the development of commercial agriculture (Steinfeld et al., 2006). During the last decades (1998–2018), the world ruminant inventory has increased in number, although with dissimilar trends among species, observing increases of 14% in cattle, 16% in sheep, and 47% in goats (Food and Agriculture Organization of the United Nations FAO, 2021a). Both Africa and Asia recorded the largest increases in the ruminant inventory with respective increases of 71% and 21%. While Africa stood out in this regard, with increases in its inventory of 93%, Europe was the only one that reported a decrease in the number of heads of CSǴs species (−18%). Besides, with the exception of Europe, goats showed significant increases in the other continents. Some situations driven these changes in global ruminant inventory pattern are associated with the average increase in economic income in countries with emerging economies, as well as due to an increased urbanization, mainly in Asia and Africa (Derner et al., 2017). A more detailed analyses regarding the 1998–2018 global inventory dynamics generates that the global small ruminant population grew 29%; Africa (77%), America (−3%), Asia (29%), Europe (−17%), and Oceania (−38%). At the species level, corresponding percentages of increases or decreases for goats or sheep among continents were: Africa 93% & 62%, America 21% & −11%, Asia 28% & 29%, Europe − 15% & − 17%, and Oceania 81% & −40%. Besides, while during the said period there were in average 20% more sheep than goats globally, at continental level Africa had 5% more goats, America 58% more sheep, Asia 11% more goats, Europe 87% more sheep, and Oceania 97% more sheep (Food and Agriculture Organization of the United Nations FAO, 2021a).

Considering the global animal inventory pattern, especially ruminants, a deterioration in both the quantity and quality of natural resources has been observed, a situation that threatens the sustainable development of the planet, especially given the needs generated by the increase in the human population (Khan et al., 2020). In this context, it is essential to promote an increase in animal outcomes not based on the number of animals but on their productivity, based on an efficient and sustainable animal production approach. Certainly, we need to meet the challenge regarding the increased requirements of protein consumption of animal origin created by the continuous rise in the human population. At the same time, this scenario requires a significant reduction in the ecological footprint (EF) of animal production to reduce the massive damage caused by global warming and environmental animal impact. The EF is made up of a family of footprints, highlighting the carbon footprint (CF), the blue water footprint (BWF), and the economic footprint (E$F), among others (Ridoutt and Pfister, 2013). Consequently, it is crucial to develop comprehensive evaluations aimed at developing sustainable animal production based on a holistic vision while aligned with other productive segments, especially the economic, environmental and socio-cultural components, to generate and promote strategies aimed to enhance both a responsible use while the sustainability of natural resources (Navarrete-Molina et al., 2019a; 2019b; 2020; Rios-Flores et al., 2018).

The quantification of EF should consider special attention in the Ruminant Production Systems (RPS), since it has been reported that these production systems emit a large amount of greenhouse gases (GHG) (Gerber et al., 2013). Furthermore, it is fundamentally important to consider the impact of the footprint considering the intensive use of water, not only in-situ in the farms (i.e. drinks & services), but also ex-situ, mainly related to the cultivation of forages and cereals used in ruminant feeding (Legesse et al., 2017). In this regard, it has been proposed that the RPS generate a large EF, however, within these systems, the he small ruminant production systems (i.e. sheep & goats; SRPS), have shown the generation of a lesser EF. The last places sheep and goats as a relevant while fundamental option in the conversion of biomass not suitable for human consumption, generating in parallel, various commodities of important value not only biological but also industrial, in particular from a perspective regarding climate change (CC) and food security. The above is particularly true in those SRPS based on organic production schemes, generally developed most of the time in marginal contexts, where cattle would hardly develop. Moreover, such SRPS generate products with important nutraceutical, biological, and innocuous values, since most SRPS base their production on extensive, non-industrial production schemes, framed in a clean, green and ethical approach (Isidro-Requejo et al., 2019; Rimbaud, 2019).

Worldwide, in 2018, there were 2278 M heads of small ruminants, with the highest concentrations observed in China 13% (297 M), India 9% (216 M), Nigeria 6% (126 M), Pakistan 5% (105 M) and Australia 3% (74 M) (Food and Agriculture Organization of the United Nations FAO, 2021a). With respect to the Latin American and Caribbean region (LAC), it contributes 5% (119.5 M) of the stocks of small ruminants at world level; in LAC, five countries concentrate almost 75% of small ruminants: Brazil (24.8%, 29.7 M), Argentina (15.8%, 18.9 M), Mexico (14.6%, 17.4 M), Peru (11.0%, 13.1 M), and Bolivia (8.1%, 9.7 M) (Food and Agriculture Organization of the United Nations FAO, 2021a). Regarding the economic impact at global level, small ruminants generated an economic spill of 84,839 M€ (97,000 MUSD), highlighting China (37.12%), India (6.08%), Iran (4.13%), Turkey (4.10%) & Australia (3.81%) (Food and Agriculture Organization of the United Nations FAO, 2021a). For its part, of such economic impact, the LAC region contributed 1.8% [1563 M€ (1787 MUSD]) with respect to the global value of the small ruminant production, standing out Argentina, Mexico, Brazil, Peru and Uruguay. Together these five countries contributed 83% of the SRPS-LAC economic value, with respective shares of 26.9%, 23.6%, 13.9%, 9.4%, and 8.8%. Even so, the SRPS must be considered within the strategies of adaptation to CC; sheep & goats have shown a high evolutionary and adaptation potential to CC, in addition to playing a preponderant role from an environmental, socioeconomic and cultural perspective in diverse regions of the world, including LAC. Furthermore, this preponderance has placed sheep and goats in a central and strategic subject of study from not only a public policy perspective, but also a scientific one (Koluman and Silanikove, 2018; Silanikove and Koluman, 2015).

Thus, we certainly believe that a comprehensive evaluation of the sustainability of SRPS in LAC is crucial to better understand the main distinctive characteristics of the different production systems, and proposing a methodological analysis to evaluate the ecological, economic and social footprint of small ruminants in the LAC region. This study is the first of a series of three contributions made by our research group, which have been developed in order to address such pending assignments. Regarding this first contribution, our working hypothesis proposes that despite the anticipated variety of the different SRPS in the LAC region, said production schemes represent an important strategy of sustainable production, with reduced environmental impact and with important economic and ecological rewards when contrasting their value of production with respect to the economic impact generated by the ecological footprint of both sheep and goats in the LAC region. Further, our results should demonstrate the central role that said species play in diverse production schemes in marginal environments, most of them arid and semi-arid, being a sustainable and resilient productive option even in the face of the challenges posed by climate change and the current SARS-COV2 syndemic, all for the benefit of the environment, the society, the producer and his family.

2. Materials and methods

2.1. Description of the study area

The Americas present intriguing differences in different issues; it is characterized by extreme differences among the countries that comprise it, not only in environmental terms, but also in geographical, climatic, socio-cultural, educational and economic standings. Thus, animal production systems are not an exception. The last is especially true, considering the countless variety of products generated, the diverse production systems associated with dissimilar biotic, abiotic economic, technological, contextualized in huge social & cultural diversity observed among the Americas' countries (Gallo and Tadich, 2018). In the Americas, there is a sub-region termed Latin America and the Caribbean (LAC), this being an ethnic-geographic concept proposed in the 19th century to identify a region within the Americas where Spanish and Portuguese are spoken as official or main languages (Fig. 1).

Although LAC does not have a precise geographical delimitation, it is widely accepted that it has an area close to 22 million km2, distributed in 33 countries and 15 dependencies, which includes all the countries located between Mexico in North America, and Argentina in South

Fig. 1. Map of the Americas, highlighting the countries included in Latin America and the Caribbean Region (LAC).

America; the observed types of climate, vegetation and topography are quite diverse, from dry desert climates with scrub vegetation to warm humid climates with jungle vegetation (Food and Agriculture Organization of the United Nations FAO, 2021b; National Center for Atmospheric Research NCAR, 2017; WB, 2013). Globally, this region plays an important role in food production, however, it also presents important concerns related to the conservation of wildlife, ecosystems and sustainable livestock production (Galindo et al., 2016). The socioeconomic and cultural situation in many LAC countries contributed to globally rank to this region as the fourth most populated with about 660 million people, equivalent to 9.0% of the world population, with an annual population growth of 0.94%, that should stabilize around 2060 (Food and Agriculture Organization of the United Nations FAO, 2017b; Worldometers, 2021). The main economies in the region are Brazil and Mexico; together they are equivalent to 57.5% of LAC's gross domestic product (GDP) [3552 kM€ (4200 kMUSD)]; the GDP-LAC represents 5% of the world GDP and 20.1% of the GDP-USA, the foregoing possibly linked to the great heterogeneity that exists between and within countries, averaging 0.76 for the human development index, higher than the world average of 0.73 (International Monetary Fund IMF, 2021; United Nations UN, 2019; United Nations Development Programme UNDP, 2019; WB, 2021). The LAC region is considered to be characterized by an expanding middle class. A family is considered middle class if its daily per capita income ranges between 10 and 50 dollars, even so, one of the problems that are still found in the region is intergenerational immobility, which is translated into the generation of high levels of income inequality and lack of opportunities, an even more complex situation in low-income social classes and even worse under rural schemes (Ferreira et al., 2013). Certainly, large differences continue to exist between the countries in southern-LAC (Brazil, Bolivia, Uruguay, Paraguay, Argentina, & Chile) and those in the center and north of LAC. With the exception of Bolivia & Paraguay, the rest of the southern-LAC countries are considered more developed, while those in the center and north are less developed and with more socio-cultural problems; 2/3 of the region's total production and economic value is generated by Brazil, Mexico, Argentina and Colombia (Gray, 2016).

2.2. Classification of the Small Ruminant Production Systems (SPPR) in Latin America & the Caribe (LAC)

To determine the SRPS-LAC, a documentary research was carried out in the main scientific dissemination platforms and institutional repositories of the core universities and journals in the study region, besides other international literature. The last to ensure a holistic view of each of the SRPS-LAC, as well as their main characteristics and typology and be able to detect strengths, threats, opportunities, weaknesses & similarities that would allow generating a more adequate classification or typology of the SRPS-LAC. Table 1 includes of the main classifications of the SRPS-LAC previously reported.

Table 1
Main classifications of small ruminant production systems in Latin America and the Caribbean.

Based on:	Systems	Specie	Source
Intensity on the use of the natural vegetation	Extensive, intensive, migratory	Sheep-Goat	Laguna-Gamez, 2011
	Free ranging, intensive grazing, & complete confinement	Sheep-Goat	Hernández and Sánchez, 2014
	Extensive, intensive, semi-intensive	Goats	Aréchiga et al., 2008; Echavarría and Gómez, 2013
	Mixed, intensive, extensive & organics	Caprinos	Lu and Miller, 2019
	Large variation, from extensive grazing systems managed by small producers and semi-subsistence production, to commercially oriented industrial production systems.	Sheep-Goat	McDermott et al., 2010
Agro-livestock systems	Extensive & subsistence, extensive with a certain degree of market integration, semi-extensive with a more advanced degree of market integration and conspicuous use of cultivated forage, and intensive more commercial & business oriented systems.	Sheep-Goat	Vasconcelos et al., 2013
Productive orientation	Milk & goat production, adult meat production, & goat production	Goats	Salinas, 1995.
	Kid-Milk, milk, & meat oriented systems	Goats	Fideicomisos Instituidos en Relación con la Agricultura - Trusts Established in Relation to Agriculture FIRA (1999)
	Intensive for meat, milk or wool production, extensive for lamb & fine wool production, day grazing-night enclosure for self-consumption, & meat & wool production	Sheep	Echavarría and Gómez, 2013
	Kid, fattened male-goat, & milk production.	Goats	Gómez et al., 2013
	Meat-manure, Meat-milk	Sheep-Goat	Arias, 1987

2.3. Databases and estimation of the Economic Value of the main SRPS-LAC

The study period included from 1998 up to 2018, scrutinizing information generated by the FAO, which involved the sheep-goat inventory, goat milk-meat production, as well as the sheep production; meat, milk & raw wool. Also, the production value of SRPS-LAC was also considered (FAO, 2021). The Economic Value (EV) was adjusted to US dollars (USD) with the year 2011 value as reference point, and its equivalence in euros; said adjustment was made using the United States consumer price index (Center for Public Finance Studies - Centro de Estudios de las Finanzas Públicas CEFP, 2021), while the conversion US dollars - euros was made adjusting the exchange rate reported by Bank of Mexico, on December 30, 2011 (Bank of Mexico – Banco de Mexico, 2021). Upon the database conformation, a series of variables such as Direct Greenhouse Gas Emissions (DGHGE), blue water footprint (BWF), economic value (EV) of said variables was quantified, also, the protein production of meat-milk-wool (Milk - Meat - Wool Protein; MMWP) and the number of annual minimum wages (AMW) generated by sheep-goat systems in LAC were computed. Using constant values as of 2011, in 1998, the gross value of production (GVP) of SRPS-LAC value was quantified to be 771.64 M€ (998.37 MUSD) observing a significant increase up to 1900.40 M€ (2458.73 MUSD) in 2018, which represented a global raise of 146% for said evaluated period.

2.4. Methodology for calculating the direct greenhouse gas emissions (DGHGE) from the SRPS-LAC

To estimate the DGHGE, the methodology proposed by the Intergovernmental Panel on Climate Change (IPCC) in Chapter 10: Livestock

Emissions and Manure Management in Volume 4: Agriculture, Forestry and Other Land Uses was consulted, also considering the 2019 Refinement manual of the IPCC Guidelines 2006 for national GHG inventories (Gavrilova et al., 2019). Because of the extension of the study area, the emission factors proposed by the IPCC corresponding to level 1 (Tier 1) were considered. Also, the conversion rates of these emissions into equivalents of the Global Warming Potential of carbon dioxide proposed by said organism, were considered. These equivalences correspond to the following: while one unit of CH_4 = 25 units of CO_2, one unit of N_2O = 296 units of CO_2. To quantify the economic value of the DGHGE impact, an international price of carbon emissions was used, which was € 15.75 t^{-1} of $CO_{2\text{-eq}}$ (Environmental Finance, 2011). According to the technique of calculating emissions for CH_4 and N_2O of the IPCC in 2019 (Gavrilova et al., 2019) for the agriculture category, three subcategories must be considered: Livestock, savannas and agriculture. In our study, only the methodology for calculating the livestock subcategories is included, considering that it is the only one that generates direct emissions. This research includes:

2.4.1. CH_4 emission by enteric fermentation

The volume of CH_4 emission by enteric fermentation depends on the type, weight and age of the animal at a very detailed level. The equation for the calculation of methane emission from enteric fermentation used was:

Where:

$$E_T = \sum_{(P)} EF_{(T,P)} * \left(\frac{N_{(T,P)}}{10^6}\right)$$

E_T = Methane emissions from Enteric Fermentation in animal category T, Gg CH_4 yr^{-1}.

$EF_{(T,P)}$ = Emission factor for the defined livestock population T and the productivity system P, in kg CH_4 $head^{-1}$ yr^{-1}.

$N_{(T,P)}$ = Number of head of livestock species/category T in the country classified as productive system P.

T = Species/category of livestock.

P = Productivity system, either high or low productivity.

The emission factor used for both goats and sheep was 5.0 kg CH_4 $head^{-1}$ $year^{-1}$, corresponding to that recommended for level 1 (Tier 1) for developing countries and low productivity systems.

2.4.2. CH_4 emission from manure management

Of the levels provided in the IPCC guidelines for estimating CH_4 emissions from livestock manure management, the level 1 method was applied. In this sense, the equation used was:

Where:

$$CH_{4(mm)} = \left[\sum_{T,S,P} \left(N_{(T,P)} * VS_{(T,P)} * AWMS_{(T,S,P)} * EF_{T,S,P}\right)/1000\right]$$

$CH_{4(mm)}$ = CH_4 emissions from Manure Management in the country, kg CH_4 yr^{-1}.

$N_{(T,P)}$ = The number of head of livestock species/category T in the country per productive system P, when applicable.

$VS_{(T,P)}$ = Annual average VS excretion per head of species/category T, for productive system P, when applicable in kg VS $animal^{-1}$ yr^{-1}.

$AWMS_{(T,S,P)}$ = Fraction of total annual VS for each livestock species/category T that is managed in manure management system S, in the country, for productivity system P, when applicable.

$EF_{(T,S,P)}$ = Emission factor for direct CH_4 emissions from manure management system S, by animal species/category T, in manure management system S, for productive system P, in g CH_4 kg VS^{-1}.

S = Manure management system.

T = Species/category of livestock.

P = High productivity system or low productivity system.

To calculate de value of $VS_{(T,P)}$ (Annual average VS excretion per head of species/category T, for productivity system P, when applicable in kg VS $animal^{-1}$ yr^{-1}) from the previous formula, the following formula was used in turn:

$$\boldsymbol{VS_{(T,P)} = \left(VS_{rate(T,P)} * \frac{TAM_{T,P}}{1000}\right) * \quad 365}$$

Where:

$VS_{(T,P)}$ = Annual VS excretion for livestock category T, for productivity system P, kg VS $animal^{-1}$ yr^{-1}.

$VS_{rate(T,P)}$ = Default VS excretion rate, for productivity system P, kg VS (1000 kg animal mass)$^{-1}$ day^{-1}.

$TAM_{(T,P)}$ = Typical animal mass for livestock category T, for productivity system S, kg $animal^{-1}$.

For these calculations, in the case of goats, the emission factors depend on the average annual temperature (AAT) of the country, using the following factors: 0.11 kg CH_4 $head^{-1}$ $year^{-1}$ for countries with AAT $< 15\,^\circ C$, 0.17 for countries with AAT between $15\,^\circ C$ & $25\,^\circ C$, and 0.22 kg CH_4 $head^{-1}$ $year^{-1}$ for countries with AAT $> 25\,^\circ C$, and a live weight per animal of 31.0 kg $head^{-1}$. In the case of sheep, the emission of methane by manure management, the following factors were considered: Excretion rate (VS) 8.30 kg VS (1000 kg of animal mass day^{-1}), recommended value for Tier 1 for LAC regardless of the productivity system, a live weight per animal of 31.0 kg per head was considered, recommended value for LAC regardless of the productivity system, 80% was considered as the regional average of the animal waste management system (AWMS) for LAC. To have all the variables expressed in the formula, the emission factors recommended for manure management in low productivity systems with dry confinement areas were used, these being: 0.90 g CH_4 kg^{-1} VS^{-1} (cold countries), 1.30 g CH_4 kg^{-1} VS^{-1} (temperate countries) and 1.70 g CH^4 kg^{-1} VS^{-1} (hot countries).

2.4.3. Direct N_2O emissions from manure management

Nitrous oxide produced during manure storage and treatment was estimated. Includes both feces and urine produced by sheep-goats, using the following formula:

$$N_2O_{D(mm)} = \left[\sum_{s}\left[\sum_{T,P}\left(\left(N_{(T,P)} * Nex_{(T,P)}\right) * AWMS_{(T,S,P)}\right) + N_{cdg(s)}\right] * EF_{3(S)} * \frac{44}{28}\right]$$

Where:

$N_2O_{D(mm)}$ = Direct N_2O emissions from Manure Management in the country, kg N_2O yr^{-1}.

$N_{(T,P)}$ = Number of head of livestock of livestock species/category T in the country, for productivity system P, when applicable.

$Nex_{(T,P)}$ = Annual average N excretion per head of species/category T in the country, for productivity system P, when applicable in kg N $animal^{-1}$ yr^{-1}.

$N_{cdg(s)}$ = Annual nitrogen input via co-digestion in the country, kg N yr^{-1}, where the system(s) refers exclusively to anaerobic digestion.

$AWMS_{(T,S,P)}$ = Fraction of total annual nitrogen excretion for each livestock species/category T that is managed in manure management system S, in the country, dimensionless to consider productivity class P, if using a Tier 1 approach.

$EF_{3(S)}$ = Emission factor for direct N_2O emissions from manure management system S in the country, kg N_2O-N/kg N in manure management system S.

S = Manure management system.

T = Species/category of livestock.

P = High productivity system or low productivity system.

44/28 = Conversion of N_2O-$N_{(mm)}$ emissions to $N_2O_{(mm)}$ emissions.

In this calculation, the emission values used in the case of goats were 0.45 kg of N per 1000 kg of animal mass per day for Mexico, 1.37 kg of N per 1000 kg of animal mass per day for the rest of the countries considered in this study; 0.02 kg of N $head^{-1}$ day^{-1} for Mexico, and

0.05 kg of N $head^{-1}$ day^{-1} for the rest of the countries considered in this study. When considering sheep, the factors used were 0.32 kg of N per 1000 kg of animal mass per day, equivalent to 3.62 kg N per animal per year, and 0.003 kg N2O-N (kg $N)^{-1}$.

2.5. Methodology for calculating the BWF of SRPS-LAC

To estimate the BWF, the values reported by Mekonnen and Hoekstra (2010) were used, which correspond to farm products and animals. The mathematical basis for these calculations is as follows:

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

Where:

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

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

Where:

$Feed[a,c,s,p]$ = The annual amount of the p-feed ingredient consumed by an animal-a category, in a c-country, in a s-production system (t $year^{-1}$),

$WF_{prod}[p]$ = The water footprint of the p-feed ingredient (m^3 t^{-1}),

$WF_{mixing}[a,c,s]$ = The volume of water consumed for mixing the feed for a-animal category, in a c-country, in a s-production system (m^3 $year^{-1}$ $animal^{-1}$) 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.

To determine the BWF value of sheep-goat milk, the information reported for milk not concentrated & unsweetened exceeding 1% but not exceeding 6% fat was used. Regarding the case of goat meat, previous information was used for the category fresh, chilled or frozen, and for sheep meat the category sheep carcasses and half carcasses, fresh or chilled. Finally, for the case of wool, the corresponding to sheep or lamb raw wool was used. In this research, it was decided to adopt a conservative position, by not considering additional water resources derived from agriculture and land use, that is, the green water footprint. In this sense, Ridoutt and Pfister (2010) reported that the consumption of green water per se does not contribute to water scarcity, until said green water turns into blue water. The above, considering that green water does not contribute to the flows of environmental water necessary to maintain the health of freshwater ecosystems and, in the same way, it is not available for human consumption and other anthropic uses, until it is turns into blue water. These authors consider green water as one of the resources provided to humanity by the planet, such as solar radiation, wind, soil, among others. However, it is considered necessary to clarify that we do not intended to minimize the importance of green water as a vital natural resource.

As commented, green water does not contribute to water scarcity, not so, blue water, at this point the competition between the different uses of available blue water should be highlighted, prioritizing human consumption at all times. Therefore, the magnitude of the contribution to water scarcity must be considered; hence, the stress-weighted BWF was determined, which results from multiplying the BWF value by a water stress index as suggested by Ridoutt and Pfister. (2010). The importance of these calculations is based on the concern related to the consumption of water in agricultural production and how this promotes the possibility of a shortage of water and thus, limiting the availability of fresh water for both human consumption and that used by the environment. That is why calculating the direct consumption of blue water is crucial (Ridoutt and Pfister, 2010). To determine this impact, it is necessary to calculate a water stress index (WSI), which assesses the impact related to fresh water consumption and is considered an indicator that evaluates water deprivation, which is why it only applies to blue water (Pfister et al., 2009). The WSI considers the water use-availability ratio (WTA), defined as the ratio of the total annual withdrawal of fresh water for human use in a defined region to the annual supply of renewable water in that region (Frischknecht et al. 2006). The WSI values range from 0.01 to 1, values that are calculated with the following mathematical expression:

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

In this study, the stress-weighted BWF value was calculated by multiplying the BWF value by a calculated WSI; said index was calculated for each of the LAC countries, using the information published by Mekonnen et al., 2014. Regarding the average annual shortage of blue water in the LAC region was mestimated at a resolution level of 30 × 30′ grid cells. In this context, Hoekstra and Mekonnen (2011) define the scarcity of blue water as the ratio between the total BWF and the availability of blue water, which represents the environmental flow requirements. Later on, this information was extrapolated with the WSI values reported by Ridoutt and Pfister (2010) for LAC countries, using geoprocessing schemes in ArcGis 10 (Esri ArcGIS® and ArcMap ™). Besides, to provide an economic value to the BWF, an international average price of € 3.53 m^{-3} (4.53 USD m^{-3}) of water was considered, as suggested by Kjellsson and Liu (2012) for some countries of the European Union (Denmark, Germany, Netherlands, Belgium, France among others).

2.6. Equivalences and statistical analyses

In this type of research that considers more than one species, a homogenization is necessary to make comparisons, that is why the required information was converted to kg of milk-meat-wool protein (Milk - Meat - Wool Protein; MMWP) for sheep and goats. To perform said transformations, the equivalences used correspond to those shown in Table 2. The transformations are identified with numbers in ***bold and italics***. Linear regressions were developed for each of the analyzed variables, establishing 1998 as the intersection for them, the software SAS (PROC REG) (SAS Inst., Cary CC, version 9.4), Minitab (Minitab Inc., State College, Pennsylvania) and Mathworks (Natick, Massachusetts) were used.

Table 2
Equivalences used in the transformation of the original data to milk - meat - wool protein sheep-goat.

1 kg of sheep meat protein	5.27 kg of sheep meat	Junkuszew et al. (2020)
1 kg of sheep milk protein	18.18 kg of sheep milk	Balthazar et al. (2017)
1 kg of sheep wool protein	1.61 kg of sheep wool	National Research Council NRC (1985)
1 kg of goat meat protein	5.31 kg of goat meat	Isidro-Requejo et al. (2019)
1 kg of goat milk protein	30.30 kg of goat milk	Urieta et al. (2001)
1 kg of sheep-goat milk	0.96 l of sheep-goat milk	Robertson et al. (2015)
1 kg of sheep-goat fat & protein corrected milk	3.24 kg of sheep-goat milk	Robertson et al. (2015)

3. Results

3.1. Characterization of the Small Ruminant Production Systems (SRPS) - LAC

Although it is complex to achieve a classification of systems that can integrate all the different SRPS existing in the LAC region, it is possible to propose a general classification including some central variables that highlight how the general typology is made up that integrate homogeneous classificatory variables in some of the main production systems in the region. For the case of this analysis, and based on scientific reports generated in the study region, four main SRPS-LAC are proposed (Table 3). In this regard, each of the identified variables was assigned with qualitative values, which represent to a greater extent the possible conditions that could be found in most of the representative production systems in the study area; four main SRPS-LAC were proposed: *Silvopastoral, Extensive Agrosilvopastoral, Intensve Agrosilvopastoral, & Intensive-Industrial.*

3.1.1. Silvopastoral systems

These are extensive grazing systems with night enclosure, for control and protection of the herd, with little or no supplementation in corral, located mainly in areas with slight rainfall (i.e. arid & semi-arid areas, < 300 mm). These are systems characterized by low human population densities, areas of high to very high marginalization, limited agroecological potential, a weak degree of integration into the commercial and market chain; an important part of animal production is used for self-consumption. Normally, herds have of low animal density, composed of Criollo animals, generally a multiracial mosaic adapted to difficult environmental conditions, and limited production rates according to the restricted access to native vegetation. Crop production in these areas is marginal and rainfed, so livestock production predominates as the main source of livelihood, given the impossibility to develop a commercial agriculture. This production scheme is developed with a high degree of marginalization from a socio-ecological-economic perspective.

3.1.2. Extensive agrosilvopastoral systems

These are extensive grazing systems also with night enclosure, which combine strategies that associate agricultural production with extensive grazing and the use of agricultural residues on farmland after harvest; rainfall in these systems ranges 300–450 mm. In these systems, an incipient use of technologies for the conservation of agricultural residues is performed for the supplementation of animals during the dry season, mainly with forages produced by the same producers and harvest residues from agricultural areas, mostly from a rainfed agriculture. Besides, the quality of natural vegetation is moderate, while the use of purchased of supplement is limited. Also, the production of meat-milk-wool shows an incipient integration to market chains as most of these systems are located in semi-arid agro-ecological zones, far away from urban centers. In some cases, these systems have access to dry agricultural areas with a certain proportion of irrigation; animal density is low to medium, and the production scheme is developed with a medium degree of socio-ecological-economic marginalization.

3.1.3. Intensive agrosilvopastoral systems

In these systems, animals may have access to pastures during some hours of the day, besides, grazing occurs on agricultural lands after harvest, with nutritional supplementation the most of the year. These systems are located in areas with higher agroecological potential; rainfall ranges from 450 to 600 mm. Therefore, in these systems, animals have access to nutritional supplementation based on cereals and concentrates, as well as forages produced by the same animal holders. Eventually, animals harvest residues of the agricultural areas or purchase of feed from areas where irrigated agriculture is practiced. These production systems are located in agricultural regions of valleys, and in temperate and tropical zones; in general, the quality and quantity of the natural vegetation is good. The genetic background of the animals is backed up with the use of sires of specialized breeds for a defined productive purpose, with access to marketing chains for most of the year, observing that the highest percentage of products of animal origin are integrated to these market chains. The density of the animal population is medium to high, and the degree of marginalization observed in these production schemes is medium to low.

3.1.4. Intensive-industrial systems

These are industrial systems, fed in a manger or corral, with zero-grazing throughout the year, with a highly variable volume of precipitation, and generally with access to groundwater by pumping or superficial water. The genetic quality of the animals is high with specialized breeds for a defined productive purpose, showing a high integration to the market and commercialization chains, there is no self-consumption, and most of these intensive systems are perfectly aligned in a vertical integrated fashion to milk-meat-wool transforming industries. The feeding, reproduction, genetics, health, and management components are developed under strict controlled conditions. Some producers transform part of their animal production to products with higher added value, longer shelf life, while exert a direct sale of selected animals as breeders (i.e. replacement sires and reproductive females). Normally, these systems have a high density of animals and develop close to urban centers; the degree of marginalization is low to very low.

3.2. Inventory, production and gross value of the small ruminant production systems in LAC

Throughout the analyzed period (1998–2018), a 1% reduction in the inventory of SRPS-LAC occurred, observing the largest decrease in 2012 (−3%) as compared to 2011. At the species level, goats reported a decrease of − 4%, while sheep − 3% when comparing 2012 vs 2011.

Table 3
Characteristics of the different small ruminant production systems in Latin America and the Caribbean.

Variable/System	Silvopastoral	Extensive agrosilvopastoral	Intensive agrosilvopastoral	Intensive-industrial
Intensity of use of native vegetation	High	Medium	Low	Null
Rainfall (mm)	< 300	300–450	450–600	Variable
Access to crop residues in agricultural areas	Null	Low-Medium	Medium-High	Null
Production objective of the system	Goats: Meat	Kid-Milk Kid-Adults	Milk & Meat	Milk-Meat-Reproducers
	Sheep: Wool-Meat	Meat-Wool-Milk	Meat-Milk-Reproducers	Meat-Milk-Reproducers
Production marketing-oriented	Selfconsumption	Selfconsumption Low scale sales	Medium scale sales Selfconsumption	High scale sales
Animal genetic background	Criollo	Multiracial	Crossbred	Pure Breeds
Animal productive efficiency	Low	Low-Medium	Medium-High	High
Animal density – population	Low	Medium	High	Very high
Marginality Index	High - Very High	High - Medium	Medium – Low	Low - Very Low
Market chain integration	Null	Low	Medium	High
Inputs to the production system	Null	Low	Medium	High

The above negatively impacted the production of milk-meet-wool protein (MMWP), which decreased by − 18% (1998–2018) going from 222.42 kt of MMWP in 1998 to 182.56 kt in 2018 (Table 4). These decreases could be related to those presented by sheep, which in 2010, reported a − 10% reduction in MMWP production as compared to 2009, with a cumulative 11% decrease during 2009–2013. This scenario can be related to the decrease observed in wool production in the SRPS-LAC, close to − 45%, as compared to the other products of small ruminant origin. Indeed, other commodities of the SRPS-LAC showed increases; goat meat (7%), goat milk (27%), sheep meat (15%) and sheep milk (15%).

A regional perspective of the inventory shows that eight countries concentrate 90% of the animal census, that is, of the 114.68 M sheep-goat in LAC, 103.45 M are concentrated in: Brazil 23% (25.87 M), Argentina 16% (18.78 M), Mexico 14% (16.43 M), Peru 14% (15.49 M), Bolivia 9% (10.0 M), Uruguay 8% (9.66 M), Chile 4% (4.11 M) and Cuba 3% (3.12 M). However, LAC presented a decreasing trend in the sheep-goat inventory, with an average annual reduction of 173,383 head, observing increases and decreases, yet, identifying four clearly marked periods in the evolution of the sheep-goat inventory. The period 1998–2002 presented a decrease of − 2%, then an increase of 8% (2002–2006), later another decrease of − 8% (2006–2014), and finally, an increase of 7% (2014–2018). In this regard, it must be noted that sheep represented 70% of the small ruminant LAC-inventory, and that during the period analyzed, the sheep census presented an overall decrease of − 8%, with an average annualized reduction of 316,126 sheep. For their part, goats only represented 30% of the small ruminant census in LAC, showing a growth of 18% during the analyzed period, with average annual increases of 142,744 goats.

When analyzing the GVP-SRPS-LAC, a general increase of 82% occurred in the period analyzed, with the highest growth (45%) registered in 2010 regarding to 2009, and the highest decrease (−28%) in 2015 as compared to 2014. Nonetheless, an average annual economic increase of 4% occurred during said period, equivalent to 72.96 M€ (94.40 MUSD) ($R^2 = 0.7$), between 1998 and 2018 (Table 4). Of the 36 countries and territories in LAC that reported income from small ruminant activities, a total of 1369.61 M€ (1772.04 MUSD), 10 of them concentrated 95% of said income: Argentina, Bolivia, Brazil, Chile, Colombia, Jamaica, Mexico, Peru, Uruguay and Venezuela. However, the three countries that reported the largest income concentration, 65% of said value (888.58 M€ or 1149.67 MUSD), Argentina got 349.78 M€ (452.56 MUSD), Mexico 285.29 M€ (369.11 MUSD) and Brazil 253.51 M€ (328.00 MUSD), equivalent to 26%, 21% and 19%, respectively.

In LAC, the average production of MMWP decreased 1749 t yr^{-1}, related to the reduction in the production of sheep protein, which decreased 2022 t yr^{-1}, while the goat protein production increased 273 t yr^{-1} in the period analyzed. In this regard, the protein originating from wool decreased 2235 t yr^{-1}, while the meat-milk protein sheep-goat showed increases in the protein of goat meat (46 t yr^{-1}), goat milk (227 t yr^{-1}), sheep meat (313 t yr^{-1}), and sheep milk (0.055 t yr^{-1}). On this respect, it is crucial to mention that sheep wool has more protein per kilogram, with a value of 62.11%, as compared to the other small ruminant products evaluated in this study. Indeed, while the protein included in one kg of sheep meat only represents 18.98%, goat meat has 18.83%, sheep milk 5.5%, and goat milk 3.3%. However, it should be noted that while meat and milk are part of the human diet, wool is not, but rather its use is focused on the textile industry, either for human clothing or as part of decorative accessories or insulating products at industrial level.

3.3. Quantification of the small ruminant production system carbon footprint (CF) in LAC

During the analyzed period, the DGHGE-LAC generated by the SRPS averaged 15,226 Gg annually, showing a decreasing trend of 22.31 Gg yr^{-1}. Considering that these emissions are directly proportional to the regional inventory of sheep and goats, increases and decreases were observed in the four periods previously mentioned (1998–2002, 2002–2006, 2006–2014 & 2014–2018) (Table 4). The DGHGE trend is presented in Fig. 2, observing a decrease at the start of the period, followed by a rapid increase until 2006 to later observe the lowest values in 2014 (14,711 Gg of CO_{2eq}), and subsequently a gradual increase until the end of the analyzed period. The emissions that showed a greater contribution were those related to methane from enteric fermentation of sheep, which participated with 97% of the DGHGE-SRPS-LAC. Therefore, sheep production contributed 70% of the total emissions in LAC in said period. In the LAC-region, five countries generated 75% of DGHGE: Brazil (3445 Gg of CO_{2eq}), Argentina (2477 Gg of CO_{2eq}), Mexico (2196 Gg of CO_{2eq}), Guyana (1747 Gg of CO_{2eq}) and Peru (1340 Gg of CO_{2eq}), equivalent to 23%, 16%, 14%, 11% and 10%, respectively.

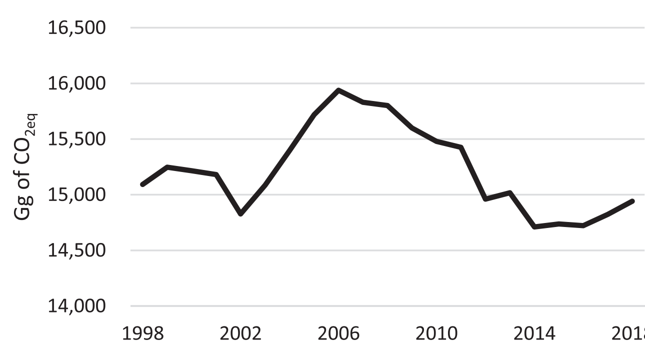

Fig. 2. Evolution of total direct greenhouse gas emissions (CH_4 and N_2O) (Gg CO_{2eq}) generated by the small ruminant production systems in Latin America and the Caribbean, across years (1998–2018).

Table 4
Inventory; gross value of production (GVP); milk - meat - wool protein (MMWP); direct emissions of methane (CH_4) and nitrous oxide (N_2O); and blue water footprint (BWF) generated by sheep-goat production systems in Latin America and the Caribbean, across time (1998–2018).

Year	Census (M head)	GVP[a] [M€ (MUSD)]	Production MMWP[b] (kt)	Direct Emissions (Gg)					BWF (Mm^3)
				CH_4	CH_4 CO_{2eq}	N_2O	N_2O CO_{2eq}	TE[c] CO_{2eq}	
1998	113.75	753.68 (975.1)	222.42	583.31	14,582.84	1.71	509.28	15,092.11	246.36
2002	111.68	732.35 (947.5)	201.60	572.87	14,321.64	1.70	505.14	14,826.77	252.89
2006	120.06	1078.91 (1395.9)	205.52	615.88	15,396.89	1.82	534.46	15,938.49	265.75
2010	116.58	1938.82 (2508.5)	199.50	598.15	14,953.82	1.76	525.68	15,479.50	279.12
2014	110.79	2164.30 (2800.2)	191.05	568.42	14,210.44	1.68	500.58	14,711.01	269.59
2018	112.46	1798.87 (2327.4)	182.56	577.15	14,428.70	1.72	512.22	14,940.91	275.58
Average	**114.68**	**1369.61 (1772.04)**	**200.44**	**588.34**	**14,708.49**	**1.74**	**517.77**	**15,226.25**	**265.63**
Grand total	**2408.30**	**28,761.73 (37,212.74)**	**4209.22**	**12,355.13**	**308,878.19**	**36.49**	**10,873.14**	**319,751.33**	**15,578.21**

[a] GVP = Gross Value of Production at constant economic values as of 2011.
[b] MMWP: Milk-Meat-Wool Protein.
[c] TE = Total Emissions.

Methane emissions from enteric fermentation and manure management are directly proportional, both to direct nitrous oxide emissions from manure management, as well as to the total GHGE emissions and, therefore, show the same trend throughout the period analyzed (Table 4; Fig. 2). However, when converting the animal production from the SRPS-LAC into kg of meat-milk-wool protein, it was observed that DGHGE grew by 21% throughout the analyzed period, going from 67.85 kg CO_{2eq} kg^{-1} $MMWP^{-1}$ in 1998, to 81.84 kg CO_{2eq} kg^{-1} $MMWP^{-1}$ in 2018, with an annualized average during the period 75.96 kg CO_{2eq} kg^{-1} $MMWP^{-1}$. An increasing and consistent annualized trend ($R^2 = 0.80$) of 0.55 kg CO_{2eq} kg^{-1} $MMWP^{-1}$ was observed (Fig. 3). At the regional level, the great variability in the analyzed information showed significant differences among countries. The highest emissions expressed in kg CO_{2eq} kg^{-1} $MMWP^{-1}$ were generated by Costa Rica (342.56), Panama (231.42), Antigua & Barbuda (179.35), Dominica (172.93) & El Salvador (138.21). Among the countries with the lowest kg CO_{2eq} kg^{-1} MMWP were Guatemala (39.72), Chile (16.48), Uruguay (15.77), Jamaica (11.40) & Ecuador (6.52). However, the countries with the highest contribution to DGHGE per kg of meat-milk-wool protein were: Brazil (94.95 kg CO_{2eq} kg^{-1} $MMWP^{-1}$), Peru (91.43 kg CO_{2eq} kg^{-1} $MMWP^{-1}$), Mexico (80.55 kg CO_{2eq} kg^{-1} $MMWP^{-1}$) & Argentina (54.96 kg CO_{2eq} kg^{-1} $MMWP^{-1}$).

Fig. 4 presents the evolution of the EV generated by the SRPS and the DGHGE; the annual average EVP was 1370 M€ (1773 MSUD), equivalent to a total spill of 28,762 M€ (37,212 MUSD) during the study period. The trend showed an average annual increase of 72.96 M€ (94.40 MUSD). The analysis of the EV-DGHGE exhibited a decreasing trend throughout the analyzed period 0.35 M€ (0.45 MUSD), equivalent to an annual average economic cost of 240 M€ (311 MUSD) while the total economic cost was 3036 M€ (3928 MUSD). According to these results, the DGHGE-economic cost represented 18% of the EVP-SRPS-LAC. Regarding the economic cost of the DGHGE per kg of MMWP, this was 1.20 € (1.55 USD) kg^{-1} of MMWP. Said cost increased 21% throughout the analyzed period, going from 1.07 € (1.38 USD) in 1998–1.29 € (1.67 USD) in 2018, per kg MMWP. By quantifying the EV per kg MMWP, a global average of 6.96 € (9.00 USD) per kg of MMWP was observed, reaching its lowest level in 1999 with 3.17 € (4.10 USD), and its highest value in 2011 with 11.60 € (15.00 USD) per kg of MMWP. Unlike the 21% increase in the DGHGE-economic cost, the observed rise of the EV per kg of MMWP showed a significant global escalation of 191%, going from 3.39 € (4.36 USD) in 1998, to 9.85 € (12.74 USD) in 2018, per kg of MMWP produced by the SRPS-LAC.

3.4. Quantification of the blue water footprint (BWF) from the small ruminant production systems in LAC

Table 4 and Fig. 5 show the BWF generated by the SRPS-LAC across time (1998–2018), observing an annualized growing trend of 265.63 Mm^3. The BWF-SRPS-LAC increased by 12%, from 246.36 Mm^3 in 1998–275.58 Mm^3 in 2018 (Table 3). The countries that contributed the most to the BWF-SRPS-LAC were Mexico (71.73 Mm^3), Brazil (46.62 Mm^3), Argentina (43.81 Mm^3), Peru (20.36 Mm^3) and Bolivia (19.52 Mm^3), which represented 76% of the total BWF-SRPS-LAC, with respective values of 27%, 18%, 16%, 8% and 7%. However, the impact generated by the BWF-SRPS-LAC is directly related to both the inventory and the use of blue water to meet the needs of both drinking and service water per animal. So, the BWF was also calculated as m^3 $head^{-1}$ yr^{-1}; the regional LAC average was 2.32 m^3 $head^{-1}$ yr^{-1}, with a global increase of 13%, from 2.17 in 1998–2.45 in 2018. Regarding the analysis based on kg of live weight (LW), an increase of 12% was observed, going from 64.78 L kg^{-1} LW^{-1} yr^{-1} in 1998 against 72.30 L kg LW^{-1} yr^{-1} in 2018, which represented a global average of 68.85 L kg^{-1} LW^{-1} yr^{-1}, with annual average increases of 13.3 mL kg^{-1} LW^{-1} yr^{-1}. The annual average BWF generated by each kg of meat-milk-wool protein produced by SRPS-LAC was 1.33 m^3 kg^{-1} $MMWP^{-1}$ yr^{-1}, with annualized average increases of 17.1 L kg^{-1} $MMWP^{-1}$ (Fig. 3). However, unlike the two variables previously calculated, the BWF in m^3 kg^{-1} $MMWP^{-1}$ yr^{-1}, registered an overall increase of 36%, going from 1.11 m^3 kg^{-1} $MMWP^{-1}$ yr^{-1} to 1.51 m^3 kg^{-1} $MMWP^{-1}$ yr^{-1}, between 1998 and 2018, respectively.

Regarding the economic impact of the stress-weighted BWF, the WSI was previously calculated by country, observing high values in Mexico (0.94), Trinidad & Tobago (0.86), Bahamas (0.85), Chile (0.81), Argentina (0.76) and Cuba (0.59). In contrast, low values occurred in Belize (0.05), French Guyana (0.06), Uruguay (0.08), Falkland Islands (0.08) & Suriname (0.09). These values fall into the low category, according to the WSI 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). This observed variability seems logical when considering the extension, the diversity of altitudes & longitudes, photoperiods, thermoperiods,

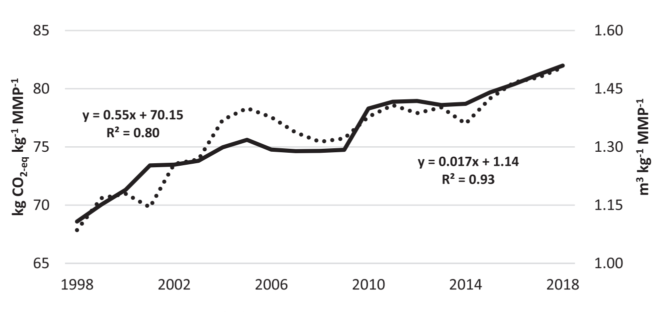

Fig. 3. Direct greenhouse gas emissions (DGHGE; kg CO_{2eq} kg^{-1} $MMWP^{-1}$) & blue water footprint (BWF; m^3 kg^{-1} $MMWP^{-1}$) per kg of meat-milk-wool protein generated by the small ruminant production systems in Latin America and the Caribbean, across years (1998–2018).

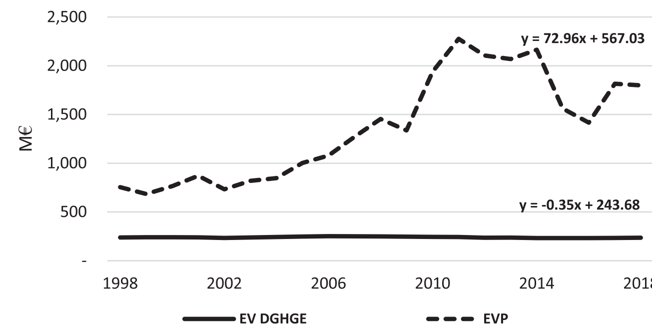

Fig. 4. Comparative analysis between the economic value of direct greenhouse gas emissions (CO_{2eq}) (EV-DGHGE) and the economic value of production (EVP), generated by the small ruminant production systems in Latin America and the Caribbean, across years (1998–2018; at constant economic values as of 2011).

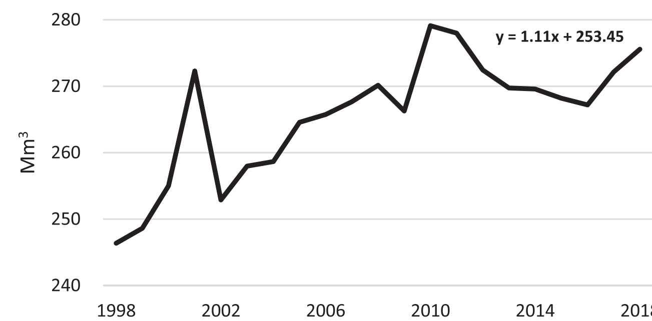

Fig. 5. Evolution of the total blue water footprint (Mm^3 yr^{-1}) generated by the small ruminant production systems in Latin America and the Caribbean, across years (1998–2018).

soils, orography among others; all of them generating a significant diversity of ecotypes and biotic resources in the study area. It is essential to highlight that this weighting of the BWF with respect to the WSI generated by agricultural activities is essential since it competes directly with human water consumption; that is, if said water had not been consumed by the small ruminants, it would be available for human consumption. By adding the stress-weighted BWF generated by the SRPS-LAC, it was determined that they contributed, with an annualized average of 142.55 Mm^3 during the period analyzed, to the regional shortage of freshwater in LAC, which could have been available for human consumption. This value increased 19% across years, going from 124.19 Mm^3 in 1998–147.80 Mm^3 in 2018, equivalent to an average annualized increase of 0.88 Mm^3.

From a per animal perspective, it was theoretically calculated that keeping one sheep or goat in LAC contributed to an annualized average to the global water shortage of 997 L, during said period. The highest value occurred in 2011 (1086 L $head^{-1}$) while the lowest arose in 1999 (911 L $head^{-1}$), generating an increase of 2.7% thru the period, from 954 L $head^{-1}$ in 1998–980 L $head^{-1}$ in 2018; the last generated a total average rise of 7.3 L $head^{-1}$ yr^{-1}. The lowest annual averages of WSI-weighted BWF (L $head^{-1}$ basis) occurred in Falkland Islands (34), Belize (56), French Guyana (103), Suriname (113) & Uruguay (116). In contrast, the uppermost values occurred in Argentina (1775), Trinidad & Tobago (1905), Mexico (4079), Jamaica (5020) & Bahamas (6371). Sizing this information from a perspective of BWF-WSI kg^{-1} MMWP, it was quantified that the annualized average for the production of 1 kg of MMWP by the SRPS-LAC, theoretically is equivalent to the world shortage of fresh water in 667 L kg^{-1} $MMWP^{-1}$. However, due to the high variability among ecotypes, production systems, & countries, the largest averages occurred in a basis of L kg^{-1} $MMWP^{-1}$ in Mexico (2453), Bahamas (2018), Trinidad & Tobago (1342), Cuba (1325) & Haiti (975). The countries with the lowest weighted water expenditure (BWF-WSI) were Brazil (112), French Guyana (110), Belize (103), Ecuador (98) & Uruguay (35). When quantifying the EV-BWF, it represented 68% of the EVP-SRPS-LAC; while the EV-BWF increased by 3.88 M€ (5.02 MUSD), the EVP increased by 72.96 M€ (94.40 MUSD) (Fig. 6).

3.5. Quantification of the socio-environmental footprint from the small ruminant production systems in LAC

3.5.1. Environmental efficiency (EV-EF/EVP)

The comparison between the EVP vs EV-EF generated by the SRPS-LAC is shared in Fig. 7. The EV-EF represented an annualized average of 86% along the analyzed period regarding to the EVP-SRPS-LAC. When breaking down the percentage contributions of the EV-EF, 68% corresponds to the EV-BWF and the remaining 18% to the EV-CF. In other words, the environmental economic impact generated by the CF, represented 25% of the economic value of the BWF. Therefore, the SRPS-LAC become an eco-friendly sustainable option in the face of climate

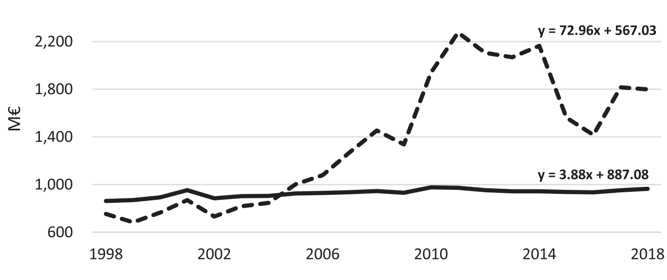

Fig. 6. Comparative analyses between the economic value of the blue water footprint (EV-BWF) and the economic value of production (EVP), generated by the small ruminant production systems in Latin America and the Caribbean, across years (1998–2018, at constant values as of 2011).

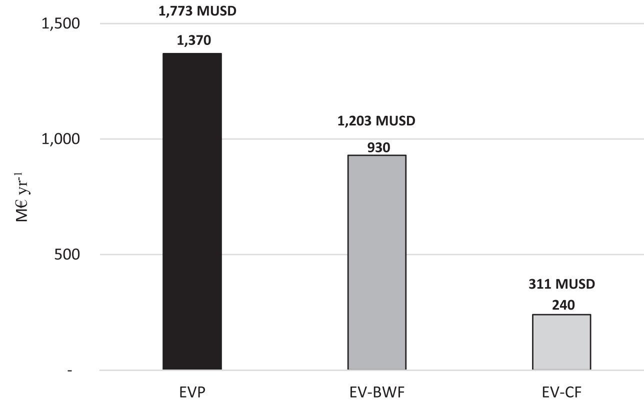

Fig. 7. Economic value of production (EVP), blue water footprint (EV-BWF) and carbon footprint (EV-CF), million euros per year (M€ $year^{-1}$) generated by small ruminant production systems for region in Latin America and the Caribbean, through the years (1998–2018), at constant values as of 2011.

change. However, this sustainability is not homogeneous throughout the study region. Although there are eco-friendlier countries such as Nicaragua, Barbados, and Trinidad & Tobago, where the EV-EF-SRPS-LAC represented 2%, 24% and 30% EVP-SRPS, respectively. The eco-friendless were Bahamas, Guatemala and Costa Rica, with respective EV-EF of 412%, 425% and 493%. As mentioned, Argentina, Mexico, Brazil, Uruguay & Peru are the countries that contributed the most to the EVP-SRPS-LAC. Certainly, when calculating their index (EF/EVP), the obtained annual values were 68%, 106%, 119% %, 62% and 99%, respectively for the period analyzed. This downward historical trend suggests that in the near future these production systems must improve their ecological performance.

As previously expressed, the EV-BWF represents the highest percentage of the EV-EF, therefore, when calculating this annualized percentage value in each country, it was observed that Uruguay, Nicaragua, & Barbados were highly water-use efficient, with respective EV-BWF values of 2%, 16% & 23%. Besides, less water-efficient countries were Guatemala, Bahamas & Guyana, with respective EV-BWF values of 386%, 356% & 316%. Regarding the countries generating more economic values (i.e. EVP) it was quantified an EV-BWF of 54%, 93%, 89%, 54% & 76%, in Argentina, Mexico, Brazil, Uruguay & Peru. The remaining values necessary to complete the EV-EF/EVP index correspond to the EV-CF participation value.

3.5.2. Socio-economic impact

According to the World Bank WB (2021), the average annual income during the analyzed period, corresponding to the EVP-SRPS-LAC, represented a fundamental economic return for about 57,000 families, distributed mainly in marginal rural areas, in fragile agroecological regions. However, it was considered essential to highlight in our analysis the great socioeconomic variability of the study region; hence, the minimum wage (MW) of the main LAC countries was deflated to 2011 (Fig. 8). Using the information published by the International Labor Office (International Labour Office ILO, 2010) and the Center for Public Finance Studies (Center for Public Finance Studies - Centro de Estudios de las Finanzas Públicas CEFP, 2021) when transforming the EVP-SRPS-LAC into MW, a global growth of 139% was observed in LAC, going from 200,000 (1998) to 478,000 (2018) annual minimum wages (AMW). The annual average increase during said period was 19, 399 MW, generating a global asset of 7.65 million MW throughout the analyzed period (Fig. 8 & 9). Regarding the countries that contributed the most to EVP-SRPS-LAC, Mexico had the highest growth while the largest AMW-contribution during said period, with 172,587 AMW, with an average annual increase of 7243 MW and a grand total MW-contribution (GTMWC) of 3,624,307 MW. To be clearer, an increase of 171% of the AMW occurred across the analyzed period, going

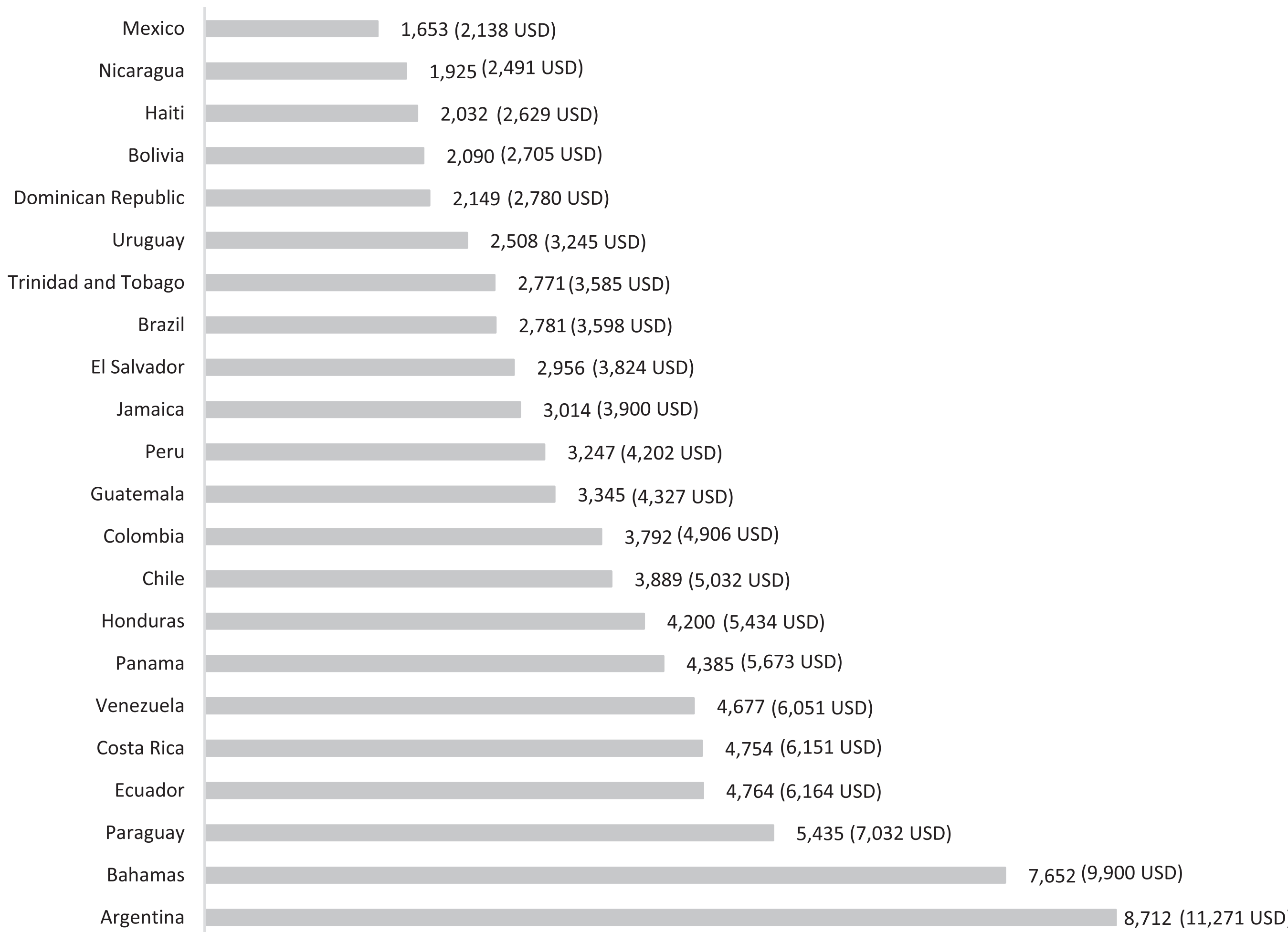

Fig. 8. Minimum wage level in Latin America and the Caribbean in 2011 in € y^{-1} (USD y^{-1}).
Source: Own Information from International Labour Office ILO, 2010 and Center for Public Finance Studies - Centro de Estudios de las Finanzas Públicas CEFP, 2021.

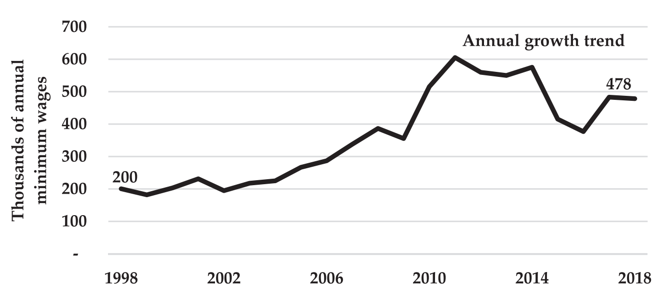

Fig. 9. Annual minimum wages (units) generated by sheep-goat production systems in Latin America & the Caribbean, across years (1998–2018), & at constant values as of 2011.

from 87,348 in 1998–236,295 in 2018. When calculating these indicators in a country basis, Argentina had an average of 40,149 AMW during the period, a GTMWC of 83,138 MW, with an increase of 19,153 (14%) in 1998–47,707 in 2018. For Brazil, the third country with the largest EVP-SRPS-LAC, the annual average generation was 91,159 MW, with a global increase of 79%; from 43,221 in 1998–77,421 in 2018, generating a GTMWC of 1,914,336 MW.

4. Discussion

Based on the results obtained and considering that our working hypothesis stated that even with the great biotic, physical and cultural diversity shown by the SRPS-LAC, these systems represent an important sustainable production strategy, with low environmental impact and important economic contribution. The above, when comparing the economic cost of the environmental impact with respect to the economic value generated by the production of sheep and goats in Latin America and the Caribbean, therefore the proposed working hypothesis is not rejected. These results demonstrate the excellent window of opportunity that sheep and goats have across different production systems, being a sustainable and resilient productive option in the face of climate change. Said productive viability persists even under the devastating effects generated by the SARS-COV-19 syndemic. The results confirm that small ruminants exhibit remarkable characteristics that allow them to maintain their production even in extreme environmental conditions, being therefore important allies in mitigating and adapting to climate change, especially in vulnerable environments and marginal agroecological contexts throughout of the LAC geography (Gallo and Tadich, 2018). Even though the socio-environmental and economic indicators were positive, it is necessary to promote the design of policies aimed at mitigating the economic cost of the BWF and DGHGE of the SRPS-LAC. Despite the low sheep-goat inventory that LAC contributes to the world (< 5%), the contribution of these species to gross domestic product and protein production play a fundamental role in diverse areas of most LAC-countries, especially those located in marginal regions from a biotic, economic, social and food perspective (Gómez et al., 2013). Moreover, since goats and sheep are excellent transformers of fibrous vegetative material, of low chemical quality not usable by humans, while generate diverse commodities (i.e. meat, milk, wool, fibers, hides & ecological fertilizers) small ruminants are an important component to promote stability and generate roots because of their interesting transformation strategy and circular revaluation of marginal natural resources, whose economic, food and biotic benefits benefit the environment, the producer and his family (Pfister et al., 2009).

4.1. Main small ruminant production systems in LAC

Table 1 shows a proposal of classification to define the main SRPS-LAC. Even considering that the great diversity of production systems, ecotypes, and territories on many occasions causes some kind of confusion, this diversity can be considered as an advantage and not a drawback, since it is desirable to find a complementarity among different systems, geographies, and agroecological areas, which generate synergies and enhance their productive expression. Any classification proposal is perfectible and subject to changes, which allow establishing the mechanisms for a more efficient and expeditious monitoring of the production systems and the changes and adjustments that these require to promote their sustainability.

4.1.1. Silvopastoral production systems

These systems have been classified as extensive (Laguna-Gamez, 2011; Arechiga et al., 2008), and as free-range subsistence (Vasconcelos et al., 2013). Other classifications place silvopastoral systems in schemes for meat production (i.e. goats) (Fideicomisos Instituidos en Relación con la Agricultura - Trusts Established in Relation to Agriculture FIRA, 1999; Arias, 1987) and even lamb-wool (i.e. sheep) (Echavarría and Gómez, 2013). Both include production systems where goats & sheep obtain directly their food in areas of natural grasslands or rangelands as they are called in Mexico, with large territorial extensions, where animals travel long distances to obtain their feed. When the ecological conditions of these grassland areas are good and there is diversity in botanical composition, the cost of feeding in these systems is minimal. However, studies carried out on the diet consumed by small ruminants in this type of systems, concluded that the animal selectivity, together with the ecological quality of the pasture, were crucial elements to maintain an adequate energy-protein balance in the consumed diet, concluding that this type of systems present a better diet in summer, coinciding with the rainy season (Echavarría et al., 2006). These systems are generally located in the arid & semiarid lands of LAC, and depend on the seasonality associated with the photoperiod and the thermoperiod, which significantly affect the level of biomass production, shrubs, bushes, and small trees. In general, the low availability of forage and the inexistent technological input in these systems generates low productivity, whether in meat, milk or wool, a condition that also affects the precarious income of producers, concomitant to a high degree of marginalization and zero incorporation of technologies to improve productivity (Echavarría and Gómez, 2013).

4.1.2. Extensive agrosilvopastoral production systems

Also classified as free-grazing (Herandez and Sanchez, 2014), semi-intensive (Echavarría and Gómez, 2013; Arechiga et al., 2008), extensive with a certain degree of market integration (Vasconcelos et al., 2013), among others. This type of system has defined the production of goat-milk as a priority (Fideicomisos Instituidos en Relación con la Agricultura - Trusts Established in Relation to Agriculture FIRA, 1999; Arias, 1987) based on a day grazing scheme with night enclosure in a corral, most of the time the obtained animal products are used for self-consumption, and a marginal marketing of animal products (Echavarría and Gómez, 2013). While the recurring economic income in these systems comes from the sale of milk, the temporary income comes from the sale of early-weaned kids; this production strategy allows the producers having a lactation whose persistence will depend on the quality of the pasture and access to agricultural surplus. This system includes production patterns where the animals obtain their food in areas of natural pastures or rangelands, not far from the management corral. In this system, animals in extensive production may use crop residues (i.e. stubble) in combination with grazing of native winter vegetation and dry matter of pasture from the previous summer. The grazing system is all year round with uncontrolled and generally excessive animal loads in relation to the supporting capacity of the rangeland. In fact, since in most of these systems the producers do not have large extensions of their own, they normally cause overgrazing in the communal rangeland, with the concomitant not only vegetative but edaphic degradation. These extensive agrosilvopastoral systems, like the silvopastoral systems, make use of criollo animals and have an incipient control over their crossing with exotic breeds, where the male is in charge of gradually improving the genetic quality of the herd (McDermott et al., 2010. Rimbaud, 2019; Salinas, 1995).

4.1.3. Intensive agrosilvopastoral production systems

Also classified as intensive grazing (Herandez and Sanchez, 2014), semi-intensive (Echavarría and Gómez, 2013; Arechiga et al., 2008), semi-extensive with a more advanced degree of integration into the markets and use of cultivated forages (Vasconcelos et al., 2013). Within this type of systems are those designed to produce both milk and meat either by goats or sheep (Fideicomisos Instituidos en Relación con la Agricultura - Trusts Established in Relation to Agriculture FIRA, 1999; Salinas, 1995) with manure production as a collateral economic income (Arias, 1987). Other more technologically advanced systems in this category include nutritional supplementation schemes at milking time, usually in the morning prior ranging & browsing, to supplement their diet intake prior or after grazing, which is carried out at very short distances from the handling pen. Occasionally, sheep and goats have access to irrigated agricultural areas and cultivated grasslands. These intensive agrosilvopastoral systems make use of up-graded criollo x dairy or meat sires; they possess a higher level of genetic improvement, with the introduction, not only of specialized sires but eventually also of female reproducers with a productive emphasis primarily focused on milk or meat production. These systems are distributed both in semi-arid regions, and in ecotypes with better agroecological conditions, with higher rainfall than the two systems previously described, which allows better forage availability. Another important aspect to highlight of these production systems is their greater commercial integration with the market chain and transforming industries (Escareño, 2010). Due to their greater investment capacity regarding extensive agrosilvopastoral systems, these intensive agrosilvopastoral systems also have better conditions that stimulate the adaptation-adoption of some technology. Although these systems are common in goat rearing, they also show positive growth trends in sheep production (Martínez and Gutiérrez, 2010). These systems are associated with grazing in artificial grasslands of high forage quality whose management requires technological knowledge aimed at an adequate rotation and animal load, according to pasture performance, mainly in the fattening of sheep and sporadically in the production of sheep and goat milk (Iñiguez, 2013).

4.1.4. Intensive-industrial production systems

These production schemes have been proposed by Aréchiga et al. (2008), Laguna-Gamez (2011), Echavarría and Gómez (2013), Lu and Miller (2019), and also referred to as complete confinement (Hernández and Sánchez, 2014). According to McDermott et al. (2010), these production schemes are industrial production systems with a high commercial orientation; while for Vasconcelos et al., (2013) are more intensive commercial and business systems, they have also been classified as production systems specialized in meat or milk production (Arias, 1987; Fideicomisos Instituidos en Relación con la Agricultura - Trusts Established in Relation to Agriculture FIRA, 1999; Gómez et al., 2013; Salinas, 1995), or as systems intensive for meat, milk or wool production (Echavarría and Gómez 2013). This type of system includes intensive stable management systems without grazing, where the animals are fed balanced diets. Due to their high cost, these systems specialize either in the production of goat's milk or in the fattening of lambs, and are therefore associated with specialized and improved breeds. These systems have a vertical integration inside the market-chain therefore, they are very efficient, showing high yields, which generate optimal levels of production to cover the investments made in technical management. Additionally, some producers give added value to the primary production, and develop direct marketing; in fact, while these intensive systems are focused to maximize the economic income, the rationale of the less intensified, *cuasi* marginal production systems have as main objective to reduce the economic risk (Iñiguez, 2013).

4.2. Characterization of the direct greenhouse emissions from the small ruminant production systems in LAC

According to Food and Agriculture Organization of the United Nations FAO (2021a), the agricultural sector emitted 5.22 Gt of CO_{2eq} worldwide, an amount very similar to that reported in 2010 for all sectors in the LAC region of 5.75 Gt of CO_{2eq} which represented 11% of global GHGE (WB, 2021). Within the agriculture sector, the livestock subsector has shown a significant increase in GHGE to the atmosphere, while, within the livestock sector, ruminants, mainly bovines, and to a lesser extent sheep & goats, have been identified as the main issuers of said carbon footprint (Opio et al., 2013). Despite this topic has presented a growing interest in the academic and scientific community, only very few studies use a more comprehensive perspective, and much less of them has considered a perspective that includes a comparison at a regional or subcontinental level. In general, these studies only include one species or one specific product, or even are developed in a particular micro-region or country. Table 5 concentrates results from other studies indicating the species(s) and product(s) considered in each of said investigations.

Buratti et al. (2017), reported that greater intensification is accompanied by an improvement in diets and management practices, which together promote greater productivity. Likewise, there is a directly proportional relationship between the intensification of production systems and the carbon footprint, recognizing extensive systems as the least generators of DGHGE. The annual average considering a kg CO_{2eq} kg^{-1} $MMWP^{-1}$ basis, during the analyzed period of the DGHGE-SRPS-LAC was 75.96 kg, which is lower than those reported for 2010, without the inclusion of wool production worldwide (152.04 kg), as well as regarding Africa (211.70 kg), Latin America and the Caribbean (171.84 kg), Asia (170.28 kg), Oceania (107.03 kg), North America (132.71 kg), and the Russian Federation (98.76 kg) (Food and Agriculture Organization of the United Nations FAO, 2017a). However, the value obtained in this study is higher than that reported for Europe (63.97 kg CO_{2eq} kg^{-1} $MMWP^{-1}$). Currently, other methodologies are available to calculate energy use for various productive activities such as Life Cycle Assessment (LCA), and the Data Envelopment Analysis (DEA). According to Kouchaki-Penchah et al., (2017), an optimization and sustainable use of energy will help reduce the environmental impact associated with the agricultural and livestock subsector.

Table 5
Average direct greenhouse gas emissions (DGHGE; kg of CO_{2eq} per kg of meat-milk-wool protein), generated by the small ruminant production systems in Latin America and the Caribbean, over the years (1998–2018) and its comparison with other studies.

Specie/Product	DGHGE (kg CO_{2eq} kg^{-1} $MMWP^{-1}$)	Region/country	Source
Goat meat-milk Sheep meat-milk-wool	75.96	Latin America and the Caribbean	This study
Sheep meat	*73.25–161.26*	California, USA	Dougherty et al., 2019
Sheep milk	*31.82–74.36*	Spain	Escribano et al., 2020
Sheep meat	*149.32*	Tunisia	Ibidhi et al., 2017
Goat milk	*11.90*	France	Kanyarushoki et al., 2008
Sheep-Goat meat-milk	*97.86*	European Union	Leip et al., 2010
Sheep-Goat milk	*176.52*	Australia	Michael, 2011
Goat meat-milk	*84.29*	Comarca Lagunera, Mexico	Navarrete-Molina et al., 2020
Sheep-Goat meat-milk	*133.53*	World average	Opio et al., 2013
Goat milk	*7.58–9.64*	New Zealand	Robertson et al., 2015
	89.86–136.49	European Union	Weiss and Leip, 2012

4.3. Characterization of the blue water footprint (BWF) by small ruminants in LAC

As in the CF, no studies have been found focusing on the BWF quantification in small ruminants in an integral fashion. Nonetheless, in the Table 6 we include some results obtained with the use of the equivalences shown in Table 2; both the kind of products and specie is registered in such information. From the total water available on the planet, only 2.5% is fresh water; from this percentage, 80% corresponds to glaciers, snow, and ice from the polar caps, 19% is groundwater, and only 1% is surface water (Tiu and Cruz, 2017). Therefore, only 20% of fresh water is available for human and animal consumption; domestic animals consume an average of 2180 km^3 yr^{-1} (Herrero et al., 2009). This is the importance of quantifying and understanding the multiple interactions that occur among water availability, human water consumption, and animal production. Besides, it is essential to understand the difference between value and price when talking about finite resources such as fresh water; most of the time, water is considered as an infinite good without value, and in the best of cases, if any, assigning it a low cost (Navarrete-Molina et al., 2019a; 2019b; 2020). Consequently, it is necessary to promote policies that contribute to giving real value to

Table 6
Average blue water footprint (BWF in m^3 per kg of meat-milk-wool protein), generated by the small ruminant production systems in Latin America and the Caribbean, through the years (1998–2018) and their comparison with other studies.

Specie/ product	BWF (m^3 kg^{-1} $MMWP^{-1}$)	Region/ country	Source
Goat meat-milk Sheep meat-milk-wool	**1.33**	**Latin America and the Caribbean**	**This study**
Goat meat-milk Sheep meat-milk-wool	**1.37** **2.61** **2.87**	**World** **Mexico** **Spain**	**Own calculations with information from FAO (2020a) &** Mekonnen; Hoekstra (2010)
Goat meat	***3.19***	Kenia	Bosire et al., 2015
Sheep meat	***7.59–101.27***	California, USA	Dougherty et al., 2019
Sheep meat	***0.04–0.12***	England	EBLEX, 2010
Goat meat	***1.20***	Central Tunisia	Ibidhi and Salem, 2016
Sheep meat	***5.80–7.12***	Tunisia	Ibidhi and Salem, 2018
Goat meat-milk	***3.30***	Australia	Michael, 2011
Goat meat-milk	***0.46***	Comarca Lagunera, Mexico	Navarrete-Molina et al., 2020
Sheep meat	***0.79***	Australia	Ridoutt et al., 2012
Sheep meat	***2.24***	Australia	Wiedemann et al., 2015
Sheep meat	***0.0014***	New Zealand	Zonderland-Thomassen et al., 2014

the use of water in the world, not only for anthropogenic, industrial and agricultural purposes, but also ensuring the quality and viability of ecosystems and the needs of future generations (Gerber et al., 2013).

The annual average BWF generated by each kg of meat-milk-wool protein produced by small ruminants corresponds to 1.33 m^3 kg^{-1} $MMWP^{-1}$, a value significantly lower than that reported for dairy cattle, beef cattle and pigs (Fig. 3); one reason could lie in the fact that these production systems base their feeding on products with a high demand for BWF. This scenario is different when considering the SRPS-LAC, which base their production on much less use in blue water. Indeed, the results of the present study denote a lower BWF that competes with human consumption in practically every geographic area, environment and climate in LAC. We must remark that it is not intended to minimize the socioeconomic importance of the rest of the livestock activities, however, it is crucial to highlight the importance and urgency of promoting public policies that contribute to the development and sustainable use of the scarce and finite natural resources available, especially of the water. Hence, promoting and valuing SRPS-LAC is fundamental to consider to goats and sheep as a productive, ecologically and socially responsible option in animal production, especially in fragile agro-ecosystems. The last is particularly true and factual in the face of the projected deleterious effects in the short-term of climate change and the catastrophic health, economic and social issues generated by the SARS COV2 syndemic at global level; with these facts in mind, it is easier to comprehend that, certainly, not all ruminants were created equal (Navarrete-Molina et al., 2020).

4.4. Characterization of the ecological footprint and the socio-economic impact by the small ruminants in LAC

The SRPS-LAC constitute, as in other regions of the world, the main component of the production systems in arid and semi-arid zones, since they offer a low-risk productive option, considering that the vast majority of producers use traditional procedures that include few technological inputs obtaining an acceptable productivity from the SRPS-LAC. In fact, more than 80% of the small ruminant population is managed by small producers, usually in marginalized rural areas with scarce resources (Iñiguez, 2013). Considering the numbers proposed by Iñiguez (2013), of an average of 68 animals per herd and 6 members per family, it was estimated that, for the analyzed period, a population of close to 1.7 million families of small producers can be potentially benefited from the SRPS-LAC. Likewise, these estimates suggest that about 10.12 million people benefit in some way, directly or indirectly, from the production of sheep and goats in LAC. These estimations highlight the importance of sheep and goats, perhaps not so much from a quantitative perspective with less than the 6% of the global population but from a qualitative perspective, since the vast majority of those more than 10 million people tend to be the most vulnerable from a biotic, economic, social, environmental and nutritional stand point.

Considering the estimations by the World Bank WB (2021), the SRPS-LAC have the potential to generate annual income for about 400, 000 families, most of them dispersed in marginal ecosystems, especially in arid and semi-arid environments. That is why small ruminants should be considered as unrestricted allies against climate change and sentinels of environmental quality (Scortichini et al., 2016). In addition, these species have shown to possess exceptional adaptations to the unrestricted advance of climate change, representing therefore, a biotic reservoir that has proven to be important in alleviating the nutritional risk of the most of the vulnerable human population, and becoming key players for the meat and dairy industries in the face of a future of climate uncertainty. The foregoing could be strengthened when considering that, worldwide, more than 50% of small ruminants are found in arid regions, this being an indication of their adaptability, physiological plasticity and competition in the face of projected temperature increases.

Undoubtedly, it is essential to reevaluate SRPS as the future producers of sustainable protein of high biological value (Gowane et al., 2017; Navarrete-Molina et al., 2020). It is necessary to highlight the great production ability of small ruminants to perform under extreme marginal environments and transforming food resources non usable by other animal species into products of high biological value, thus satisfying the growing demand of society in the adoption of clean, green and ethical production systems (Navarrete-Molina et al., 2020). The generation of public policies and collective efforts that strengthen the sustainability of the SRPS-LAC will be fundamental, especially with a defined strategy to safeguard and prioritize the human right to have water, in quality and quantity, allowing them to satisfy their basic needs, while promoting policies that contemplate changes in the population's consumption patterns and their relationship with the use and degradation of natural resources (Navarrete-Molina et al., 2019a; 2019b; 2020; Thiaw et al., 2011).

5. Concluding remarks

Given the increase in demand for products of animal origin, the stability of diverse ecosystems and their services to society is certainly threatened. The results of this original approach to characterize the environmental, economic and social impact of sheep and goats in Latin America and the Caribbean place small ruminants as multidimensional and resilient species, capable of performing in diverse environments, most of them hostile and marginal. In fact, the significant variability observed in this north-south development axis in LAC with about 9000 km long, makes unquestionable while complicated, the tremendous variability of the observed LAC-ecotypes based on a wide biological, socio-cultural, economic, and physical diversity. Undoubtedly, there is a massive variety of climates, photoperiods, rainfall, soils, orography, native and induced vegetation, from the arid and dry north, with extreme climates of Mexico to Southern Patagonia with low temperatures and abundance of rain in the west and scarce rainfall in the east, yet with presence of snow; all of this diversity coupled with an assorted cultural background. The last has promoted a differentiated development of both species: while goats and sheep develop together in small to medium-sized herds in the North, the Caribbean and the Central-LAC, sheep production tends to be more present with herds with greater density towards the southern cone. Unquestionably, this first analysis of the SRPS-LAC, evidenced goats and sheep as fundamental species in the use of natural resources, generating necessary products of high biological value (i.e. meat & milk), and industrial-artisanal use (i.e. wool & skins), which demand to re-value and re-dimension the physiological plasticity that allows them the production of diverse commodities under production contexts and biosystems in mostly clean, green and ethical settings. Our results demonstrate that the SRPS-LAC are an eco-friendly while sustainable option in the face of climate change. However, this sustainability is not homogeneous throughout the study region; further studies must address this type of environmental impact by the SRPS-LAC in a regionalized fashion within Latin America and the Caribbean; it is certainly a pending assignment. Moreover, it is fundamental to generate transformation and revaluation strategies based on a circular bio-economy perspective, whose various ecosystem products and services benefit the environment, the producer and his family. Certainly, in our extensive, diverse, while complex Latin America and the Caribbean region, thousands of producers, most of them socially and economically marginalized need these species, society undoubtedly demand their products, and the vast majority of agroecosystems need their recovery; sheep and goats meet these three fundamental while vital requests.

Ethics statement

Not applicable.

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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 in this manuscript.

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In loving memory, Ing. Santos I. Arbiza-Aguirre, 1927–2014; Dr. Nissim Silanikove, 1950–2017; Dr. Santiago Zuñiga-García, 1983–2020.

Data repository resources

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

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