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Livestock and Water Resources: A Comparative Study of Water Footprint in Different Farming Systems

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Abstract: Livestock production systems are major consumers of freshwater, potentially compromising the sustainability of water resources at production sites. The water footprint (WF) quantifies the water consumed and polluted by a product or service. The aim of this study was to evaluate the WF of steer production from the cradle to the farm gate in representative intensive, extensive, and mixed farms located in the southeast of Buenos Aires province, Argentina. The WF to produce a live steer varied between 4247 and 5912 m^3/animal. The extensive system contains the highest green WF but is also the most sustainable compared to industrial and mixed productions since it does not have an associated pollutant load or blue water. This work is the first approach to calculating the WF of live steers in Argentina carried out with local and detailed data and focuses on grey WF related to nitrogen leaching from effluents in intensive systems, showing that the blue and grey footprints increase as production intensifies. The information may be relevant for consumers and producers to make more informed decisions. Furthermore, it is essential for governments to promote sustainable practices in livestock farming, recognizing the dependence on water resources both domestically and throughout international supply chains, in order to assess their environmental policies and ensure national food security.

Keywords: steer production systems; green water; blue water; grey water; feeding scenarios; industrial versus grazing systems

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1. Introduction

Together with rising global incomes, population growth has led to changes in people's diets, which now contain fewer cereals and a higher proportion of meat and dairy products, increasing the demand for these foods worldwide [1–7]. This so-called 'Livestock Revolution' [8] has led to more industrial livestock production systems requiring less land, having less sustainable water footprints (WF) than more extensive agricultural systems, and entailing certain negative environmental impacts such as higher greenhouse gas emissions [6,9].

In assessing livestock production environmental sustainability, it is essential to consider that the food system is the main consumer of freshwater [9–11]. It involves direct water use in the form of drinking water and services and large indirect water use in the supply chain, such as feed production for livestock, which can compromise the sustainability of water resources at production sites. Therefore, from a global perspective, producing beef for export in places where water resources are relatively abundant is both an advantage and a way to save water. For a national government, the knowledge of the dependence on water resources elsewhere is relevant for assessing not only its environmental policy but also national food security [11].

In this context, countries that base their economies on the production of food with rainwater become relevant. Argentina, which is mainly an agricultural and livestock-farming country, is a good example. Ranking sixth in the world of beef-exporting countries, its beef industry is an important contributor to the global food system and to the national and global economy [12].

Cattle production in Argentina is concentrated in the Pampean region, which includes Buenos Aires province, with 37% of the total production, and part of La Pampa, Entre Rios, Santa Fe, and Córdoba provinces. Cattle stock varies according to the market price of cattle. According to the 2018 National Agricultural Census, Argentina has 40,411,905 heads of cattle and a population of 40,117,096 inhabitants, which means almost one cow per person [13–16].

In the 1990s, the territorial expansion of Argentinean agriculture resulted in a significant reduction of the livestock area and the replacement of extensive livestock production by more intensive systems [17,18], although it was not until 2006–2007 that farm dynamics were recorded. These records show a significant increase in intensive activity over the last 15 years both at the national level and in Buenos Aires province [19–21]. In 2023, 3% of national livestock (1,657,453 heads) were fattened in industrial systems (feedlots). The thirty one percent of the cattle fattened in Argentinean feedlots were located in Buenos Aires province (521,224 heads) [21]. The most produced animal category in feedlots was steer (39%).

Argentinian beef exports have increased exponentially since 2018 as a result of China emerging as a major consumer of this product [21–23]. Although beef exports in 2023 were 7.9% higher in volume than in 2022, they were 20% lower in price (USD 2.735 billion). The main destinations for Argentinian meat in 2023 were China (78% of the tons exported), followed by Israel, Germany, the USA, Chile, the Netherlands, Brazil, Italy, and Spain [24].

The water footprint methodology focuses on the analysis of freshwater use, scarcity, and pollution in relation to consumption, production, and trade. Its application at a local scale provides an understanding of how local economies and their use of freshwater are integrated into a global economy [25]. This tool quantifies the volume of water needed for the production of goods and is composed of three footprints: blue, green, and grey [26]. The green and blue WF refer to the consumptive use of water either from rainfall or from surface or groundwater reservoirs, while the grey WF expresses the appropriation of the assimilative capacity of pollutants. For example, the WF of an animal at the end of its lifetime is the sum of the total water needed to produce the feed consumed during its lifetime, as well as drinking and service water [9].

Some authors have progressed in assessing the WF of livestock under different production systems in the USA [27,28], Australia [29], Brazil [30], South Africa [31], Spain [32], and globally [9]. However, there are no detailed studies of this kind about Argentina or Buenos Aires province even though it is the province with the highest livestock production.

International virtual water trade studies related to livestock usually lack adequate consideration of the different livestock production systems. Therefore, this study used a water use assessment method based on local data to evaluate the three types of geographically defined cattle production systems in an important production and export region: Buenos Aires province, Argentina.

The aim of this study was to assess the green, blue, and grey water footprints of a live steer from the cradle to the farm gate in representative intensive, extensive, and mixed farm types located in the southeast of Buenos Aires province. This study is relevant because of Argentina's role as a major beef exporter, where its farming practices influence global water allocation. By evaluating the water footprints of different livestock systems, this paper provides insights to improve water use efficiency, with implications for both Argentina and water-stressed countries that import steer beef.

2. Materials and Methods

2.1. Description of the Study Area

Buenos Aires is one of the 23 provinces of Argentina and part of the Pampean region. It is divided into 135 municipalities, covering an area of 307,571 km^2 (Figure 1). It is regarded as the country's most important province because of its vast size, large population (45% of the country's population) [33], and the relevance of its economic activities. In terms of livestock production, Buenos Aires accounts for 37% of the national steer stock.

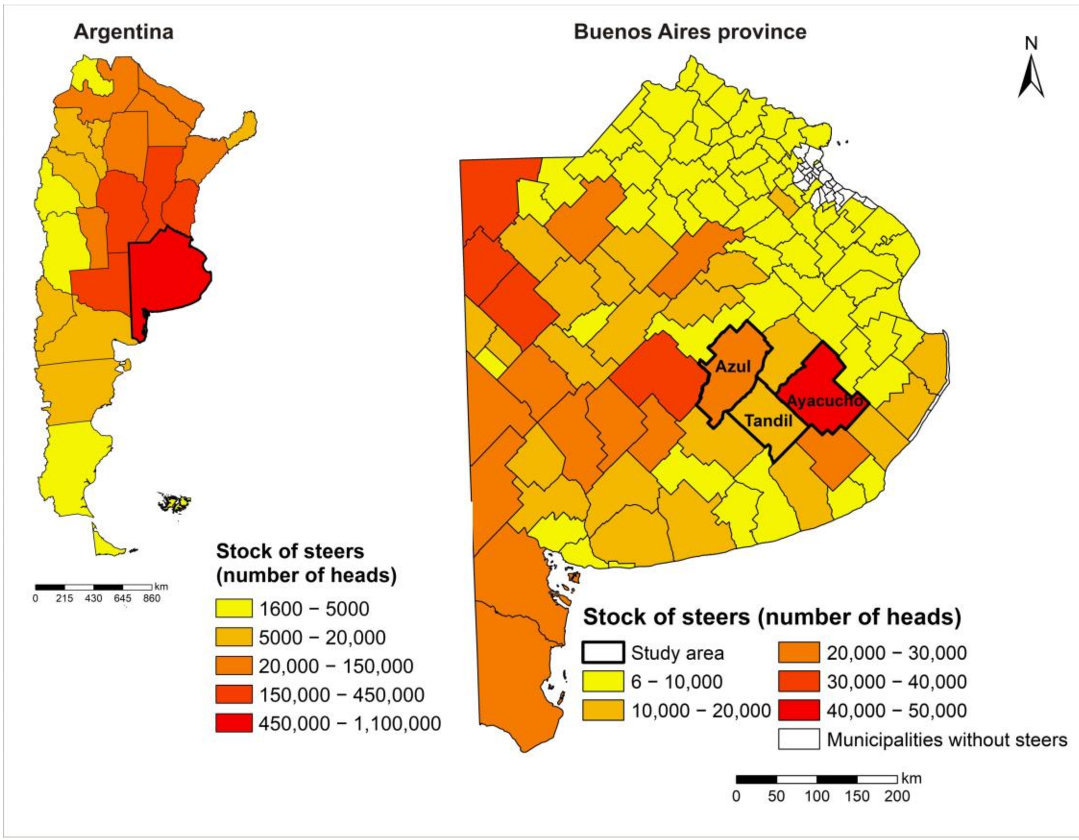

Figure 1. Number of heads of steers in the provinces of Argentina (**left**) and in the municipalities of Buenos Aires province (**right**). The municipalities under study (Tandil, Azul, and Ayacucho) are highlighted on the map.

According to the Thornthwaite–Mather classification, the weather is humid–sub-humid [34], with average potential evapotranspiration values between 712 and 885 mm per year. The climate is subtropical with a decreasing humidity gradient from east to west and southwest. The studied farming systems are located in the southern sector of the province where the climate is humid temperate, with rainfall distributed homogeneously over the area. Average annual temperatures range between 20 and 14 °C and decrease towards the south.

The topography is flat and undulating with depressed flood plains gently sloping towards the Atlantic Ocean and draining into the main rivers. It also includes low hills and plains. The drainage network in the northern sector is south–southwest to north–northeast. In contrast, in the southern sector, it drains east–southeast towards the Atlantic Ocean [35].

The predominant soils are Mollisols, mainly Argiudolls, Haplustols, Hapludols, and Natracuols. They feature agricultural soils with a surface horizon rich in organic matter, which gives them their dark or brown colour. The dominant vegetation is grass steppe or pseudo-steppe and its species composition varies according to the characteristics of the local climate and soil, with the Gramineae family being dominant [35].

Agriculture and maintaining livestock are among the most important activities in Buenos Aires province. It has 36,700 farms for agricultural and forestry use located in 23,753 thousand hectares (14.6% of the country's total) [14]. Out of this total, 24,311 are commercially oriented cattle farms. According to the latest agricultural 2018 census [14], the province contains 37% of the country's bovine stock. There are 14,883,528 heads of cattle in total in Buenos Aires province, with steers between 1 and 2 years old in fourth place with 1,078,401 animals (36% of the country's stock of steers) after calves, steers, and cows. However, steer is the main category of meat exported from Argentina [36].

2.2. Description of the Livestock Production Systems Analysed

The three farming systems under study, intensive, extensive, and mixed, are located in the municipalities of Tandil, Azul, and Ayacucho, respectively, which are in the southeast of Buenos Aires province (Figure 1, Table 1). These municipalities are located in the Tandilia System [37], which extends from Olavarría to Mar del Plata, with maximum altitudes of 500 m above sea level [38].

Tandil, Azul, and Ayacucho concentrate the largest number of cattle in general and of steers between 1 and 2 years old in particular [14]. Ayacucho leads the ranking for having not only the largest number of cattle (697,177 heads, i.e., 4% of provincial stock) but also the largest number of steers aged between 1 and 2 years old (43,086 heads). Azul is in fourth place with 352,512 animals (2.3% of provincial stock) and Tandil is further down, in 22nd place, with 239,736 cattle (1.6% of provincial stock) standing out for its concentration of feedlots, being among the 10 municipalities with the most feedlots in the province (six farms) [39]. The three districts are located in a homogeneous area from the climatic, edaphic, and vegetative points of view.

The intensive farming system refers to feedlot cattle fattening, which consists of confined areas with adequate facilities for the complete feeding of animals (mainly based on balanced feed and grains) for productive purposes [40]. In the case analysed, the feed is produced on the farm, consisting of corn grain, soybean cake, or other crops, which is not common in all farms. This intensive system began in the early 1990s. It was in 2000 that it became an important activity for cattle finishing and an alternative production for the livestock sector. This intensification process stems from the increase in both the number of farms and the number of cattle under this practice.

Extensive systems feature a limited use of technological advances, low productivity per animal and per hectare, and feeding mainly based on natural grazing from the farm's agriculture, as well as the low use of agrochemicals [41].

Mixed systems are those in which the animals are fattened in two phases. First, they are reared under grazing, and then they are finished in the pen with a grain-based diet [42]. This type of system offers greater flexibility in cattle management since the producer can decide when to move the animals to feedlot fattening depending on market conditions and input prices.

Table 1. Characterization of the three livestock production systems analysed in Buenos Aires province.

<table>
<tr><th colspan="3"></th><th>Extensive</th><th>Mixed</th><th>Intensive</th></tr>
<tr><th colspan="3">Location</th><th>Azul</th><th>Ayacucho</th><th>Tandil</th></tr>
<tr><td colspan="3">Number of steers</td><td>225</td><td>240</td><td>9000</td></tr>
<tr><td colspan="3">Area (hectares/animal)</td><td>0.35</td><td>0.83</td><td>0.003</td></tr>
<tr><td rowspan="5">Days of live</td><td colspan="2">Breastfeeding</td><td>180</td><td>270</td><td>180</td></tr>
<tr><td colspan="2">Rearing</td><td>180</td><td>30</td><td>-</td></tr>
<tr><td rowspan="2">Fattening</td><td>Grazing</td><td>180</td><td>150</td><td>-</td></tr>
<tr><td>Pen</td><td>-</td><td>80</td><td>180</td></tr>
<tr><td colspan="2">Total</td><td>540</td><td>530</td><td>360</td></tr>
<tr><td colspan="3">Type of feeding</td><td>Depending on the availability of pasture, it can be a mixture of grasses, wheat grass and maize, or oats.</td><td>Grazing period: whole plant maize silage in the morning; oats or ryegrass in the afternoon; and natural grass in the evening.
Intensive farming period: maize grain and concentrated feed.</td><td>Maize grain, soybean cake, minerals/vitamins, and other crops (barley; whole plant maize silage).</td></tr>
<tr><td colspan="3">Weight at the beginning of fattening (kg)</td><td>290</td><td>300</td><td>280</td></tr>
<tr><td colspan="3">Weight at the end of fattening (kg)</td><td>445</td><td>440</td><td>550</td></tr>
<tr><td colspan="3">Destination of manure</td><td>Directly into the soil as organic fertilizer during grazing.</td><td>Directly into the soil as organic fertilizer during the grazing period. In the intensive period, the manure is directly on the floor of the pen, on a smaller surface without vegetation, draining by gravity to the lower areas.</td><td>Directly on the ground, and then manure is discharged in effluent ponds without liners or treatment.</td></tr>
</table>

2.3. Functional Unit, System Boundaries, and Water Footprint Assessment Method

The water footprint of a live steer produced under different beef production systems (intensive, extensive, and mixed) from the cradle to the farm gate in 2018 was assessed following the methodology of Hoekstra et al. [26] and taking into account the guidelines of FAO [43].

The steer animal category was selected because it can be reared both intensively and extensively and is the main category of meat exported.

The methodology proposed by Mekonnen and Hoekstra [9] was used to calculate the green, blue, and grey WF of the entire steer production chain from the cradle to the farm gate (Figure 2). For each livestock production system, a WF calculator was developed with adjustments for Argentina (Supplementary Materials). The parameters considered in the calculator are related to animal husbandry (animal drinking water, water used for services), feeding, and manure management. All data in the calculator referring to kilos of feed, natural grass, and forage consumed by the animal, as well as the data loaded for the N balance, were analysed in terms of dry matter content.

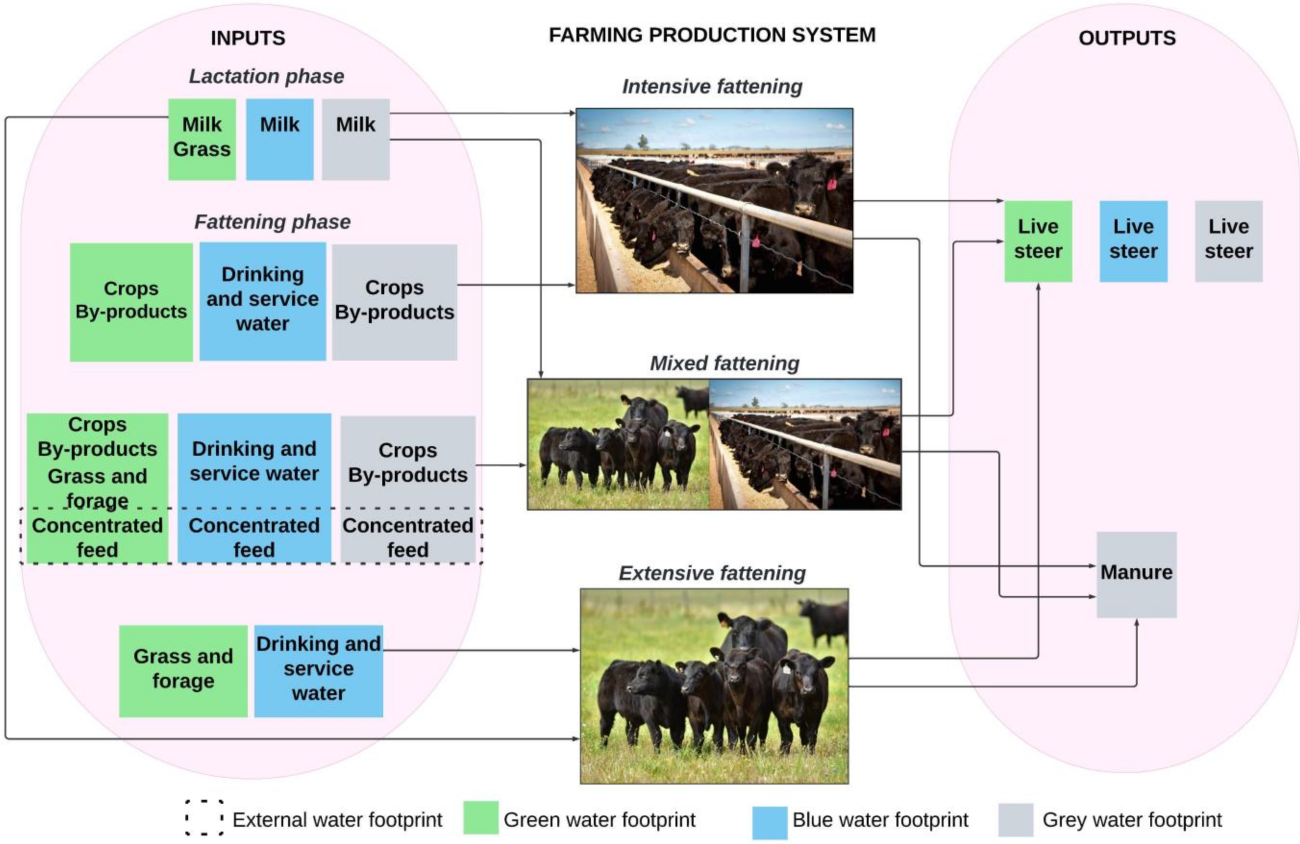

Figure 2. Schematic of the use of water inventory for steer production.

Primary and secondary sources of information were used. For the collection of primary data, interviews and visits were carried out for livestock producers of the three systems (feedlot, mixed, and extensive) to collect data such as number of steers, phase (breastfeeding, rearing, and fattening), duration of each phase, diet composition, and quantities. Where no primary data were available, secondary data from the literature were used, such as the values of milk and grass consumption during breastfeeding, service water, and dry matter consumption in grazing.

2.4. Water Footprint Assessment of the Steers on the Farm

2.4.1. Blue Water Footprint Associated with Drinking and Service Water

Drinking water was calculated according to the National Research Council [44], which takes into account environmental, biological, and dietary factors. The parameters were adjusted with local data from the case study.

$$\text{Drinking water} = -18.63 + (0.3937 \times \text{MT}) + (2.432 \times \text{DMI}) - (3.870 \times \text{PP}) - (4.437 \times \text{DS}) \quad (1)$$

where MT is the maximum temperature in degrees Fahrenheit, DMI is the dry matter intake of daily feed in kg, PP is the precipitation in cm/day, and DS is the percentage of salt in the diet.

The climate data for all cases were based on the Argentinian National Meteorological Service database [21] (SMN, 2023).

Drinking water was then related to the number of days the steers lived from cradle to farm exit, obtaining the blue WF of drinking water in litres/animal.

As regards the service water component, literature reference values according to Mekonnen and Hoekstra [45] of 9.8, 7, and 4.3 L were used for the intensive, mixed, and extensive production systems, respectively. This component only refers to the water used directly on the livestock, i.e., cleaning of the animal, pen, or drinking troughs or cleaning of machinery for feed distribution.

2.4.2. Water Footprint of Animal Feed

The green, blue, and grey WF were calculated for each phase (breastfeeding, rearing, and fattening) in each type of production system. Different scenarios were developed taking into account the availability of feed within each production system.

Water Footprint of Milk

According to interviews with producers and veterinarians, in intensive and extensive systems, calves are normally weaned at six months of age, 180 days, and in the mixed system at 9 months (270 days).

The average weight of a calf at birth is about 30 kg [46,47], and the weight of a calf at weaning was considered according to each farm.

The daily feed intake of a calf is 10% of its live weight [48]. During the first months of life, this percentage is composed only of maternal milk, but as the calf develops, its diet is complemented with grass intake [49,50]. As milk production decreases, the grass fed to the calf increases. Bavera [48] indicates calf milk consumption and grass percentages per month.

The lactation period was divided into two-month periods, which were assigned an average calf weight based on the weighted average of the kilogram gained over the entire stage in each case study and given a percentage of milk and pasture consumption.

The milk WF was taken from the appendix of Mekonnen and Hoekstra [45] for milk with a fat content between 1 and 6% raised on pasture. This percentage was determined in consultation with vets.

Finally, to obtain the WF of milk consumed per animal (m^3/animal) during the lactation period, the milk WF (m^3/tons of milk) was multiplied by the amount of milk consumed by the animal in that period (tons of milk/animal).

Water Footprint of Animal Feed

The forage and balanced feed were obtained from crops and grass grown in Buenos Aires province. The green WF of the crops for each municipality was taken from Rodríguez et al. [51]. The green WF of the natural grass and pastures (oat and wheat) was estimated using the CROPWAT model using the grass pasture crop coefficients [52]. The grey WF of crops was calculated based on a soil nitrogen balance following the methodology by the Spanish Ministry of Agriculture, Fisheries, and Food [53] and Aldaya et al. [54]. In this study, we assume that all crops are rainfed, considering the blue WF of the crops being zero. This is because crop production in Buenos Aires province is mainly rainfed by reason of abundant rainfall, with only 1.5% of the cultivated area being irrigated [14], of which there is a lack of detailed data available.

For the estimation of the green WF of the soybean cake by-product, the product fraction was applied following Hoekstra et al. [26]. The green WF of soybean [51] was multiplied by a mass allocation coefficient of 0.8 (which refers to the quantity of the soybean cake obtained per quantity of soybean crop) according to FAO [55].

Both the volume and composition of feed consumed by the steers vary according to the production system (Tables 2 and 3). In the case of the feedlot, the steers gained, on average, 550 kg at the end of fattening, out of which 270 kg were gained in the 180 days of confinement (Table 1). During confinement in outdoor pens, each animal was fed 12 kg of dry matter per day. The composition of the feed depends on the availability of the crops at the time and was supplemented with minerals/vitamins, so different scenarios were worked out (Table 3). The water footprint of the minerals/vitamins was taken from Klopatek et al. [56] and Klopatek and Oltjen [27].

Table 2. Scenarios used according to diet composition.

Production System	Scenario	Diet
Extensive	E1	Mixture of pasture in rearing and oats in fattening
	E2	Mixture of pasture in rearing and maize plant in fattening
	E3	Wheat pasture in rearing and oats in fattening
	E4	Wheat pasture in rearing and maize plant in fattening
Intensive	I1	Maize, soya cake, minerals/vitamins, barley, whole plant maize silage
	I2	Maize, soya cake, minerals/vitamins, whole plant maize silage
	I3	Maize, soya cake, minerals/vitamins, barley
Mixed	M1	Rearing feed based on rye grass, whole plant maize silage, and natural grass
	M2	Rearing feed based on oat pastures, whole plant maize silage, and natural grass

Table 3. Percentage of ingredients of feed in the daily diet used in the different scenarios in intensive, extensive, and mixed production systems.

Production System	Ingredients of Feed		Scenarios	Percentage of Ingredients in the Daily Diet
Intensive (I)	Maize grain, soybean cake, minerals/vitamins, barley, and whole plant maize silage		Scenario I1	70–9–3–8–8
	Maize grain, soybean cake, minerals/vitamins, whole plant maize silage		Scenario I2	70–9–3–16
	Maize grain, soybean cake, minerals/vitamins, barley		Scenario I3	70–9–3–16
Extensive (E)	Rearing	Natural grass	Scenario E1–E2	ad libitum
		Pasture wheat	Scenario E3–E4	ad libitum
	Fattening	Pasture oats	Scenario E1–E3	ad libitum
		Plant of maize	Scenario E2–E4	ad libitum
Mixed (M)	Rearing	Natural grass	Scenario M1–M2	ad libitum
	Extensive phase	Plant maize silage, rye grass, natural grass	Scenario M1	ad libitum
		Plant maize silage, pasture oats–natural grass	Scenario M2	ad libitum
	Intensive phase	Maize grain, concentrate feed	Scenario M1–M2	90–10

The mixed production system consists of different phases (Table 1) lasting 530 days in all, with the steers gaining 440 kg. The fattening phase is 180 days of grazing and 80 days of confinement, where the steers gain 260 kg (Table 3). This productive system is the only one involving concentrated feed in its diet, the composition of the concentrate (Table 1) being soybean cake (1.2%), sunflower cake (1%), wheat bran (4%), maize (3.5%), and minerals/vitamins (0.30%) (from the manager of a feed production plant; personal communication, 2018). The green and grey WF of each component was calculated by taking into account the green and grey WF of that crop grain and the mass allocation coefficient according to FAO [55].

Steer extensive rearing based on grazing in Azul has different phases depending on the availability of feed, with a complete cycle duration of 540 days and a weight gain of 445 kg (Table 1). The phases are breastfeeding; rearing, which can be carried out with a mixture of pasture or wheat pasture; and fattening on corn or oats (Table 3).

The daily kilos grazed by the steers in the extensive phases are not known because the steers consume ad libitum. Therefore, the amount of intake per animal was estimated taking into account that the animal consumes 10% of its live weight in green matter per day [48], which equals 3% of dry matter. The steers fatten about 265 kg in this phase. According to livestock experts consulted, their diet is based on 35% maize silage, 25% pasture, and 40% natural grass (from a livestock production expert; personal communication, 2023).

Depending on the composition of the diet in each system, different scenarios were used (Tables 2 and 3).

Feed Mixing Water

The blue water use for feed mixing was only considered for the mixed production system, as no concentrate feed was used either in intensive or extensive systems.

First, the tons of feed eaten by each animal in the days of feedlot fattening were calculated. This value was then related to the 0.5 L of water used to produce 1 kg of feed as established by Mekonnen and Hoekstra [9], obtaining the litres of water involved in feed production per animal.

2.4.3. Manure Water Footprint

The grey WF of manure values varied depending on whether the production system was intensive, extensive, or mixed.

For extensive livestock farming, the soil N balance of the forage on which the animal grazes was carried out, taking into account the kg of N per animal per day supplied by excreta, which involves carrying out a balance of manure application (including grazing input) by crops, fallow land, and permanent grazing areas. The considered N balance inputs were N in the seed, taken from the literature data [57–60]; atmospheric deposition; and N from the excreta of grazing steers. For estimating the N content in the animal excreta, the value given by MAPA [53] of the N kg contained in animal manure per animal category was taken into account and related to the number of animals and the number of days in the cycle. The contribution from mineral fertilization was not considered because no chemical fertilizers were applied.

As for the outputs, the N removal from the aerial part of the plant and the gaseous losses from the soil were considered. Roots were considered storage. The plant N partitioning coefficients were taken from MAPA [53] for winter cereal and fodder crops. The N extraction coefficients for cereals (wheat, oats, and maize) were adjusted from the Argentine literature [61], except for the natural grasses. In that case, we took the N extraction coefficient of grasses (Gramineae) from MAPA [62], as they are predominant in the Pampas grassland [35].

Volatilisation data were taken from the regional literature [63–67]. As this is a region with homogeneous soil and climatic conditions, there is no significant variation of this factor in the different crops. Therefore, a volatilisation percentage of 6% was used for wheat, barley, sorghum, and oats; 7% for maize and sunflower; and 6.5% for soybean.

Once the balance was performed, the pollutant load (L) was obtained and applied in the grey WF Equation (2) proposed by Hoekstra et al. [26]. It was calculated only for groundwater because it has greater storage volume and use in relation to surface water [34].

$$\text{WF Grey} = \text{L}/(\text{Cmax} - \text{Cnat}) \quad (2)$$

where Cmax refers to the maximum acceptable concentration of nitrate in water, which, according to the Argentinean Food Code for drinking water, is 45 mg/L. Cnat refers to the natural concentration of nitrate in the receiving water body. Further, the calculation was carried out taking into account a Cnat = 0, as proposed by the methodology in cases where the natural concentration is not known [26,68], although agriculture and livestock farming have been carried out in this study area for decades. Therefore, the base concentration of nitrogen in the water bodies is already modified, and it would be correct to take locally measured values other than 0.

For intensive farming systems, the grey WF was estimated following four steps as follows: first, the leaching fraction was calculated according to Franke et al. [68]. Then, the percentage of N volatilisation of the total N excreted was calculated, taking data from MAPA [53,62]. Then, the L was estimated, applying the Intergovernmental Panel on Climate Change [69] method. Finally, with the obtained L, the equation proposed by Hoekstra et al. [26] for calculating grey WF was used.

Estimation of the Leaching–Runoff Fraction

The approach proposed by Franke et al. [68] estimates the overall leaching–runoff fraction but it does not differentiate between leaching to groundwater and direct runoff to surface water parts. The value of α is the result of many factors and can be estimated from information on the state of environmental factors and agricultural practices by applying Equation (3):

$$\alpha = \alpha\text{min} + \left[\frac{\sum_i \text{Si} \times \text{Wi}}{\sum_i \text{Wi}}\right] \times (\alpha\text{max} - \alpha\text{min}) \quad (3)$$

where αmin is the minimum leaching runoff fraction and αmax is the maximum leaching runoff fraction, which was taken from Franke et al. [68]. Wi is the weight of the factor, and Si is the leaching–runoff potential score.

Estimation of the Percentage Volatilisation of N

- The amount of kg of N in animal manure/year [53]. For the intensive production system, the value given for males between 1 and 2 years old is considered, as it refers to animals confined indoors, although in Argentina, the animals are confined outdoors.
- The percentage of manure N volatilisation, in order to calculate how much N remains in the manure and can infiltrate or run off. The outdoor volatilisation value of 19.77% [62] was taken for males between 1 and 2 years old.

With these data, the kilos of N volatilised per animal/year and the kg of N remaining in the manure were calculated. The latter was multiplied by the number of steers in confinement, giving the kilos of N in manure for the total number of animals/year.

Quantification of the Applied Pollutant Load

Based on the data calculated in steps 1 and 2, the IPCC [69] formula in Equation (4) was applied to calculate the pollutant load (L), i.e., how much nitrogen actually reaches the groundwater.

$$\text{N}_{\text{leaching}}\text{MMS} = \sum_{S}\left[\sum_{T}[\text{N(t)} \times \text{Nex(t)} \times \text{MS(T,S)} \times (\text{Frac leachMS} \div 100)(\text{t,s})]\right] \quad (4)$$

where N is the number of head of steers on the farm, Nex is the kg of N in manure after volatilisation per year (calculated in step 2), DM is the fraction of all excreta managed on the farm, and Frac leachMS is the percentage of excreted N that can be leached (calculated in step 1).

The result in kg N leached per year for the total number of animals was converted into kg N during fattening/animal to obtain the L (pollutant load).

Assessment of the Grey Water Footprint of Manure

The grey WF of manure was estimated using Equation (2). The calculation was carried out considering a current concentration of nitrate in groundwater (Cnat) of 0 mg/L.

The final result was converted to m^3/animal.

In the case of mixed productive systems, a soil nitrogen balance was applied for the extensive phase, and then, the intensive production methodology was applied for the confinement phase (see Section 2.4.3).

3. Results

The WF to produce a live steer in Buenos Aires province in 2018 varied under different beef production systems, being on average 4767, 47, and 1098 m^3/animal for the green, blue, and grey WFs in the intensive system; 4074, 37, and 137 m^3/animal the green, blue, and grey WFs in the mixed system; and 5593, 38, and 48.5 m^3/animal the green, blue, and grey WFs in the extensive system (Table 4 and Figure 3).

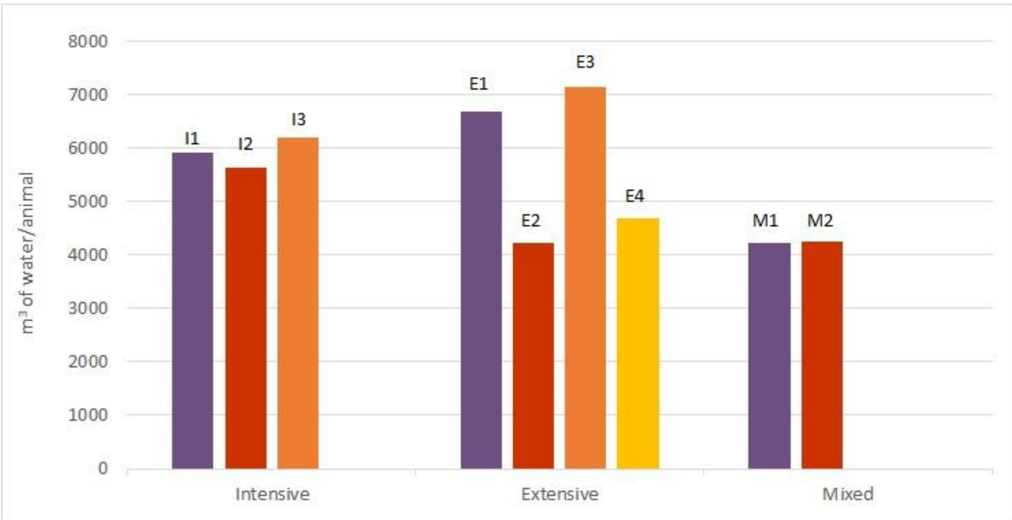

Figure 3. Total water footprint (green, blue, and grey water footprints) of steers under different scenarios in intensive, extensive, and mixed systems (the scenarios are specified in Tables 2 and 3).

During lactation, the WF of milk was the same for extensive and mixed livestock production systems, with green component values of 640, 18 for blue, and 7 for grey m^3/animal, while the intensive system had a WF of milk of 887, 26, and 9 m^3/animal for the green, blue, and grey components. In contrast, the green WF of lactation grazing varied according to the type of system and the weight of calves, amounting to 1926 in the extensive system, while 2015 and 3067 m^3/animal in the mixed and intensive ones.

Table 4. Water footprint of meat in intensive, mixed, and extensive production systems (the scenarios are specified in Table 3).

			Intensive System	Mixed System	Extensive System
			WF (m^3/Animal)		
WF of feed	Milk	Green	887	640	640
		Blue	26	18	18
		Grey	9	7	7
	Lactation grazing	Green	3067	2015	1926
	Grazing in rearing	Green	-	174	E1 − E2 = 1392.50 E3 − E4 = 1849.12
	Fattening grazing	Green	-	M1 = 843.7 M_2 = 870	E1 − E3 = 2682.2 E2 − E4 = 131
		Grey	-	0	E2 − E4 = 83.4
	Supplementary feed	Green	I1 = 812 I2 = 755 I3 = 870	387	-
		Blue	I1 − I2 − I3 = 5	0.128	-
		Grey	I1 = 775 I2 = 544 I3 = 1007	0	-
Service water		Blue	3.52	3.71	2.32
Drinking water		Blue	13.44	14.94	16.55
Manure		Grey	313	130	0
WF of a live steer (average)		Green	4767	4073	5593
		Blue	47	37	38
		Grey	1098	137	48.5
		Total	5912	4247	5679.5

3.1. Water Footprint of the Steers in Intensive System

The total green WF of the steers reared in the feedlot varied between 4709 and 4825 m^3/animal in the three scenarios. The grey WF ranged between 867 and 1329 m^3/animal, while the blue WF was 47 m^3/animal, the same in the three cases. Scenario I2, with a diet based on maize grain, soybean cake, minerals/vitamins, and whole plant maize silage (Table 3), had the lowest water footprint in comparison with the other two scenarios, which include barley (I1 and I3) (Figure 4).

As shown in Table 4, drinking and service water added up to a blue WF of 17 m^3/animal in the intensive systems.

In the confinement period of the different scenarios, the green WF of the feed varied between 755 and 870 m^3/animal, the grey WF related to feed ranged in size from 544 to 1007 m^3/animal, and the blue WF and the grey WF of manure were the same for all scenarios (Table 4).

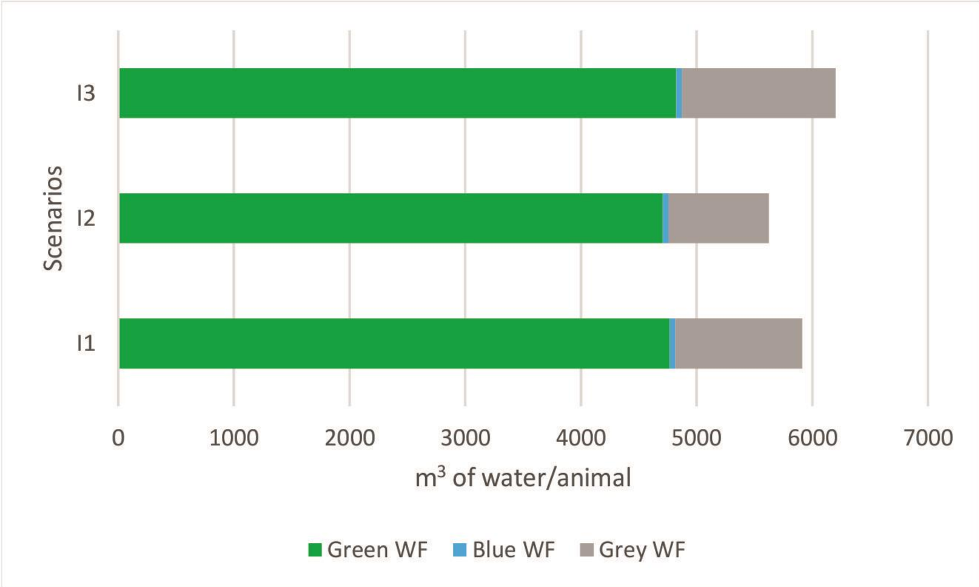

Figure 4. Green, blue, and grey water footprint of steers under different scenarios for the intensive system (the scenarios are specified in Tables 2 and 3).

3.2. Water Footprint of the Steer in Mixed System

According to the scenarios analysed, the green water footprint took values of 4060 and 4087 m^3/animal in scenarios M1 and M2, respectively, while the blue and grey components of steers did not vary in the two scenarios, being 37 and 137 m^3/animal, respectively (Figure 5).

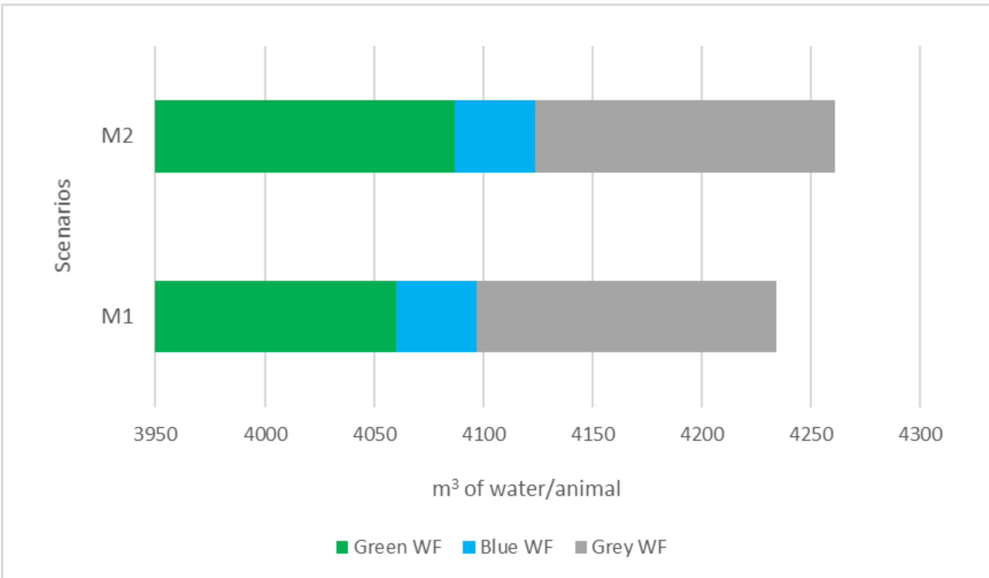

Figure 5. Green, blue, and grey water footprint of steers under different scenarios, reared in a mixed system (the scenarios are specified in Tables 2 and 3).

Both drinking water (calculated for rearing and fattening in the feedlot) and service water were 18 m^3/animal (Table 4).

The green WF of grass consumed during lactation and rearing amounted to 2015 and 174 m^3/animal, respectively.

The green WF of the feed in the extensive phase was 844 or 870 m^3/animal, depending on the scenarios based on rye grass or oats. Finally, during the confinement period, the WF took values of 387 m^3/animal for the green component and the grey WF was 0 m^3/animal, while the blue water footprint from minerals/vitamins was negligible (0.1284 m^3/animal) (Table 4).

This type of production system had a blue mixing water requirement for the feed preparation, of 0.04 m3/animal.

Only the confinement phase of the system had a grey WF of 130 m^3/animal because the N balance carried out for the extensive rearing phase was negative (Table 4).

3.3. Water Footprint of the Steer in Extensive System

When adding up all WF components of the scenarios of the extensive production system, the green WF varied between 4090 and 7097 m^3/animal; the blue WF did not vary, being 38 m^3/animal; and the grey WF took values of 7 and 90 m^3/animal (Figure 6). This proves that the green component is responsible for 99% of the total WF in all the extensive system scenarios.

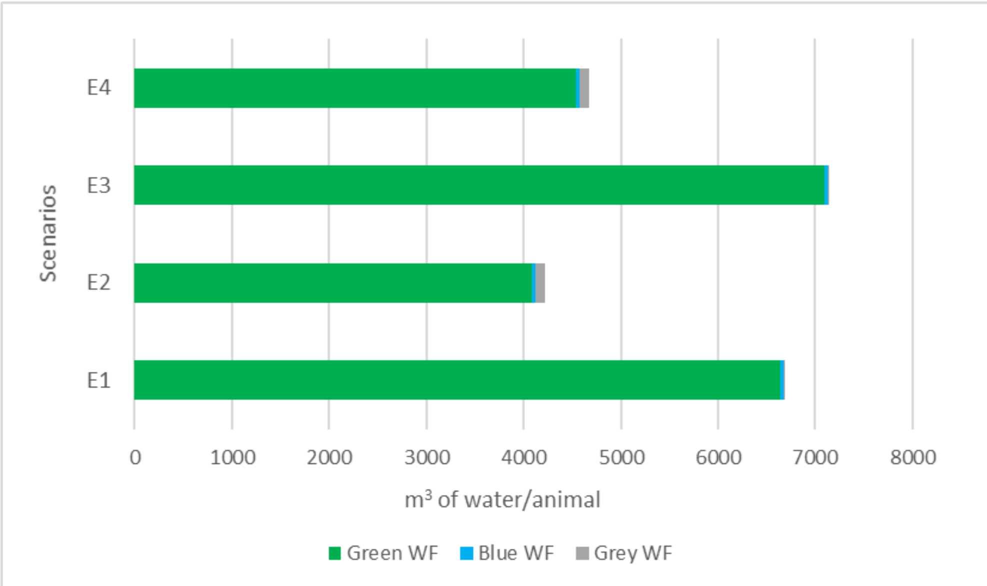

Figure 6. Green, blue, and grey water footprint of steers under different scenarios, raised in an extensive system (the scenarios are specified in Tables 2 and 3).

Two of the four extensive production system scenarios, E2 and E4, have similar total WF values to the intensive and mixed scenarios due to the large green water components in the extensive systems.

The drinking water was 16.55 m^3/animal as an average value for the rearing and fattening phases. When added to the service water, it resulted in a blue WF of 19 m^3/animal.

During lactation, the calf consumed 1.868 tons of grass, which involves a green component of the WF of 1926 m^3/animal.

As for feeding during rearing, it varied according to the availability of the pasture (Table 3). The green WF varied between 1392.50 and 1849.12 m^3/animal (Table 4) depending on whether the diet was based on a mixture of pasture or wheat pasture alone.

After rearing, the steers enter the pasture fattening phase, where feeding also varies depending on the availability of pasture at the time of the year, which can be done on oat pasture or whole plant maize (Table 3). If the feed is based on oat pasture, the WF is 2682.2 m^3 of green water per animal, while if the feed is whole plant maize, the green WF decreases to 131 m^3/animal but a grey WF of 83.7 m^3/animal is generated.

To assess the manure water footprint, a grey WF of 0 was obtained as a result of the N balance for each of the feed sources on which the steer grazed.

4. Discussion

4.1. Comparison Between the Water Footprint of Steer Production Systems

The livestock production system with the highest WF is the extensive one, obtaining values between 4218 and 7142 m^3/animal. The green component contributed 99% of the total because grasses and pastures are rainfed and water-intensive. The large variation between scenarios was the result of the type of feed supplied, with the highest WF being obtained when oat and/or wheat pastures were supplied (Scenarios E1 and E3).

It is important to highlight that this type of extensive system does not have a grey WF from manure management, as the excreta ends up as manure in the fields where the livestock graze. The N balance carried out in the extensive and mixed systems being negative indicates that there was no N pollution load that could reach the groundwater. In addition, the extensive production system uses little blue water resources, only in drinking and services water and lactation, which highlights the fact that producing with green water does not involve a depletion of available water resources as it is one of the few activities that uses rainwater, contributing to water security in the area.

In contrast, the industrial and mixed livestock systems had the lowest WF values per animal, which does not mean that they are more sustainable or efficient in their water use. In fact, although in the case of an intensive system the green component accounts for 78–84% of the WF, the grey component becomes more relevant than in the extensive or mixed systems, with values between 15 and 21% of the total, mainly caused by the inadequate management of excreta, which can easily leach into the groundwater because of a lack of liners in the effluent ponds.

In terms of green WF, the industrial system uses by-products such as soybean cake, which results in lower footprint values, as it makes use of a waste product. Therefore, if soya beans were used directly instead of their by-product (soybean cake), the WF would be higher. In addition, the green WF values per animal had a slight variation of about 116 m^3 between different feeding scenarios, which was due to the inclusion of maize silage or barley in the diet, with higher results when barley was incorporated. This effect is also noted in the total grey footprint, although in this case, the variation was 1.5 times greater when barley was incorporated than when maize silage was supplemented. This increase in WF is observed in scenarios I1 and I3 due to the fact that barley has higher green and grey WFs (m^3/ton) than maize silage [51].

In terms of drinking water, industrial system steers consume twice as much water as the extensive system-fattened steers, and 1.4 times more than in the mixed system fattening, which is mainly due to the salts supplied in the feedlots feeding.

The mixed system is similar to the extensive since the green water footprint is responsible for 95% of water consumption, while the blue and grey water footprints per animal are negligible. In the mixed system, there are no major differences in water use between the two scenarios (27 L of water per animal more in scenario M2). Blue WF on the farm resulted in very low values because this water is associated with feed processing and the minerals/vitamins supplied to the animals during the confinement phase.

The major difference in the total WF between scenarios for the mixed systems (27 m^3 of water per animal more in M1) occurs in the extensive fattening phase depending on whether the steer eats rye grass (M1) or oats (M2).

To sum up, there is a notable variation between intensive, extensive, and mixed production systems to produce 1 kg of beef in terms of water use (Table 4). The difference between the highest and lowest total WF is 2925 m^3 per animal (both of which are in the extensive system), which is mainly found in the feed. It is imperative to emphasise that we are comparing two production systems of different scales, one of industrial size with 9000 animals/year versus a small farm with 300 animals/year. This may influence the results, with the industrial system benefiting by dividing its water use by a higher number of animals and having a lower WF. Another point to highlight is the animal's life cycle; while in the intensive systems, the animal lives a total of 360 days, in the mixed and extensive systems, the life cycle lasts 530 and 540 days, respectively, which means that the consumption of feed and, therefore, water will be higher (Table 1).

4.2. Water Footprint of Livestock: A Comparison

This work is pioneering for several reasons. Firstly, it evaluates in detail the WF of steers raised under different farming systems (extensive, mixed, and intensive) grown in Argentina from the cradle to the farm gate. Secondly, it focuses on grey WF related to N leaching from effluent ponds in intensive steer production systems, while most WF studies focusing on livestock highlight the blue and green WFs, and only in some cases do they include the grey WF related to the animal feed while paying no attention to the manure grey WF. In this respect, Table 5 compares our results with other studies.

There are some aspects of key importance in the water footprint results in the different studies (see Table 5). Firstly, all the studies analysed different categories of animals, and none of them were based on steers. Secondly, the carcass weight differs for each animal. And thirdly, some studies [27,32] considered the slaughterhouse phase, with higher blue and grey water footprints compared to this present study.

Some authors do not include the manure grey WF because of the difficulty of its calculation and the unavailability of appropriate methodologies [27,30,70], whereas others consider it in their studies but they either take theoretical values or do not differentiate between appropriate methodologies for different types of fattening systems [9,32], as was performed in this research.

In agreement with previous studies [31,32,70], we found that the main difference in the final WF is mainly found in the feed and specifically in the production of the ingredients. In particular, we agree that the grey component takes relevance in intensive fattening systems.

González Martínez et al. [32] estimated the WF (green, blue, and grey water) of Spanish Ternera de Navarra fattened in feedlots, obtaining a final value of 4593 m^3/animal, similar to this present study. But there are some relevant differences to highlight. Although the green component is still the main one, in their case, the blue (12% of the total WF) and grey (12% of the total WF) components take relevance, whereas, in our case, the green, blue, and grey WF components in the intensive system reached an average of 81%, 1%, and 18%. This might be due to the fact that González Martínez et al. [32] included the slaughterhouse phase, which contributes to increasing the blue and grey WF.

Mekonnen and Hoekstra [9] obtained lower results for the green and grey components than this present study for Argentina; this may be due to the fact that they worked with databases, which are not adjusted with local and regional data, and they may have underestimated the water use of beef, especially the grey component. Despite numerical differences, this research agrees that while the total WF of the animals decreases as systems intensify, the opposite occurs with blue and grey WFs. Furthermore, the green WF of feed is responsible for the largest percentage of the total animal footprint. The global average WF estimated by Mekonnen and Hoekstra [9] for each production system is higher than the values found in our research. The causes may be due to global variations in production systems, different climatic conditions, and water use practices, as well as the availability of water resources, which can significantly increase the average total water footprint.

Table 5. Comparison of studies on water footprint (WF) (L/kg) of bovine.

Livestock System	**WF**	**Present Study (Average)**		**Mekonnen and Hoekstra [9]**		**Government of San Luis Province [70]**	**Klopatek and Oltjen [27]**	**Palhares et al. [30]**	**González–Martínez et al. [32]**
Country		**Buenos Aires–Argentina**		**Argentina**	**World Average**	**San Luis**	**United States**	**Brazil**	**Navarra, Spain**
Animal Category		**Steer**		**Bovine Carcasses and Half Carcass**		**Bovine of Beef Meat**	**Beef Cow**	**Beef Cattle**	**Ternera of Navarra PGI**
Functional Unit		**m^3/Animal**	**L/kg of Animal**	**L/kg of Meat**		**L/kg of Animal**	**L/kg of Meat**	**L/kg of Meat**	**L/kg Meat**
Intensive	Green	4767	8667	1973	6283	12,322	not included	5038	9955
	Blue	47	85	120	483	5436	2275	769	1577
	Grey	1098	1996	42	505	not included	not included	not included	1731
Mixed	Green	4073	9256	4436	10,510	not included	not included		
	Blue	37	84	143	359				
	Grey	137	311	10	285				
Extensive	Green	5593	12,568	5069	14,996	9500			
	Blue	38	85	112	328	269			
	Grey	48	107	3	172	not included			

Research from the province of San Luis did not include the grey WF of the animals, and only considered the green and blue components, obtaining higher values than those of this work in both intensive and extensive systems and not reflecting the premise described previously in the work of Mekonnen and Hoekstra [9]. The main causes of these differences may be due to the fact that they considered the theoretical blue water needed for crops and the low yields of crops that are subsequently fed to livestock.

Klopatek and Oltjen [27] calculated the blue WF of the beef cow, with results 27 times higher than ours. This difference is mostly explained by the fact that all crops and pastures destined for animal feed were irrigated, being responsible for the largest portions of blue water use. Other than that, the study covers the period from the cradle to the slaughterhouse gate, which can increase the blue component of the WF. On the other hand, it uses data from a global database, as opposed to us, who worked with local data.

4.3. Water Footprint Improvement and Reductions

The incorporation of by-products into animal diets is an emerging viable practice to reduce the negative impacts of livestock farming, as shown in numerous studies [32,71–75]. Especially in industrial systems, it is a beneficial opportunity because it contributes both to the recycling and revalorisation of wastes and to national food security by recycling low-opportunity cost feed; it also reduces animal feed costs and helps to minimise environmental pressure on the livestock sector, encouraging it to be more sustainable by minimising the carbon footprint and WF per animal [32]. For this reason, it would be interesting to further study the improvement and reduction of the steer WF from a circular economy perspective, such as the incorporation of by-products generated in the study areas (agricultural, brewing, dairy) in diets together with the use of manure as a fertilizer.

In addition, further adjustments to the grey WF are necessary that focus on the use of values of natural nitrate concentration in water updated to the current situation. As indicated in the methodology section, Buenos Aires province is no longer in pristine condition due to the fact that it is an area where agriculture has been carried out for decades.

5. Conclusions

This study is the first approach to the calculation of the water footprint of live steers in Argentina based on local and detailed data. The results show significant differences in water use across production systems. The weather conditions in Buenos Aires province provide a comparative advantage to an extensive production system, which relies on rainfed grass and feed. This is reflected in the total green WF, which is highest in extensive systems (5593 m^3/animal), compared to mixed (4073 m^3/animal), and intensive systems (4767 m^3/animal). While reliance on rainwater is advantageous in water-abundant regions, it becomes a limitation in rainwater-scarce areas, which would need to rely on blue water sources. On the other hand, the nitrogen-related grey WF is higher in the analysed intensive farming system (1098 m^3/animal) versus mixed (137 m^3/animal) and extensive ones (48.5 m^3/animal). This is due to both the indirect nitrogen fertilizers used in supplementary feed production and manure management. The combination of crops differs in the mixed system, which also includes a grazing period where nitrogen acts as an organic fertilizer, resulting in a lower grey WF.

It is imperative to emphasize that the substantial variability in WF among livestock systems and local conditions, including climate and soil, indicates that generalizations about livestock and livestock products should be avoided. However, in water-abundant regions, non-irrigated, low-input, pasture-based livestock production systems that incorporate by-products have a relatively low impact on freshwater bodies. Further research is needed to refine the WF estimations per production system and diet using more accurate local data to better capture the diversity of production systems. Data collection efforts are needed to extend the WF analyses to the slaughterhouse gate, alongside strategies to reduce the WF at different states of the supply chain. These findings can be a valuable input for agricultural, environmental, and water policies, which should be integrated with other sustainability aspects, such as carbon emissions, social indicators, sensory analyses, and nutritional studies.

To conclude, these types of studies allow for the environmental profiling of the relevant products within specific geographical areas. In an international context, these analyses have become increasingly necessary as many global markets aim to ensure the sustainability of the products they market. As consumer demands and international environmental policies grow, these studies enable countries and producers to comply with global standards, improve their competitiveness in international trades, and access commercial opportunities, while contributing to the reduction of their environmental impact and the responsible management of water resources.

Supplementary Materials: This research includes the development of a water footprint calculator for each steer production system. We share the complete dataset at http://hdl.handle.net/11336/248559. Access on 25 November 2024.

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