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Water Footprint Analysis of Sheep and Goat from Various Production Systems in Northern China

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Abstract: Water scarcity is a significant global problem. Considerable water resources are consumed in the production of livestock and poultry products, thus posing a huge challenge to global freshwater resources. Sheep meat has the second highest water footprint among livestock meat products. Furthermore, as the demand for sheep meat increases on a year by year basis, water consumption continues to rise as a result. In order to make better informed decisions around water management, it is necessary to estimate the water footprint of animal husbandry. This study offers a comprehensive overview of the water footprint of sheep in Northern China. It analyzes the water footprint of feed production and virtual water using CROPWAT, based on the water footprint of sheep and goats in Shanxi under different production systems and feed components. The water footprint was calculated to be 6.03 m^3/kg for sheep and 5.05 m^3/kg for goats, respectively. Therefore, the water footprint of three farming modes, including grazing mixed and industrial in the Shanxi region was slightly higher than what other experts have evaluated for China. These data provide crucial information that can help reduce water resource consumption in animal husbandry and contribute to the development of sustainable strategies.

Keywords: water footprint; north China; CROPWAT; sheep and goat; sustainable development

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1. Introduction

Nearly 91% of the water footprint from human activities has been correlated with the agriculture, of which 30% comes from livestock and poultry products [1]. In 2020, the world's stock of sheep and goats was about 1.097 billion. China's stock of sheep and goats was about 331 million, accounting for 30% of the world's stock. In the same year, the world's lamb production was 16.105 million tons, while China's lamb production was 4.92 million tons, respectively, accounting for approximately 30% of the world's total production [2,3]. Under the dual effects of the release of the grazing prohibition policies and the increasing demand for animal husbandry products, the transition from traditional and mixed farming to industrial farming systems has been foreseeable [4–6]. The impacts of the increased consumption of animal products on the environment has been discussed by many experts [7,8]. The reason for choosing mutton sheep as the research object among ruminants is because it has the following characteristics: 1. it requires a large amount of water resources for breeding; 2. the market demand continues to rise; and 3. fast release speed and large inventory. Due to the Shanxi Province being recognized by the Ministry of Agriculture and Rural Affairs of China as an advantageous area for sheep farming, and is where most farmers mainly graze, it has been deemed as representative. About 70% of the world's freshwater resources are consumed by the agriculture. Although the high-water consumption of livestock products is well known to the general public [9–11], so far, few people have paid attention to the overall impact of animal husbandry on the global freshwater resource demand. Agricultural water consumption accounts for over 60% of China's water resources consumption, and the utilization rate of water resources has been at a low level for a long time, with serious waste [12]. Due to a lack of understanding among consumers regarding the production process of animal products, the consumption of fresh water is still relatively unknown [13].

Furthermore, a nationwide study conducted by Ridoutt et al. (2017) [14] revealed that the water footprint (WF) of sheep produced in Tunisia (18,900 L/kg) was approximately 50% higher than the average WF of Tunisian sheep meat calculated by Mekonnen and Hoekstra in 2010 using global scale analysis (9417 L/kg) [10]. The average water footprint of milk in Morocco based on the global scale analysis conducted by Mekonnen and Hoekstra (3060 L/kg) was approximately 50% higher compared to the water footprint of milk from small dairy farms in the Sais region of northern Morocco reported by Sraïri MT et al. [15] (2016) (1620 L/kg). The disparity between the global and local evaluations of the water footprint primarily stems from the data used to calculate the water footprint of livestock. This is because the data related to climatic parameters, fodder cultivation, soil type, and other factors are site-specific and more precise. Additionally, variations in the climatic conditions and production system patterns exist among countries, and global estimation averages out these differences.

Allan proposed the concept of virtual water [16] to analyze the water consumption of a product, although only the direct consumption of water in the production process was considered, which led to limitations. This concept became more precise in 2002 when Dutch experts (e.g., Hoekstra and Hung [17]) began to quantify the global virtual water. The concept of the water footprint (WF) emerged to account for the appropriation of the natural capital in terms of the amount of water required for human consumption and is used as an indicator for the amount of water used directly and indirectly by consumers or producers. The virtual water footprint differs from the water footprint in that the water footprint can indicate not only the amount of water consumed, but also the type of water source, as well as the amount of pollution and the type of pollution. The amount of water consumed can be presented by accounting for direct and indirect water use. The water footprint comprises three types, being blue water, green water, and the gray water footprint [18]. The blue water footprint represents the amount of surface water and groundwater consumed in the production of the product (evaporation after abstraction); the green water footprint represents the amount of rainwater consumed; and the gray water footprint designates the amount of fresh water required to absorb pollutant loads by the existing ambient water quality standards.

The calculation of the water footprint is founded on the global water footprint standard. Numerous foreign researchers have estimated the water footprint of animal products in various countries and farms, yet their estimations were based on rough assumptions regarding their diverse feed ingredients. Furthermore, the water footprint of feed crops is typically estimated using the national average climate. The objectives of this experiment are therefore as follows: (1) to use the CROPWAT model to simulate the growth environment of feed crops and obtain a more accurate water consumption in the feed process for the climatic conditions of a certain year in Taiyuan City, Shanxi Province (including parameters such as the maximum temperature, minimum temperature, relative humidity, wind power, light intensity, etc.); (2) to estimate the feed consumption and water consumption of different breeds and breeding systems by calculating the feed conversion rate and local lamb production; and (3) calculate the water consumption for each stage of sheep production, and provide support for improving the water efficiency and sustainable development strategies.

2. Materials and Methods

2.1. Selection and Situation of the Test Site

Shanxi Province, with a livestock industry scale of 47%, surpassing the national average by 11%, holds a prominent position as a major breeding province in China. The experimental site is situated in Taiyuan, Shanxi Province, at coordinates 112.50 E and 37.78 N, with an elevation of 779 m above sea level. This region features a temperate semi-arid monsoon climate with an annual precipitation of 450 mm. The soil type prevalent in the area is cinnamon soil [19], making it conducive to various types of livestock breeding.

2.2. Animal Water Footprint

The water footprint of sheep and goats under three different farming modes was studied based on the characteristics of the Shanxi region. The water footprint of live animals comprises three components, including direct and indirect water for feed, drinking water, and service water [1,11]. The animal water footprint was expressed as follows [10]:

$$\mathrm{WF}[a,s] = \mathrm{WF_{feed}}[a,s] + \mathrm{WF_{drink}}[a,s] + \mathrm{WF_{serv}}[a,s] \tag{1}$$

where $\mathrm{WF_{feed}}[a,s]$, $\mathrm{WF_{drink}}[a,s]$, and $\mathrm{WF_{serv}}[a,s]$ represent the water footprint of feed, drinking water footprint, and service water in Class *a* animals (sheep and goats) under the production system *s* (grazing, mixing and industrial), respectively. Service water includes the water required for farm cleaning, animal washing, and environmental maintenance, measured in m^3/yr/animal. Furthermore, the distribution of the farming modes in Shanxi includes approximately 36.6% for grazing, 33.9% for mixing, and 29.5% for industrial farming, respectively. Additionally, in 2020, goats accounted for 39% of the stock, while sheep accounted for 61%, respectively.

2.2.1. Feed Water Footprint

The water footprint of the feed component covers the water footprint of a variety of feed ingredients and the water adopted to mix the feed. The formula is as follows [10]:

$$\mathrm{WF_{feed}}[a,s] = \frac{\sum_{\mathrm{p}=1}^{\mathrm{n}}\left(\mathrm{Feed}[a,s,p] \times \mathrm{WF^{*}_{prod}}[p]\right) + \mathrm{WF_{mixing}}[a,s]}{\mathrm{Pop}^{*}[a,s]} \tag{2}$$

Feed[*a*,*s*,*p*] denotes the annual consumption of *p* (t/year) of feed ingredients for Class *a* animals and the production system *s*;

$WF^{*}_{prod}[p]$ denotes the water footprint of the feed ingredient *p* (m^3/t);

$WF_{mixing}[a,s]$ indicates the amount of water (m^3/year/animal) consumed to mix the feed for class *a* animals and the production system *s*; and

$Pop^{*}[a,s]$ denotes the number of animals slaughtered per year in Class *a* and the production system *s*.

The largest water consumption footprint in livestock industry originates from feed consumption, accounting for 98% of the total water footprint, with drinking water, domestic water, and feed mixing water taking up 1.1%, 0.8%, and 0.03%, respectively [20–22]. Given its small contribution, the feed mixing water component was therefore not considered in this study.

2.2.2. Water Footprint of Feed Ingredients

The feed type, volume, and composition of the water footprint consumed for different crops, roughage, and crop by-products vary depending on the animal type and the production system. The feed water footprint is estimated using the CROPWAT model. The formula is as follows [10]:

$$\mathrm{WF^{*}_{prod}}[p] = \frac{\mathrm{P}[p] \times \mathrm{WF_{prod}}[p] + \sum_{\mathrm{n_e}}\left(\mathrm{T_i}[n_e,p] \times \mathrm{WF_{prod}}[n_e,p]\right)}{\mathrm{P}[p] + \sum_{\mathrm{n_e}}\mathrm{T_i}[n_e,p]} \tag{3}$$

where $P[p]$ denotes the production volume (t/year) of the feed product *p*; $T_i[n_e,p]$ represents the quantity of imported feed product *p*; n_e is the amount of feed product *p* imported (t/year); $WF_{prod}[p]$ expresses the water footprint of the domestically produced feed product

p (m^3/t); and $WF_{prod}[n_e, p]$ represents the water footprint of the feed product p in the exporting country n_e. The water footprint of crop residues (e.g., rice straw, hulls, and sugar beet leaves) have already been accounted for in the main product, such that the water footprint has been set to zero [10].

2.2.3. Consumption and Ingredient of the Feed

Feed consumption and composition vary depending on the animal type and farming system. Feed consumption was estimated using the Hendy (1995) method [15]. The total annual feed consumption (including concentrate and roughage) was calculated based on the annual production of animal products and feed conversion efficiency. The total feed consumption of sheep in Shanxi was obtained by multiplying the feed consumption per sheep by the total number of sheep.

The total feed for the respective production system for ruminants is written as follows [10]:

$$\text{Feed}[a, s] = \text{FCE}[a, s] \times \text{P}[a, s] \quad (4)$$

where *feed*[*a*,*s*] denotes the total amount of feed consumed by Class *a* animals in the production system *s* (t/year); *FCE*[*a*,*s*] represents the feed conversion efficiency (kg dry weight) for Class *a* animals in the production system *s*; and *P*[*a*,*s*] is the total amount of product (t/year) produced by Class *a* animals in the production system *s*.

2.2.4. Estimation of the Feed Conversion Efficiency

The feed conversion rate, also termed as the feed efficiency, refers to the ratio of the weight of feed consumed to the weight of the animal products obtained, and is estimated for different categories of sheep and goats in their respective production systems. A low feed conversion efficiency indicates a high feed utilization efficiency. This conversion rate has been usually adopted in poultry studies. Hendy (1995) [22] proposed a method for calculating the conversion efficiency of non-ruminant feed (such as ducks and pigs). For ruminants (goats and sheep) the feed conversion efficiency can be estimated by dividing the per capita intake by the per capita annual production (sheep and goat meat). The formula is as follows [10]:

$$\text{FCE}[a, s] = \frac{\text{FI}[a, s]}{\text{PO}[a, s]} \quad (5)$$

where *FI*[*a*,*s*] represents the per capita intake (kg dry weight/year/animal) for Class *a* ruminants in the production system *s*, while *PO*[*a*,*s*] denotes the per capita product yield (kg product/year/animal) for Class *a* animals in the system *s*. The product yield per animal for ruminants (sheep and goat meat) is expressed as follows [10]:

$$\text{PO}[a, s] = \frac{\text{p}[a, s]}{\text{Pop}[a, s]} \quad (6)$$

where *P*[*a*,*s*] represents the total annual output (kg/y) of Class *a* meat in the production system *s*, while *Pop*[*a*,*s*] denotes the total number of Class *a* animals in the production system *s*.

2.2.5. Estimation of Feed Composition

There are generally two types of feed: “concentrated feed” and “roughage”. The amount of concentrated feed for each animal category and production system can be estimated using the following approach:

$$\text{Concentrate}[a, s] = \text{Feed}[a, s] \times \text{f}_\text{c}[a, s] \quad (7)$$

where concentrate[a,s] represents the amount of concentrate feed consumed (tons/year) by the Class *a* animals in production system *s*. The proportion of concentrate feed in the total feed is denoted by $f_c[a, s]$. The data for the $f_c[a, s]$ were derived through combining the information obtained from Bouwman et al. (2005) [4], Hendy (1995) [22], and the specific conditions in Shanxi. Assumptions were made regarding the composition of the concentrate feed for different sheep species in Shanxi. Hendy (1995) [22] suggested that poultry diets typically consist of 50–60% cereals, 10–20% oil meal, and 15–25% of other concentrates, respectively. Feed composition data provided by Wheeler (1981) [23] for different animal categories were used as the basis for estimating the dietary composition of sheep using the FAOSTAT national average volume of concentrated feed.

2.3. Water Footprint Accounting Methods for Feed Crops

2.3.1. Alfalfa Grass

Alfalfa grass is a common weed found in rural areas. It exhibits growth and flowering in April, making it suitable for summer cultivation. Being a perennial grass, it has been widely recognized as an excellent forage grass. The plant produces edible seeds containing oil, thereby making it suitable for fattening purposes. It can be cultivated in various locations as a palatable forage grass, and can also serve as a natural fertilizer [24].

Alfalfa, known as the "king of forage grass", is a highly nutritious plant rich in proteins and multiple vitamins. It can be cultivated in most parts of China [25], with significant cultivation areas in North China, and in the Northwest and Northeast of China [26]. alfalfa is propagated through seeds and can be sown in the autumn (August to September) or spring (March to May). It can be harvested three-to-four times a year, yielding from 60,000 kg to 120,000 kg of fresh grass, or 18,000 kg to 36,000 kg of hay per hectare, respectively. The first crop typically has the highest nutritional value [27].

Alfalfa can be used for grazing, green-feeding, haymaking, ensiling, and as a source of pulp feed for various livestock [28]. Moreover, many experts have verified the positive effects of alfalfa grass on ruminant breeding [29,30]. When used for modulating hay, it should be harvested during the early flowering stage, taking precautions to prevent excessive exposure to sunlight, which can lead to leaf loss. When feeding ruminant animals, such as cows and sheep with fresh-cut alfalfa hay, it is recommended to combine it with other grasses from the *Poaceae* family. For ensiling purposes, it is beneficial to include *Poaceae* grasses with a higher carbohydrate content.

2.3.2. Alfalfa Grass Blue Water and the Green Water Footprint Calculation

The key factor for calculating the crop water footprint is water demand, which is derived from Qing-Song Duan, B. F. He et al. [31] as follows.

$$\mathrm{ETc} = \mathrm{P_e} + \mathrm{I} + \mathrm{U} - \mathrm{D} - \mathrm{R} - \Delta\mathrm{Dw} \tag{8}$$

where *ETc* denotes the crop water requirement; *p* represents the effective rainfall; *I* represents the amount of irrigation; *U* and *D* represent the difference in water infiltration between the upper and lower layers, approximately taken as 0; and *R* represents the amount of surface runoff loss. The formula is as follows:

$$\mathrm{ETc} = \mathrm{P_e} + \mathrm{I} - \Delta\mathrm{Dw} \tag{9}$$

where ΔDw denotes the change in soil mentioned water content before sowing and after harvesting, which is expressed as:

$$\Delta\mathrm{Dw} = \sum\nolimits_{i=1}^{n} (\delta v2 - \delta v1) \times \mathrm{hs}$$

where $\delta v2 - \delta v1$ denotes the volumetric water content of the soil layer *i* at harvest, when growth begins; and *h*s expresses the soil thickness, which was calculated as 200 mm.

In the water balance equation, P_e (mm) denotes the effective rainfall. The FAO provides a recommended formula for calculating the effective rainfall, and in this study, the

CROPWAT-embedded algorithm developed by the FAO was used to determine the effective rainfall. The formula is as follows:

$$P_e = \begin{cases} P(4.17 - 0.2P)/125 & (P \leq 8.3\ \text{mm}) \\ 4.17 + 0.1P & (P > 8.3\ \text{mm}) \end{cases} \tag{10}$$

where P_e is the effective rainfall (mm); and P is the rainfall amount (mm).

The blue water footprint is as follows:

$$W_{blue} = I \tag{11}$$

while the green water footprint is calculated as follows:

$$W_{green} = P_e - \Delta D_w \tag{12}$$

2.3.3. Alfalfa Grass Gray Water Footprint Calculation

The crop gray water footprint can be assessed by diluting the amount of water used for fertilizer pollution during crop growth, assuming that no pesticides were sprayed in the accounting, so the impact of fertilizer application is the only variable to be considered. The crop gray water footprint is correlated with the soil type and the fertilizers available at the production stage. In general, nitrogen, phosphorus, and potassium fertilizers are dominant in the growing season, with phosphorus being capable of reacting chemically with other minerals to produce compounds that are not easily soluble. Thus, it is difficult to pollute water bodies. Potassium has a mobility between nitrogen and phosphorus in the soil, but potassium ions can be attracted by soil colloidal ions, making potassium difficult to filter. Nitrogen can easily enter the groundwater and surface water by leaching to form nitrite ions to pollute the water resources, such that the water required for the dilution of leached nitrogen in the calculation of alfalfa grass gray water in this study is represented by the dilution of nitrogen in the groundwater to meet the standard as the gray water footprint.

$$W_{grey} = 1000N/C_{ON} \tag{13}$$

where W_{grey} represents the amount of gray water (m^3/hm^2); 1000 is the conversion coefficient for the water volume unit, and C_{ON} is the nitrogen standard in the groundwater, based on the Chinese groundwater quality standard, which is set at 20 g/m^3; and N denotes the amount of nitrogen leaching (kg/hm^2). The calculation formula is as follows:

$$N = 10\% \times Nt \tag{14}$$

where 10% is the rate of nitrogen fertilizer leaching [32]; and Nt represents the total amount of nitrogen fertilizer required in the growth period. Fertilizers containing 17% of nitrogen fertilizer were employed in this study.

2.3.4. Alfalfa Grass Crop Coefficient Calculation

The crop coefficient Kc refers to the ratio of the water requirement to the reference crop take-off during the growing period. It can represent the impacts of the crop physiological traits and the growth environment on the water demand. The calculation formula is as follows:

$$Kc = ETc/ETo \tag{15}$$

where Kc is the crop coefficient; ETc is the crop water requirement in mm; and ETo is the reference crop evapotranspiration, which is calculated based on the Penman–Monteith equation, and which was automatically calculated in this study using the CROPWAT model with the following equation.

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma\frac{900}{273+T}\mu2(ea - ed)}{\Delta + \gamma(1 + 0.34\mu2)} \tag{16}$$

where *Rn* is the net radiation of the reference crop surface; *G* is the soil heat flux; *T* is the mean temperature; $\mu 2$ is the wind speed at 2 m from the ground; *ea* and *ed* are the saturation water vapor pressure and the actual water vapor pressure; Δ is the slope of the temperature for *T* in the middle line of the temperature-saturated water vapor pressure relationship curve; and ϒ is the humidity table constant.

2.4. CROPWAT Model Water Demand Calculation

Crop water demand is a crucial factor in calculating the crop water footprint. There are two methods for measuring crop water demand: the field trial method involves direct measurements in the field, and the CROPWAT model utilizes local meteorological data for calculation.

CROPWAT is a model developed by the FAO to calculate the crop water requirements. It is capable of measuring crop evapotranspiration and irrigation water requirements based on the regional meteorological data and rainfall data, and planning irrigation patterns and schedules based on the meteorological and rainfall conditions at the planting site. The applicability of the model in irrigation research was verified by Chunyu Song in 2003 using the CROPWAT model for irrigation trials of cotton, sugar beets, and potatoes in the Middle East [33], and Dandong Qiu's [34] predictions for six Chinese provinces combined with field plantings in Beijing concluded that the CROPWAY model refers to a good response to the water requirements during crop production [35]. Its functions include: (1) calculating the reference crop ETo; (2) calculating the effective precipitation; (3) calculating the crop irrigation water requirement; and (4) formulating a reasonable irrigation plan based on precipitation.

2.4.1. Calculation of the Water Requirements of Feed Crops Based on the CROPWAT Model

The water requirement and irrigation water requirements of alfalfa grass during the growing period can be determined through entering meteorological data, rainfall data, and the crop coefficients for Taiyuan, Shanxi Province in the CROPWAT model. The water requirements are correlated with the meteorological conditions (e.g., temperature, sunshine, humidity, and wind speed), species, development cycle, and irrigation and drainage in Taiyuan. The model requires inputting the daily maximum and minimum temperatures, humidity, light hours, wind speed, monthly average precipitation, and crop coefficients for the growing period of alfalfa grass in Taiyuan.

After obtaining the water demand, the blue water and green water consumptions during the growing period of the alfalfa grass were obtained based on the water footprint theory and the water balance equation [36]. The equation is written as follows:

$$\mathrm{IR} = \mathrm{CWR} - \mathrm{ER} \tag{17}$$

when $ER \geq CWR$, $IR = 0$, blue water consumption is 0, and green water consumption is written as follows:

$$\mathrm{W_g} = \mathrm{CWR} \tag{18}$$

when $ER < CWR$, the blue water consumption is written as follows:

$$\mathrm{W_b} = \mathrm{IR} \tag{19}$$

blue water virtual water content is written as follows:

$$\mathrm{VW_b} = \mathrm{IR}/\mathrm{Y} \tag{20}$$

green water consumption is written as follows:

$$\mathrm{W_g} = \mathrm{ER} \tag{21}$$

and virtual green water virtual water content is written as follows:

$$VW_g = ER/Y \quad (22)$$

where *IR* is the irrigation water use; *CWR* is the crop water requirement; *ER* is the effective rainfall. W_g represents the green water consumption; W_b represents the blue water consumption; and *Y* represents the crop yield.

2.4.2. Data Sources

The meteorological data (e.g., daily maximum temperature, daily minimum temperature, precipitation, relative humidity, light, and wind speed in Taiyuan, Shanxi Province) originated from the CLIMWAT software (v: 8.0) developed by the FAO, and the planted area and unit yield were obtained from the China grass statistics. Tables 1–3 present the interface for entering the meteorological data, rainfall data, and the outputting crop water requirement data in the CROPWAT model, respectively.

Table 1. Taiyuan meteorological data input.

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	Km/day	hours	$MJ/m^2/day$	mm/day
January	−12.2	1.5	49	199	5.7	9.0	1.11
February	−8.8	4.6	49	207	6.0	11.5	1.48
March	−2.5	11.3	50	242	6.3	14.7	2.42
April	4.6	19.2	47	259	6.5	17.6	3.89
May	10.3	25.4	49	233	7.5	20.6	4.96
June	14.7	28.6	57	190	8.1	22.0	5.19
July	18.1	29.2	72	156	6.9	19.9	4.48
August	16.9	27.8	75	147	6.4	17.9	3.96
September	10.5	23.1	73	138	6.4	15.6	3.12
October	4.0	17.6	68	156	6.5	12.9	2.31
November	−2.9	9.2	64	181	5.5	9.3	1.48
December	−10.0	2.5	57	181	5.7	8.3	1.03
Average	3.6	16.7	59	191	6.4	14.9	2.95

ETo: the reference crop evapotranspiration

Table 2. Taiyuan rainfall data input.

	Rain (mm)	Eff Rain (mm)
January	2.3	2.9
February	6.3	6.2
March	10.7	10.5
April	23.8	22.9
May	35.3	33.3
June	54.6	49.8
July	120.2	97.1
August	94.4	80.1
September	64.3	57.7
October	29.1	27.7
November	12.1	11.9
December	3.2	3.2
Total	456.9	403.4

Eff: effective rainfall.

Table 3. CROPWAT output.

Month	Decade	Stage	Kc	ETc	ETc	Eff Rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
May	1	Int	0.73	3.36	33.6	9.8	23.8
May	2	Int	0.73	3.62	36.2	10.9	25.3
May	3	Int	0.73	3.67	40.4	12.8	27.6
Jun	1	Int	0.73	3.78	37.8	13.8	24.0
Jun	2	Int	0.73	3.86	38.6	15.2	23.4
Jun	3	Int	0.73	3.66	36.6	20.9	15.7
Jul	1	Deve	0.78	3.66	36.6	29.1	7.4
Jul	2	Deve	0.86	3.84	38.4	35.4	3.1
Jul	3	Deve	0.94	4.07	44.7	32.5	12.2
Aug	1	Mid	0.99	4.07	40.7	28.7	12.0
Aug	2	Mid	0.99	3.90	39.0	26.9	12.1
Aug	3	Mid	0.99	3.63	39.9	24.4	15.6
Sep	1	Late	0.99	3.38	33.8	21.9	11.9
Sep	2	Late	0.99	3.10	31.0	19.5	11.5
Sep	3	Late	0.99	2.83	28.3	16.1	12.2
					555.8	317.9	237.9

KC, ETc, Eff, and IRR represent the crop coefficient, the crop water demand, the effective rainfall, and the irrigation water demand, respectively.

2.5. Drinking Water Volume Accounting

Local meat sheep breeds in the Shanxi Province mainly comprise Mongolian sheep, Guangling Big Tail sheep, Taihang Green Mountain sheep, and the Lvliang Black Mountain sheep; introduced meat sheep breeds mainly include Dupo, Texel, German Merino, Dausert, Suffolk, Little Tail Cold Sheep, and Ujumqin sheep; introduced meat goat breeds mainly comprise Boer goats; and lambs of large meat breeds are mostly slaughtered at 3–5 months of age, including, for example, small-tailed cold sheep, Boer goats, etc. Usually, sheep grow faster than goats and are slaughtered earlier; slaughter is also earlier in the case of high levels of housing and feeding. In this study, the slaughter was based on 5 months for free-range, 4 months for mixed breeding, 3 months for large-scale sheep, 6 months for free-range, 5 months for mixed breeding, and 4 months for large-scale goats, respectively.

Daily water consumption varies among the different varieties and growth stages. The average value in Table 4 was calculated based on the most frequently cited range for the main varieties. For the mixed tillage system, the average value of the other two systems was used.

Table 4. Drinking water requirement for different animals in different farming systems (liter/animal/day) [1].

Animal	Drinking Water Requirement		
	Industrial System	Grazing System	Mixed System
Sheep (sheep)	7.5	6.0	6.1
Goats (mountains)	3.8	3.5	3.5

[1] Sources: Chapagain and Hoekstra (2003) [11].

2.6. Service Water Accounting

Data from Alberta (1996) [37] and Jermar (1987) [38] were mainly used, and the mean values were taken whenever possible. The results are presented in Table 5.

Table 5. Service water requirements for different animals in different farming systems (liter/animal/day).

Animal	Service Water Requirement			
	Weighted Average	Industrial System	Grazing System	Mixed System
Sheep	1.8	5	1.3	1.3
Goats	1.9	5	1.3	1.3

3. Results

3.1. Alfalfa Grass Water Footprint

The sowing of alfalfa grass took place on May 1st, where the first crop growth occurs during May, June, and July, the second crop occurs during August, and the third crop during September, respectively. The effective rainfall of the first crop was 180.2 mm, accounting for 57% of the total rainfall during the growing period. The effective rainfall for the second crop was 25% of the total rainfall in August, while the effective rainfall of the third crop reached 18% of the total rainfall in September, respectively. The irrigation amount was obtained from the CROPWAT model.

According to Equation (9), the actual water consumption during the growth period, which determines the amount of developed alfalfa grass, can be calculated. Since hay is commonly used as feed, the hay yield, irrigation amount, and evaporation during the three stages under the given conditions are presented in Table 6.

Table 6. Alfalfa grass growth: hay yield, irrigation, and evaporation.

Items	Yield (kg/hm^2)	Irrigation Water (mm)	Evapotranspiration (mm)
First crop	3640 ± 13	162.5	448.34
Second crop	2740 ± 18	39.7	122.76
Third crop	2530 ± 8.5	35.6	93.6

The blue water footprint based on Equation (11), the green water footprint based on Equation (12), and the gray water footprint based on Equation (13) are all shown in Table 7.

Table 7. Alfalfa grass water footprint.

	First Crop Water Footprint	Second Crop Water Footprint	Third Crop Water Footprint	Total (m^3/hm^2)
Blue water	1625	397	356	2379
Green water	745.6	771.4	574	2091
Grey water	255	255	255	765
Total water Footprint	2625.6	1423.4	1185	5235

By incorporating the blue water virtual water content based on Equation (20), the green water virtual water content based on Equation (22), and the gray water virtual water content divided by the amount of fertilizer applied to the yield, the virtual water content can thereby respond to the crop utilization of blue water, green water, and grey water. The results are shown in Table 8. The first crop of Alfalfa grass exhibits the highest blue virtual water content, which represents the utilization rate of blue water. The first crop demonstrates the highest green virtual water content, which indicates the efficiency of crops in utilizing rainfall and soil moisture. The grey virtual water content, influenced by uniform fertilization, exhibits a negative correlation with hay yield, leading to the highest utilization rate in the third crop.

Table 8. Virtual water content of alfalfa grass.

	First Crop Virtual Water Content	Second Crop Virtual Water Content	Third Crop Virtual Water Content
Blue water	0.44642	0.14489	0.14071
Green water	0.49505	0.29233	0.22806
Grey water	0.07005	0.09306	0.10079
Total virtual water content	1.01152	0.53028	0.47667

The above analysis revealed that the virtual water content of alfalfa grass was nearly 1 m^3/kg for the first crop, 0.5 m^3/kg for the second crop, and 0.5 m^3/kg for the third crop, respectively, and that the water utilization decreases with the increase in the harvesting crop. In addition, the above data was obtained from dry matter.

3.2. Animal Water Footprint

The water footprint of feed ingredients is estimated by combining the feed conversion ratio, and the water footprint of animal products can be highly influenced by the production system and geographical distribution. When shifting from grazing to industrial production systems, feed conversion efficiency will improve (Table 9). For example, the Netherlands has a smaller water footprint than India as the Dutch animal production system is dominated by scale, and therefore their water footprint will be lower than in their grazing and mixing. In addition to this, the climate and agricultural practices in India result in a larger water footprint per ton of feed compared to in the Netherlands.

Table 9. Feed conversion efficiency (kg of feed output per kg of dry weight).

Animal Category	Animal Production System	East Asia	World
Sheep and goats	Grazing	49.2	49.6
	Mixed	21.1	25.8
	Industrial	13.6	13.3
	Overall	24.8	30.2

The output weight refers to the weight of the carcass.

From free-range systems to hybrid systems to industrial systems, the water footprint of lamb products decreases sequentially [14,17,21,39–42]. In brief, the total life cycle water footprint of sheep in the Shanxi Province under a wide variety of farming modes has been listed in Table 10.

Table 10. Water footprint of sheep.

Species	Breeding Method	Water Footprint of Living Animals at the End of Life (m^3/t)	Average Water Footprint at the End of Life (m^3/only)	Weight at the End of Life (kg)	Fermentation Cycle (Months)	Average Water Footprint (m^3/kg)
Sheep	Free-range raising	8895	346.89	39	5	8.89
	Mixed	6331	246.91		4	6.33
	Industrial	4113	160.41		3	4.11
	Weighted average	6032	235.24			6.03
Goat	Free-range raising	7482	224.47	30	6	7.48
	Mixed	4750	142.50		5	4.75
	Industrial	3006	90.20		4	3.0
	Weighted average	5056	151.69			5.05

The largest water footprint of animal production originates from feed consumption, accounting for 98% of the total water footprint. Potable water, service water, and feed mixes only take up 1.1%, 0.8%, and 0.03% of the total water footprint, respectively.

4. Discussion

4.1. Comparison with Existing Research

The water footprint theory has garnered significant attention from the academic community since its inception. Thus far, the water footprint research worldwide has primarily focused on the global scale, national scale, and the basin scale water footprint of consumption, involving agriculture, industry, and other water-using sectors. Moreover, there is a lack of research on the water footprint of animal husbandry in China, despite Shanxi being among the top ten regions in terms of sheep population. Therefore, we will begin by comparing our water footprint per ton of mutton with previous studies, and subsequently assess the total water footprint associated with animal feed production, comparing it to findings from the previous five studies.

The results of representative global research on sheep footprints are presented in Table 11. Due to the influence of the scale, the water footprint (WF) of livestock products has been better reflected in local analysis compared to global analysis.

Table 11. Existing research on the water footprint of sheep in China and worldwide (m^3/t).

Species	China				World Average				Source
	Herding	Mixed	Industrial	Weighted Average	Herding	Mixed	Industrial	Weighted Average	
Sheep	4147	2304	1021	2300					Mekonnen and Hoekstra (2010) [20]
	9994	5805	2839	5813					Mekonnen and Hoekstra (2012) [10]
					7294	3686	2452	4278	Mekonnen total water footprint (1996–2005) [20]
	8730	8730	8730	8730					Huang Deng Ying and Yang Hong (2018 Xinjiang) [43]
	8895	6331	4113	6032					Author's Data
Goat	2790	1521	653	1620					Mekonnen and Hoekstra (2010) [20]
					5412	2856	1578	3078	Mekonnen total water footprint (1996–2005) [20]
	5345	3048	1624	3270					Mekonnen and Hoekstra (2012) [10]
	6230	6230	6230	6230					Huang Deng Ying and Yang Hong (2018 Xinjiang) [43]
	7482	4750	3006	5056					Author's Data

The mutton water footprint estimated in this paper provides new support for the accounting of the water footprint of animal husbandry in Northern China, as shown in Table 11. Although the test data is similar to the average WF of Chinese sheep estimated by Mekonnen, the water footprint of goats in our study was slightly higher than his estimate. As mentioned in the introduction, there are three factors that can explain the differences between this paper and the predecessors in the water footprint of sheep in China. Firstly, the quantity and composition of animal feed in this study were determined using more accurate data. Secondly, different scenarios and the weighted averages of three production systems were considered. Thirdly, the gray water footprint and the water consumption in each stage were considered. For the analysis of the sheep WF in Xinjiang by Deng-Ying Huang et al. [43], Xinjiang has a temperate continental climate with an average annual precipitation of nearly 150 mm. The climate in Xinjiang is dry, with a long sunshine duration and scarce precipitation. Xinjiang young goats have a slaughter cycle of about 10 months, meaning they eat more during the growth period. At the same time, Xinjiang's breeding mode is dominated by grazing, resulting in a high average water footprint. There will be a corresponding gap in the WF due to the different agricultural characteristics (e.g., soil, landscape, and climate) [20,44–47] In other words, the WF will be lower in the humid areas than in the arid areas. In a study by Bosire et al. (2015) [45], the WF of milk was compared among three ecosystems: arid, semi-arid and humid. The findings indicated that the WF of milk in the humid areas (1200 L/kg) was lower than that in the semi-arid and arid areas (2000 L/kg). In addition, Ibidhi et al. (2017) [21] also compared the sheep meat WF in Tunisia for different conditions, and their results showed that the carcass meat WF in arid areas (24,500 L/kg) > semi-arid areas (19,300 L/kg) > humid areas (12,800 L/kg). The reason for this variation is likely due to the high evapotranspiration and low crop yield in the arid areas, thereby causing a higher WF with water use [47].

4.2. Strategies for Reducing the Water Footprint in Livestock Production

The increase in the feed conversion efficiency when transitioning from a grazing to an industrial production system (Table 9) explains the outcome. Free-range lamb production requires approximately three-to-four times more feed per unit of product compared to an industrial system. As the feed quantity increases, the water usage in the feed production also increases. The industrial system relies more on concentrate feed compared to the mixed production system, and the mixed system relies more on the concentrate feed compared to the free-range system. The overall roughage to concentrate ratio is 7:3 for sheep and 8:2 for goats, respectively. Concentrate feed has a larger water footprint compared to coarse feed of the same weight, which negatively impacts the total water footprint of the industrial and mixed systems. However, this negative factor is insufficient to compensate for the low feed conversion rate of the grazing system.

Most researchers are currently focused on the determination of the WF of livestock products in various countries, and less research has been performed on how to reduce the WF of livestock product production [36,46,48]. The following methods to reduce the WF in sheep, but not limited to sheep alone, have been proposed: (1) reducing the environmental WF production from the feed, (2) improving the efficiency of feed resource utilization, (3) strengthening the management water and drinking water link control, and (4) advocating people to change their daily dietary habits.

Due to the significant contribution of feed production to the water footprint of livestock products (approximately 98%), it is therefore crucial to utilize water resources efficiently in this stage of production. There are specific methods that can be implemented to effectively reduce the WF: (1) select cultivars suitable for the local climate: It is important to choose crop varieties that are well-adapted to the local climate conditions. By selecting cultivars with a low water demand and drought tolerance, water consumption can thereby be minimized. Additionally, optimizing irrigation methods, such as using precision irrigation techniques, or employing water-saving practices can significantly increase the irrigation efficiency and reduce water usage. (2) Rationally use waste and optimize farming methods [49]: waste management plays a vital role in reducing the WF. Proper utilization of agricultural waste can contribute to a sustainable feed production. By adopting effective waste management strategies and optimizing farming methods, such as implementing organic farming practices or using integrated farming systems, the overall water footprint can be minimized. (3) Deepening the research on water technology: continuous research and development in water-saving technologies are essential for reducing the WF. Investing in innovative water technologies, such as advanced irrigation systems, precision farming techniques, and hydroponics, can lead to more efficient water use in feed production. (4) Select feed similar to agricultural by-products: High-water-footprint grains used in feed production can be replaced with alternative feed options that have lower water footprints. For example, agricultural by-products, such as crop residues or agro-industrial products can be utilized as feed sources. These alternatives not only reduce the water usage, but also contribute to waste reduction and resource efficiency.

By implementing these practical measures, it is possible to significantly reduce the water footprint associated with feed production for livestock, thereby contributing to more sustainable and efficient livestock farming practices.

4.3. Limitations and Prospects

In addition to the existing research on the water footprints of terrestrial livestock, it is important to consider the water footprints of marine animals to comprehensively assess the environmental impacts of animal-based food production. In the current body of water footprint (WF) research, there has been a limited focus on marine animals. However, it is crucial to include marine organisms in the analysis as they offer potential alternatives to meat products with their high nutritional value. It is worth noting that the inclusion of marine organisms in livestock production may also exert pressure on declining fish stocks. Therefore, understanding the WF associated with marine animals is essential to gain a comprehensive understanding of the environmental impacts of animal-based food production. Further research in this area will provide valuable insights into the potential role of marine organisms in reducing the livestock WF while addressing sustainability concerns regarding fish stock declines [50].

Obtaining accurate data sources for global water footprint evaluations is challenging, often relying on regional estimations, which increase uncertainty in allopatric water footprint calculations. Schyns and Hoekstra (2014) [51] observed a 20% uncertainty in the crop production water footprint estimates during their assessment of Morocco's water footprint. The majority of the water footprint for livestock products originates from the fodder-growing segment, potentially introducing bias in the accuracy of the data.

While the water footprint (WF) provides valuable insights into water resource consumption by livestock production, it is essential to reinforce the concept of the ecological footprint and adopt a comprehensive approach to the sustainable utilization of all ecological resources. Given the increasing attention to the livestock water footprint (WF), it is crucial to conduct in-depth studies on standardized measurement indicators, accurate data sources, and predictive models to address the various uncertainties associated with it.

Future research should focus on strategically reducing unnecessary productions in animal husbandry, aiming to enhance water utilization efficiency, optimize irrigation technology in feed production, promote the rational use of rainwater, and strengthen animal husbandry management practices.

The proposal of the WF serves as a significant gateway for global water management. Given the disparity between the global freshwater supply and demand, the estimation of the livestock WF plays a crucial role in identifying the key areas of high-water consumption and formulating effective mitigation strategies. In light of the variability observed in the water footprint estimates compared to other studies, conducting sensitivity analyses on various input factors can greatly contribute to further understanding the factors that influence these significant differences, particularly those related to the climate. By exploring the impact of these changing key inputs, such as climate variables, we can gain valuable insights into the underlying causes of variations in water footprint assessments. This will enable researchers and policymakers to make informed decisions and develop targeted strategies to mitigate the water footprint of livestock production. Additionally, sensitivity analysis can guide future research in identifying the critical areas for improvement and refining the accuracy of the water footprint calculations. This will be the goal of the author's next research work.

5. Conclusions

In conclusion, this study focused on assessing the water footprint of sheep in Northern China, and its implications for water resource management in animal husbandry. The findings revealed that sheep meat has a significant water footprint, ranking second among the livestock meat products. With the increasing demand for sheep meat, water consumption in this sector continues to rise, exacerbating water scarcity issues.

By analyzing the water footprint of feed production and the virtual water using the CROPWAT model, this study provided a comprehensive overview of the water footprint of sheep and goats in different production systems and feed components. The results showed that the water footprint of sheep was 6.03 m^3/kg, while for goats it was 5.05 m^3/kg, respectively. Notably, the water footprint of grazing, mixed, and industrial farming modes in the Shanxi region was slightly higher than previous evaluations for China by other experts.

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